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Natural Radioactivity in Nordic Fish and Shellfish – Final report

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Abstract

The objective of the NANOD project is to fill knowledge gaps related to the concentration of naturally occurring radionuclides in the fish and shellfish species commonly consumed in the Nordic region, in order to enable more accurate dose assessments for seafood and the total diet in the Nordic countries.

^{210}Po concentrations in the samples of wild fish caught in the Nordic region ranged from 0.01 to 3.4 Bq/kg (fw). The highest concentration of all samples was observed in blue mussels, containing up to 73 Bq/kg. Results of the present and previous work indicate that influences on ^{210}Po concentrations in fish and shellfish are complex, and several factors may play a role. Analyses of ^{210}Pb show an overall lower content. Most ^{226}Ra and ^{228}Ra results were below detection limits of approximately 0.1 Bq/kg or less.

Ingestion dose estimates for the Nordic countries show average national doses ranging from 31 to 58 µSv/y from the examined radionuclides. ^{210}Po accounted for approximately 80-90% of this dose, while the dose from radium isotopes was negligible and below 2%. Despite their low consumption, canned tuna, blue mussels and shrimp accounted for a large share of the dose due to their high ^{210}Po content relative to other species consumed in larger quantities.

Key words

seafood, radioecology, fish, shellfish, natural radioactivity, ingestion dose, diet, polonium

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Final Report from the NKS-B NANOD project 2018-2019 (Contract: AFT/B(19)5)

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Introduction

1.1. Background

The major portion of the ingestion dose received by the general population is caused by naturally occurring radionuclides (O'Connor et al. 2014; Komperød et al. 2015; UNSCEAR 2000). Nonetheless, natural radioactivity in food receives far less attention than anthropogenic radionuclides. The reasons for this is perhaps their natural origins, and that there is no legislation regulating their concentration in food products. In addition, some of the most important natural radionuclides are relatively costly and time-consuming to analyse.

In several countries, previous studies have found seafood to be the single food group that causes the largest contribution to the mean ingestion dose, due to the relatively high content of natural radionuclides in fish and shellfish (Komperød & Skuterud 2018; Ota et al. 2009; Renaud et al. 2015; Watson et al. 2005). Concentrations of natural radioactivity have also been shown to vary dramatically between species (Carvalho et al. 2011; Díaz-Francés et al. 2013; HELCOM 2018; Yamamoto et al. 1994). Therefore, in order to make relevant dose assessments for fish and shellfish, it is important to use activity concentration data for the species that are actually consumed in the respective country or region.

1.2. Scope and objectives

Due to the importance of seafood to the ingestion dose, and its relatively high consumption in the Nordic countries, the NANOD project focuses on the knowledge gap associated with naturally occurring radionuclides in the fish and shellfish species commonly consumed in this region. The aim of the project is to enable more accurate dose assessments for seafood and the total diet in the Nordic countries.

Based on the radionuclides identified as most important to ingestion doses in earlier work, the analyses in this study are limited to ^{210}Po, ^{210}Pb, ^{226}Ra and ^{228}Ra, with ^{210}Po expected to be the single largest contributor[1] (Komperød & Skuterud 2018; Ota et al. 2009; Renaud et a. 2015). ^{210}Po, ^{210}Pb, and ^{226}Ra are all products in the ^{238}U decay chain, while ^{228}Ra is a progeny of ^{232}Th. These radionuclides are ubiquitous in the environment and in our food in varying concentrations.

This report covers the work completed in 2018 and 2019 in the NANOD project. Activities and results published in NKS-416 report "Natural Radioactivity in Nordic fish and shellfish – summary report 2018" (Komperød et al. 2019) are also included in this report.

The Danish representative from DTU could not be involved in the final stage of the NANOD project due to staffing adjustment at the end of 2019. As a result, the DTU was not available not take part in the writing of the final version of this report.

[1] ^{40}K is one of the largest contributor to dose from the diet, and has in some work found to be equal to or exceeding that of ^{210}Po, but since the amount of K (incl. ^{40}K) is strictly regulated by the body, the dose is constant regardless of dietary intake. This means that the ^{40}K content in food is not relevant for calculating doses from food products.

2. Nordic consumption

2.1. Total fish and shellfish consumption

Although fish and shellfish are an important part of the diet in all Nordic countries, the consumption level varies considerably between the countries. The most recent consumption data available for adults in each country is presented in Figure 2.1-1. It should be noted that differences between national data might also arise due to different methods of recording dietary data and time passed since the most recent survey, as national statistics show there have been both increases and decreases in national fish consumption during the last decade.

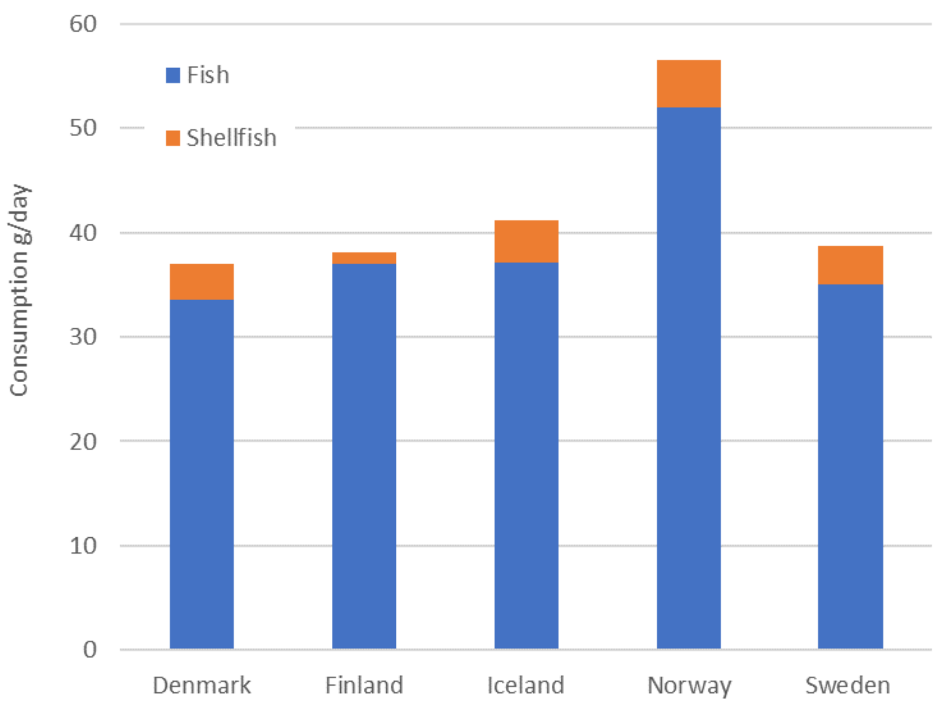

Figure 2.1-1. *Mean consumption (g/d) of fish and shellfish (edible parts) for adults in each Nordic country*[2].

According to the dietary data obtained, Norwegian mean fish consumption is the highest among the Nordic countries, with an average of 52 g/d in the adult population, while Denmark, Finland, Iceland, and Sweden have similar intake of fish ranging from 34-37 g/d. The consumption of shellfish (molluscs and crustaceans) ranges between approximately 1 g/d in Finland and 4.5 g/d Norway[2].

Of course, the consumption varies dramatically within the populations, and certain groups will receive ingestion doses from seafood that are several times higher – or lower – than the mean population data presented in Figure 2.1-1. For example, the 95th percentile for combined fish and shellfish consumption (including fish products) by Norwegian adults is 248 g/d (Totland et al. 2012).

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[2]For references, see footnotes to Table 2.2-1.

2.2. Estimated consumption by species

It has proved somewhat difficult to obtain reliable species-specific consumption data for fish and shellfish in the different countries, and considerable effort was put into making the best possible estimates from different sources of information and new inquiries. An overview of the resulting estimated consumption by species in each of the Nordic countries is provided in Table 2.2-1. A list of all Latin species names relevant for this report is given in Appendix C.

While some non-Nordic seafood species such as *Pangasius* and Alaska pollock have become increasingly significant in the Nordic diet, especially in processed products, species native to the Nordic region still make up the major share of Nordic consumption according to the collected dietary data. Overall, cod, salmon, rainbow trout, herring, mackerel, plaice, and haddock are the main species consumed, although there are clear differences between countries in their relative consumption. Canned tuna, often originating from Asian countries, is also an important food product, especially in Finland and Denmark. Shrimp is the main type of shellfish consumed – mainly the deep-water species northern prawn, which is caught in large volumes both by Denmark, Iceland, and Norway.

Due to its brackish environment, different species tend to inhabit the Baltic Sea than the open seas, especially inner areas like the Gulf of Bothnia. This naturally affects the choices of species consumed and partly explains the significant differences in preferred species, for example between Finland and Iceland. Likewise, there is also a significant difference between the share of saltwater vs. freshwater species consumed, with the Finnish population consuming larger amounts of freshwater species. However, it should be noted that several of these typical freshwater species also inhabit the brackish environments in the inner parts of the Baltic Sea, sometimes making it difficult to draw a clear distinction between freshwater and marine origins based on information on species consumption. In comparison, in Norway for example, fish caught in freshwater is estimated at only approx. 5% or less of total fish and shellfish consumption (Komperød et al. 2015).

Import makes up an important part of some Nordic fish markets; however, fish imported from other Nordic countries appear to make up the major fraction of that import. For example, in Sweden, almost 75% of fish and shellfish consumed is imported; however, Norway is the main country of origin for the 10 most consumed species of that import, followed by Denmark (Ziegler & Bergman 2017). Similarly, in Finland, import accounts for approximately 80% of fish sold, of which around 50% is imported from Norway. Therefore, it appears that the fish and shellfish consumed within the Nordic countries mainly originate from within the Nordic region.

***Table 2.2-1**. Consumption of various species in the different Nordic countries. See footnotes for references. Consumption data was not available for all species in all countries.*

Species	Mean consumption (g/d)				
	Denmark[3]	Finland[4]	Iceland[5]	Norway[6]	Sweden[7]
Alaska pollock[a]	1.7			3.4	0.5
Atlantic salmon[b]*	3.6	11	2.6	12.5	4.9
Arctic char[c]			2.6		
Atlantic cod[b]	2.05		9.7	14	8.6
Atlantic mackerel[b]	5.5			4	5.6
Tuna, canned[b]	6.2	4.1	0.9	2	1
Cod roe[b]				1	1.2
Crab[b]	0.07			0.4	
European perch[d]		1.1			
European plaice[b]	3.5		1.8	0.5	4.1
European whitefish[d]		0.8			
Greater argentine[b]				3.4	
Haddock[b]			13.2	3.9	0.78
Halibut[b]			1.8	1	
Herring [b]	7.4	2.2	1.8	1	4
Mussels[b]			0.1	0.3	
Northern pike[d]		1.1			
Norway lobster[b]			1		
Pangasius[a]*					0.3
Pike-perch[d]		1.1			4.3
Rainbow trout[c]*		5.5		1	
Redfish[b]			0.9	1	
Saithe[b]		1.1	0.9	3	
Scallops[b]			1	0.1	
Shrimp[b]	3.3	1.1	2	3	4
Vendace[a]		1.6			
Wolffish[b]			0.9	0.5	
Other fish		7.4			

[a] Mainly freshwater origin
[b] Mainly seawater origin (some species extend into brackish sea)
[c] Both freshwater and seawater/brackish water origins are common (e.g. in Norway, rainbow trout is farmed in sea; in Finland, it is farmed both in freshwater and in brackish water)
[d] Freshwater/brackish water origin
*Mainly farmed

[3] Based on total consumption from The Danish National Survey of Diet and Physical Activity 2011-2013. Data from Pedersen et al. (2015) and Jeppe Matthiessen at DTU Food (personal communication regarding shellfish consumption). Relative species-specific consumption estimated based on SEAFOODplus (2016) for fish and data from the Danish dietary survey 2005-2008 available in the EFSA database (EFSA 2018).
[4] Natural Resources Institute of Finland, Statistics service. Fish consumption 2017. (Natural Resources Institute 2018)
[5] Estimated based on the dietary surveys of Hrolfsdottir et al. (2019) and Gunnarsdottir et al. (2016).
[6] Data collected through the National dietary survey Norkost 3 2010-2011 (Totland et al. 2012), with species-specific estimates based on VKM (2014). Based on NRK (2018), species composition in fish products was adjusted from VKM assumption of 100% cod to 25% each of cod, haddock, Alaska pollock and greater argentine.
[7] Total consumption from Riksmaten 2010-2011 (Amcoff et a. 2012). Share of most consumed species estimated from Swedish Market Basket 2015, Annex 1 (Darnerud et al. 2017).

3. Previous studies on natural radioactivity in seafood in Nordic areas

Literature review was performed for previously collected activity concentration data for ^{210}Po, ^{210}Pb, ^{226}Ra and ^{228}Ra in seafood in the Nordic region. Each country also looked for relevant published or unpublished data at their institution. A limited number of reports and scientific publications were obtained, as well as some unpublished data. The largest data source in terms of analyses performed was the HELCOM database, which contains data on various sample types from the Baltic Sea (HELCOM 2018).

The overall observation is that data for ^{210}Po was available for several species, although with few analyses in most cases. Several studies included measurements of ^{210}Po in cod and herring, although the results were highly variable. Relatively little data was available for ^{210}Pb, ^{226}Ra, and especially ^{228}Ra. Results for ^{226}Ra and ^{228}Ra were usually below the detection limits. Radium levels in muscle and edible parts are generally very low, but due to a higher dose per Bq emitted, this does not necessarily mean that doses are insignificant. However, the significance of radium isotopes is difficult to establish from the limited information available, especially considering that detection limits are often high. For these reasons, efforts were made to try to obtain detection limits as low as possible for ^{226}Ra and ^{228}Ra in this project.

For several of the commonly consumed species, no data whatsoever on naturally occurring radionuclides was found from the Nordic countries.

A summary of the data collected from previous studies is summarised in Table 3-1. More detailed information on the relevant previous work is provided in Appendix A.

Table 3-1 *Summary of radionuclide concentrations (Bq/kg fw) in previous studies on commonly consumed species in the Nordic region (Table 2.2-1). In this table, n reflects the number of samples analysed, regardless of the number of individuals included in each sample. The number of studies/sources is given in parentheses. The commonly consumed species are included in this overview also in instances when no activity concentration data is available, in order to illustrate the lack of data in these instances. In some cases, the specific species names were not identified in the consumption data and/or in the studies referenced, and therefore could not be specified in this overview. Just over half of these studies are from the Baltic Sea. Other species commonly consumed, but not of Nordic origin, include tuna,* Pangasius, *and Alaska pollock. See Appendix A for more details and references.*

Species	^{210}Po			^{210}Pb			^{226}Ra			^{228}Ra		
	n	Mean	Min-max	*n*	Mean	Min-max	*n*	Mean	Min-max	*n*	Mean	Min-max
Arctic char	0			0			0			0		
Atlantic cod	82 (9)	1.34	0.043 - 4	6 (2)	0.064		79	0.19	0.042 - 4.9	0		
Atlantic mackerel	23 (2)	1.9		1 (1)	0.08		0			0		
Atlantic salmon, farmed	7 (1)		0.003 - 0.23	7 (1)		0.03 - 0.07	100		<0.04 - <0.18	100		<0.006 - <0.39
Baltic clam	0			0			3	2.5	0.64 - 3.98	0		
Blue mussels	(2)		7.5 - 37	(3)		1.2-2.8	11	1.4	0.029 - 12	3	1.5	0.35-3.4
Capelin	1 (1)	5.3		0			0			0		
Cockle	0			0			1	0.71		0		
Cod roe	0			0			0			0		
Crab	0			0			0			0		
Flounder	15 (1)	6.7	2.7-16	0			71	0.046	0.026 - 0.075	0		
Haddock	4 (2)	1.4		0			1	0.188		0		
Halibut	0			0			0			0		
Herring	55 (12)	2.86	0.19 - 23	75 (7)	0.19	0.076 - 0.45	1	0.028	0.02 - 0.055	0		
Norway lobster	0			0			0			0		
Perch	16 (5)	0.19	0.038 - 0.37	14 (4)	0.05	0.010 - <0.15	3		<0.95-<3.2	3	0.54	<0.54-<1.3
Pike	3 (2)	1.9	0.94 - 3.8	1 (1)	0.092		0			0		
Pike-perch	0			0			0			0		
European plaice	47 (4)	4.7	0.26 - 12	4 (1)	0.1	0.055 - 0.15	0			0		
Rainbow trout	(2)		0.039 - <0.26	(2)		0.013 - <0.26	1	<0.73		1	<0.25	
Redfish	1 (1)	0.16		0			0			0		
Saithe	2 (1)	0.92		0			0			0		
Scallop	0			0			0			0		
Shrimp	0			0			0			0		
Sprat	0			0			75	0.073	0.05 - 0.11	0		
Vendace	3 (1)	1.3	0.79 - 1.6	3 (1)		<0.38 - <0.47	3		<2.2 - <4	3		<0.64 - <1.2
Whitefish	(5)	3.2	<0.23 - 13	(4)	0.02	0.018 - <0.25	4		<0.43 - <0.96	4		<0.16 - <0.37
Wolffish	0			0			0			0		

4. Methods

4.1. Identification of species prioritised for sampling

Since the main objective of this study is to collect and produce the data needed to make more appropriate dose estimates for seafood in the Nordic countries, the following factors were prioritised when selecting species to be sampled:

- Species with high consumption in the Nordic countries (Chapter 2.2)
- Species with no or insufficient existing data from prior studies, or exhibiting highly variable levels in previous work
- Species with suspected high levels of ^{210}Po, typically shellfish and plankton-eating fish (see chapter 6)

Some species were also sampled at several locations, in order to examine whether there were substantial regional differences in natural radioactivity levels. Practical considerations were also sometimes limiting in determining what species were possible to sample, such as seasonal changes in availability. A recent survey on farmed salmon from Norway, the main producer in the Nordic region, was recently performed, and this data was found to be sufficient to cover this important product (Heldal et al. 2017).

The different countries chose different ways of sampling species to be analysed in the project. A summary of the samples collected is available in Table 5-1, while more details regarding each sample is provided in Appendix B. An overview of locations for all samples collected in this study is shown in Figure 4.1-1.

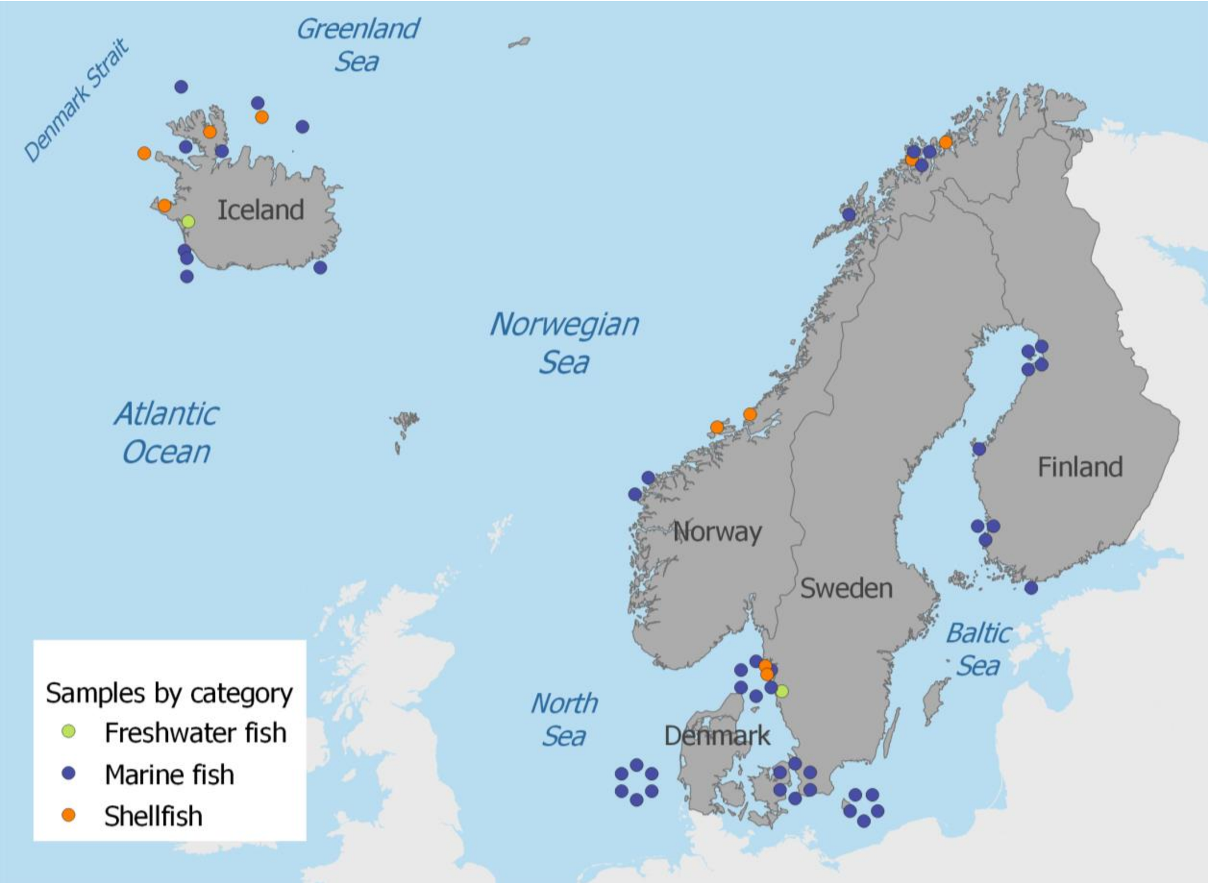

Figure 4.1-1. *Map showing location of the samples collected in this study. Most sampling points show approximate location only. (Exact coordinates only available for Icelandic marine samples.) Rings of points represent several samples from the same regional reference (exact location is unknown).*

4.2. Sampling and analyses for each country

In all, 53 samples of fish and 10 samples of shellfish were sampled and analysed for this work. Only fish muscle or edible parts of shellfish were analysed. According to the project plan, all samples should have been analysed for ^{210}Po and ^{210}Pb, and approximately half for ^{226}Ra and ^{228}Ra; however there were some changes to this plan along the way.

Due to unforeseen events, planned analyses for Danish and Icelandic samples unfortunately did not go as planned, and only ^{210}Po and ^{226}Ra results were obtained. Radium analyses were performed for more samples than initially planned.

The methods of sampling and analyses for each country is described below.

Denmark

Samples of fish and other marine biota were mainly sampled through personal contacts with professional fishermen, some of the sampling was also done by DTU staff. Edible parts of the various foodstuffs were separated manually and freeze-dried for further analysis. A suitable fraction of the freeze-dried material was taken for ^{210}Po analysis (10-30g), and the remaining samples was prepared for gamma spectrometry measurement.

The dried samples were weighted to a beaker, and ashed at 450 °C overnight. The ashed samples were packed into a standard container and sealed, and then measured by gamma spectrometry using HPGe detector for 2-3 days. The concentration of ^{226}Ra in the samples was calculated by analysis of the gamma spectrometry, the detector were pre-calibrated for energy and counting efficiency, and the measurement results of radionuclides were corrected for geometry, self-adsorption and sum coincidence.

A fraction of freeze-dried sample was weighted into a flask. After spiked ^{209}Po yield tracer, concentrated HNO_3 and HCl were added, the samples was digested by heating on hotplate at 250 °C for 5 h. The sample solution was transferred to a beaker, and the solution was evaporated to dryness on a hotplate at 120 °C. 10 mL 30% H_2O_2 and 1 mL 12 M HCl were added, and the solution was heated and evaporated to dryness on a plate. 10 mL 12 M HCl was added and evaporated to dryness on plate. After added 1mL of 12m HCl and 15 mL water, the sample was digested for 30 minutes, then the solution was filtered through a filter paper. HCl was adjusted to 0.3-0.5 M HCl, and 0.3 g of NaCl was added. The solution was transferred to a glass cell and a sliver holder was suspended in the cell. Polonium in the solution was deposited on the silver disc under magnetic stirring for 3 hours, and the deposition cell was put into a water bath of 90 °C during deposition. The silver disc was dismantled from the hold and washed using H_2O by dipping into water 3 times, and then air dried. The disc was then dried at 90 °C in an oven for 15 minutes. ^{210}Po (and ^{209}Po tracer) on the silver disc was measured using an alpha spectrometry.

Finland

Samples were collected as a part of the Surveillance Programme of Environmental Radiation and Monitoring Programme of Radioactive Substances in the Baltic Sea (HELCOM-MORS).

The edible parts of fish samples were dried overnight at 105 °C and minced before the measurement. The samples were directly transferred to a standard plastic container. STUK uses three main measurement geometries of which two simple cylindrical containers were used for activity measurements of fish samples (diameters 42 mm and 74 mm, filling heights 0–26 mm and volumes 0–30 mL and 0–100 mL, respectively). All samples were measured on top of the detector end-cap. In the case of simple cylindrical samples, the efficiency calibration is determined for the sample thickness of 0 mm. Analysis software (UniSampo-Shaman) corrects this for real sample thickness and density. The measuring time of fish samples varied from 6 to 14 hours. Some of the samples were vacuum-packaged to obtain secular equilibrium between radon and its daughters in order to reliably determine the ^{226}Ra activity concentration.

A sample (3-5 g) was spiked with ^{209}Po (first deposition) or ^{208}Po (second deposition) tracer and wet ashed by using concentrated HNO_3 and concentrated HCl. Polonium was deposited on silver planchet and measured by alpha spectrometry. The solution from the first deposition was stored about 6 months to allow the in-growth of ^{210}Po from ^{210}Pb. The second deposition was performed and its ^{210}Po activity is measured. ^{210}Pb content is calculated and the in-growth of ^{210}Pb is subtracted from the results of the first ^{210}Po deposition.

Iceland

Sampling was coordinated by the Icelandic Radiation Safety Authority (IRSA). Samples of cod, haddock, ling, saithe, and black halibut were collected during experimental trawling trips organised by the Marine and Freshwater Research Institute in February and March 2018. Each fish sample consists of a pool of at least ten individuals of a specific length distribution. Standardized sample preparation was in the hands of Matís (Icelandic Food and Biotech R&D). The skinless fish fillets from the individuals were pooled, homogenised and freeze-dried for further analysis.

Samples of Atlantic halibut, plaice, farmed arctic char, and Atlantic herring were bought fresh by IRSA from a trusted source at a fish market. The edible part from about 5 kg (fw) of each species was pooled and dried at 40 °C in a slow-airflow drying cabinet, then ground in a food processor.

Three samples of northern prawn were obtained directly from two fisheries in West-Iceland that were able to provide 5-kg samples of freshly caught shrimp with full sample information, processed for the market and ready for consumption. These samples were dried at 40°C in a slow-airflow drying cabinet, then ground in a food processor. The sampling of blue mussels was carried out by specialists of the University of Iceland's Institute of Research Centre in Suðurnes, for IRSA near Reykjanes. All soft tissue of 100 individuals (length ~50mm, commonly used for human consumption) was removed from the shells and divided into three 2-litre beaker glasses for drying at 50 °C for 4 days.

Analyses were carried out by the Danish partner, as described above.

Norway

Samples collected in Norway were purchased directly from producer or at fish markets that had knowledge of when and where the fish and shellfish were caught. A minimum of 10 individuals were obtained for each species.

Equal amounts of muscle/edible parts were removed from each organism in order to make a representative bulk sample for each species. Care was taken to remove any detectable pieces of bones and shell as not to affect the ^{226}Ra and ^{228}Ra analyses, since this material generally contains several times higher concentrations of radium than soft tissues. Samples were dried at 80 °C for a minimum of 48 hours and homogenised before further treatment.

Determination of ^{210}Po was carried out according to a slight modified version of the method described by Chen et al. (2001). ^{209}Po tracer was added to dried samples. After treating sample several times using *aqua regia*, $NaNO_3$, H_2O_2, HCl, H_2O and NH_2-HCl, the sample was deposited onto silver discs before measurement with Canberra Alpha Analyst. The sample solution was used to determine the ^{210}Pb activity. Adding ^{209}Po tracer once more, the sample was stored for 6 months before a new spontaneous deposition. Then, the sample was measured once more with Canberra Alpha Analyst to determine the ^{210}Pb content from the new ingrowth of ^{210}Po.

Samples of sufficient size (rainbow trout, plaice, northern prawn, blue mussels, saithe, haddock and cod) were ashed at 550 °C in order to achieve detection limits as low as possible for ^{226}Ra and ^{228}Ra. The samples were prepared in hard plastic cylindrical beakers. To prevent radon leakage, the beakers were placed in aluminium-lined bags, and evacuated and sealed using a commercial vacuum packing machine. The samples were stored for a minimum of three weeks to ensure equilibrium and analysed by using HPGe detectors. The ^{226}Ra activity was determined by using a weighted mean of the background-corrected signals from the 295 keV and 352 keV peaks of ^{214}Pb and the 609 keV peak of ^{214}Bi (Mauring et al. 2014). The ^{228}Ra activity was determined by a weighted mean of 338 keV, 911 keV and 969 keV peaks of ^{228}Ac

Sweden

Samples collected in Sweden were purchased in fish markets where Swedes usually buy seafood. Approximately 2-4 kg of a representative number of individuals for each species were collected during the sampling campaigns.

As standard pre-treatment, the samples were washed and non-edible parts (skin, bones, etc.) were removed. Then, each sample was ground and mixed before dried at 80 ºC to constant weight. After the drying process, the samples were again milled, sieved and mixed to ensure the total homogenization of the sample before radiochemical determinations.

Determination of ^{210}Po was carried out according to the radiochemical procedure described by Díaz-Francés (2016). ^{209}Po was added as tracer to check the yield recovery. For the radiochemical determination of ^{210}Po, 2-4 g of dried sample were acid digested by Microwave Digestion System (Milestone Ethos Easy) using 65% Nitric Acid and 35% oxygen peroxide as reagent. Then, polonium was separated by liquid-liquid solvent extraction method using Tributyl Phospahate (TBP) and HNO_3 (8M). For the source preparation, Po was deposited on a copper disk in HCl (2M) at 80 ºC, shaking continuously the sample during 5h. Finally, ^{210}Po was measured by high-resolution alpha spectrometry in order to determine the activity concentration.

In order to determine ^{210}Pb, a second measurement of ^{210}Po was done, in a different aliquot, after waiting at least 6 months to allow a significant ingrowth of ^{210}Po from ^{210}Pb. Then, based on the measurement of ^{210}Po at two different times the activity concentration of ^{210}Pb was calculated by Bateman’s equation (García-Orellana & García-León 2002).

For the determination of ^{226}Ra and ^{228}Ra, dried samples were reduced to ashes at 450 ºC in order to remove organic matter and improve the detection limits. Samples were milled, sieved and homogenized to prepare optimal gamma measurement beaker. Finally, the measurement containers were sealed, using a commercial vacuum packing machine, to avoid any loss of radon in order to determine ^{226}Ra and ^{228}Ra by secular equilibrium. The samples were stored for a minimum of three weeks to ensure secular equilibrium before the measurement by HPGe gamma spectrometry. The ^{226}Ra activity was determined by using a weighted mean of the background-corrected signals from the 352 keV peak of ^{214}Pb and the 609 keV peak of ^{214}Bi. The ^{228}Ra activity was determined by a weighted mean of the 237 keV peak of ^{212}Pb and 911 keV peak of ^{228}Ac.

5. Results

The results from the analyses are provided in Table 5-1. All activity concentrations refer to fish muscle or edible parts of shellfish and is provided in Bq/kg fresh weight (fw). More details regarding each sample is provided in Appendix B.

Table 5-1. *Summary of results (Bq/kg fw) from the NANOD study, including measurement uncertainty (in Bq/kg fw, k=2). More details on sampling location and time is provided is Appendix B.*

Species	Country	Sample origin	^{210}Po	^{210}Pb	^{226}Ra	^{228}Ra
Arctic char[a,b]	IS	Inland, Southern Iceland	0.061 ± 0.02		<0.030	
Atlantic cod	DK	Baltic Sea	0.17 ± 0.06			
	DK	Baltic Sea	0.11 ± 0.01		<0.058	
	DK	Kattegat	0.12 ± 0.03			
	DK	Kattegat	0.09 ± 0.01		<0.052	
	DK	North Sea	1.1 ± 0.11			
	DK	North Sea	0.62 ± 0.03		<0.052	
	IS	Atlantic Ocean	0.16 ± 0.01		<0.026	
	NO	Norwegian Sea	0.070 ± 0.01	0.03 ± 0.007	<0.022	<0.062
	SE	Kattegat/Skagerrak	1.37 ± 0.05	0.1 ± 0.01	<0.057	<0.090
Atlantic halibut	IS	Atlantic Ocean	0.06 ± 0.02		<0.034	
Atlantic herring	DK	Kattegat	1.1 ± 0.07			
	DK	Kattegat	0.36 ± 0.02		<0.052	
	DK	North Sea	0.96 ± 0.09			
	DK	North Sea	0.37 ± 0.02		<0.083	
	IS	Atlantic Ocean	0.97 ± 0.06		<0.063	
	SE	Kattegat/Skagerrak	0.92 ± 0.03	0.12 ± 0.02	<0.084	<0.138
Atlantic mackerel	NO	Norwegian Sea	0.76 ± 0.07	0.07 ± 0.01	<0.42	<0.90
	SE	Kattegat/Skagerrak	1.9 ± 0.06	0.25 ± 0.04	<0.05	<0.081
Atlantic salmon (wild)	DK	Baltic Sea	0.17 ± 0.05			
	DK	Baltic Sea	0.14 ± 0.01		<0.11	
Baltic herring	FI	Baltic Sea	1.3 ± 0.27	0.3 ± 0.05		
	FI	Baltic Sea	2.5 ± 0.42	0.83 ± 0.10		
	FI	Baltic Sea	3.4 ± 0.59	0.68 ± 0.1		
	FI	Baltic Sea	2.2 ± 0.39	0.74 ± 0.1		
	FI	Baltic Sea			<0.44	<0.18
	FI	Baltic Sea			<0.96	<0.26
Black halibut	IS	Greenland Sea	0.16 ± 0.01		<0.033	
Common ling	IS	Atlantic Ocean	0.074 ± 0.009		<0.033	
	IS	Atlantic Ocean	0.11 ± 0.002		<0.042	
European plaice	DK	Baltic Sea	1.2 ± 0.16			
	DK	Kattegat	1.4 ± 0.08			
	DK	Kattegat	1.5 ± 0.05		<0.052	
	DK	North Sea	1.3 ± 0.11			
	DK	North Sea	1.4 ± 0.04		<0.052	
	IS	Atlantic Ocean	0.81 ± 0.03		<0.034	
	NO	Norwegian Sea	0.29 ± 0.04	0.02 ± 0.004	<0.038	<0.093

	SE	Kattegat/Skagerrak	1.3 ± 0.04		<0.049	<0.076
Haddock	IS	Atlantic Ocean	1.2 ± 0.03		<0.042	
	NO	Norwegian Sea	0.31 ± 0.04	0.04 ± 0.007	<0.016	<0.037
Hake	SE	Kattegat/Skagerrak	1.15 ± 0.04	0.03 ± 0.01		
Perch	FI	Baltic Sea	0.04 ± 0.02	0.04 ± 0.02		
Pike	FI	Baltic Sea	1.1 ± 0.29	0.17 ± 0.04		
	FI	Baltic Sea	0.78 ± 0.12	0.14 ± 0.02		
	FI	Baltic Sea	0.01 ± 0.00	0.35 ± 0.04		
	FI	Baltic Sea	0.55 ± 0.11	0.25 ± 0.04		
	FI	Baltic Sea			<0.309	<0.122
	FI	Baltic Sea			<0.603	<0.226
	FI	Baltic Sea			<1.66	<0.371
Pike-perch	SE	Inland, Sweden	0.24 ± 0.01	0.03 ± 0.004		
Rainbow trout[b]	NO	Norwegian Sea	0.020 ± 0.007	0.03 ± 0.007	0.038 ± 0.02	<0.061
Saithe	IS	Greenland Sea	0.23 ± 0.009		<0.035	
	NO	Norwegian Sea	0.39 ± 0.03	0.04 ± 0.008	<0.034	<0.091
	SE	Kattegat/Skagerrak	0.56 ± 0.02	0.01 ± 0.002	0.08 ± 0.003	<0.075
Skipjack tuna[c]	NO	Thailand/Vietnam	10 ± 0.71	0.18 ± 0.05	<0.11	<0.22
Blue mussel	IS	Atlantic Ocean	61 ± 1.7		<0.14	
	NO	Norwegian Sea	73 ± 5.4	9.7 ± 0.92	1.1 ± 0.11	1.5 ± 0.15
	SE	Kattegat/Skagerrak	37 ± 0.99	6.35 ± 0.80		
Brown crab	NO	Norwegian Sea	5.3 ± 0.39	0.41 ± 0.039	<0.059	<0.12
Great scallop	NO	Norwegian Sea	0.93 ± 0.09	0.16 ± 0.05	<0.22	<0.45
Northern prawn	IS	Atlantic Ocean	0.72 ± 0.05		<0.026	
	IS	Atlantic Ocean	0.77 ± 0.05		<0.026	
	IS	Greenland Sea	0.85 ± 0.05		<0.026	
	NO	Norwegian Sea	2.1 ± 0.16	0.08 ± 0.04	<0.025	<0.054
	SE	Kattegat/Skagerrak	30 ± 1.7	1.6 ± 0.14	<0.064	<0.099

a. Freshwater origin
b. Farmed
c. Mix of six common, affordable brands

5.1. ^{210}Po and ^{210}Pb activity concentrations

Concentrations of ^{210}Po in wild fish caught in the Nordic region ranged from 0.01 to 3.4 Bq/kg, with a mean of 0.8 Bq/kg for all samples analysed in this study. In general, herring, plaice and mackerel were among the species with the highest levels of ^{210}Po (Fig. 5-1). Relatively high concentrations were also found in samples of haddock, hake and pike. Halibut, ling, perch and wild salmon displayed overall lower levels, along with the samples of farmed char and farmed rainbow trout. The results also showed quite variable results for some species. For example, data for cod ranged from 0.07 to 1.4 Bq/kg.

In addition to the 52 samples of Nordic fish included in the project, a bulk sample of six different brands of canned tuna was also included due to its importance in some Nordic diets. This sample had by far the highest ^{210}Po content out of the fish samples analysed, containing 10 Bq/kg. The reference date for the analysis for this sample was set to the date of purchase, in order for the exposure to be realistic for consumption in Nordic countries.

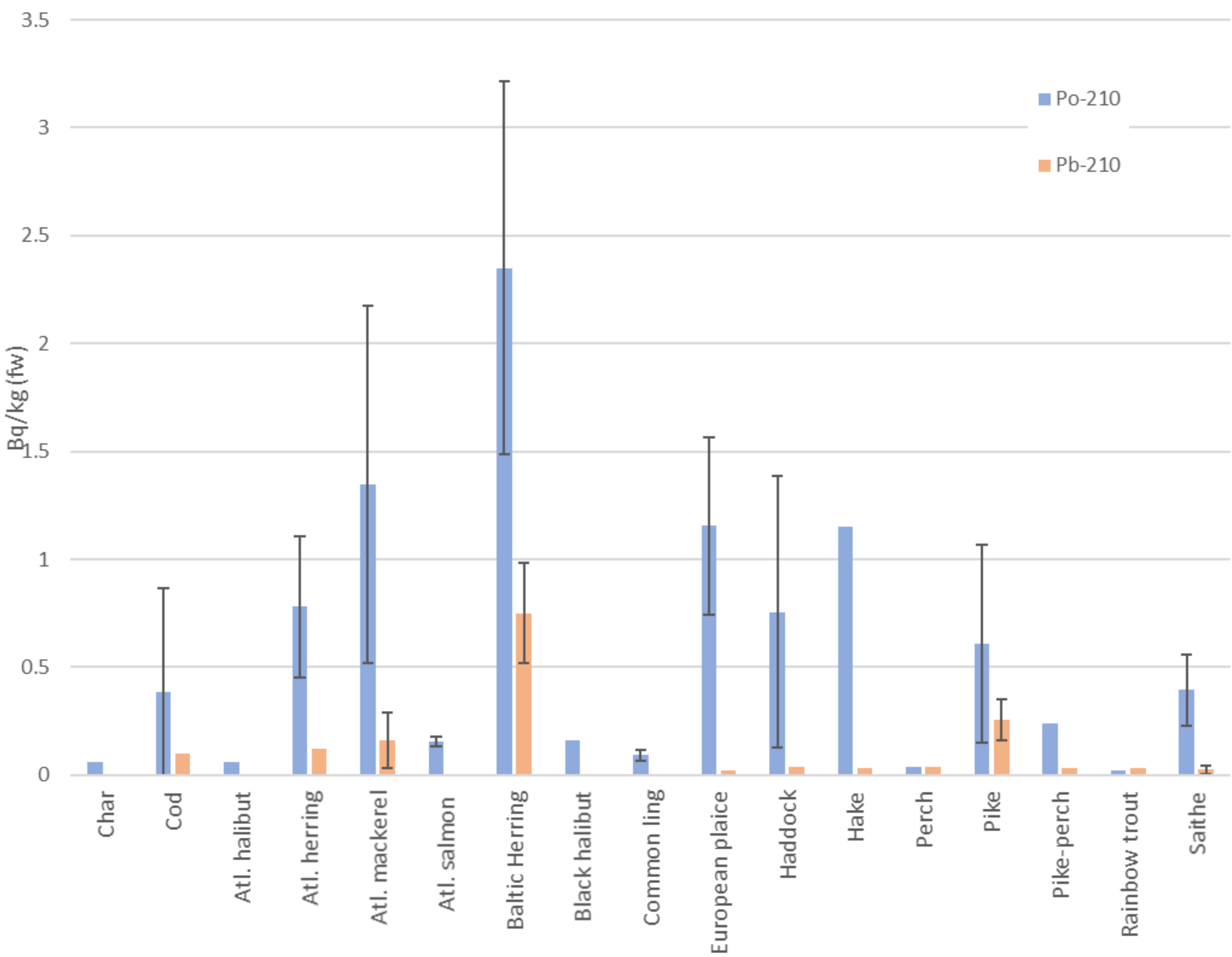

Figure. 5-1. *Mean ^{210}Po and ^{210}Pb concentrations (Bq/kg fw) and standard deviations for samples from the various species of fish from the Nordic countries.*

Shellfish and canned tuna generally contained more ^{210}Po than Nordic fish samples, ranging from 0.72 to 73 Bq/kg. The results are shown in Fig. 5-2. The highest concentrations were found in blue mussels, ranging from 37 Bq/kg in an Icelandic sample to 73 in a Norwegian sample.

Concentrations of ^{210}Po in northern prawn were highly variable. Three Icelandic samples ranged from 0.72 to 0.93 Bq/kg, a sample from Northern Norway contained slightly more at 2.1 Bq/kg, while a Swedish sample caught in the Kattegat/Skagerrak area was found to contain 30 Bq/kg. The sample of scallops analysed included only pure muscle, which might explain the much lower concentrations than in blue mussels, in which the digestive gland was included in analysis as this also is normally consumed.

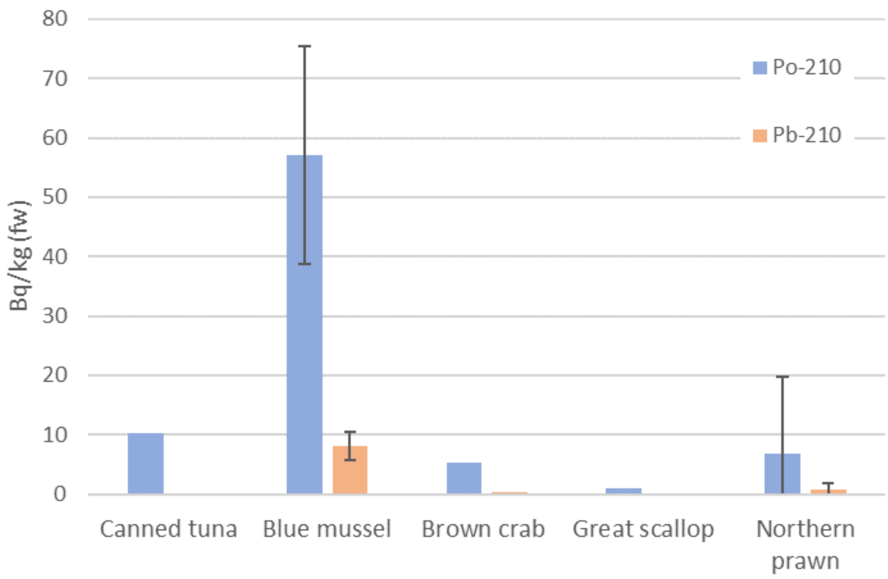

***Figure 5-2**. ^{210}Po and ^{210}Pb concentrations (Bq/kg fw) with standard deviation and shellfish and canned tuna.*

As described in chapter 4.2, ^{210}Pb results are not available for Danish and Icelandic samples. Results from Finnish, Norwegian and Swedish samples nonetheless show that ^{210}Pb concentrations in fish and shellfish are, as expected, much lower than its decay product ^{210}Po. ^{210}Pb concentrations ranged from 0.01 to 0.83 Bq/kg. The highest levels observed were found in Baltic herring. Concentrations above 0.1 Bq/kg were also found in mackerel, pike and Atlantic herring.

Similarly to ^{210}Po, ^{210}Pb levels are also higher in shellfish than in fish, and were in the range of 0.08 Bq/kg in a sample of Norwegian prawn to 9.7 Bq/kg in a sample of blue mussels, both caught in the Norwegian Sea.

5.2. ^{226}Ra and ^{228}Ra concentrations

Radium acts similarly to calcium, and accumulates mainly in such tissues as bones and shell. Not surprisingly, radium analyses for muscle tissues show very low activity concentrations, and mainly below detection limits. However, results below the limit also provide valuable information – and the lower the detection limit, the more valuable the information.

Efforts were made to carry out analyses with detection limits as low as possible. By ashing the samples before performing gamma spectrometry, very low detection limits were obtained for most samples. Ashing reduced the weight of the dried samples by up to 95%, depending on the species and therefore allows for more sample material to be included in the analysis. Fig. 5.2-1 shows that detection limits obtained for ashed samples are overall much lower than for dried samples. This clearly indicates that ashing is a preferred sample preparation method for radium analysis by gamma spectrometry, if a sufficient amount of sample material is available.

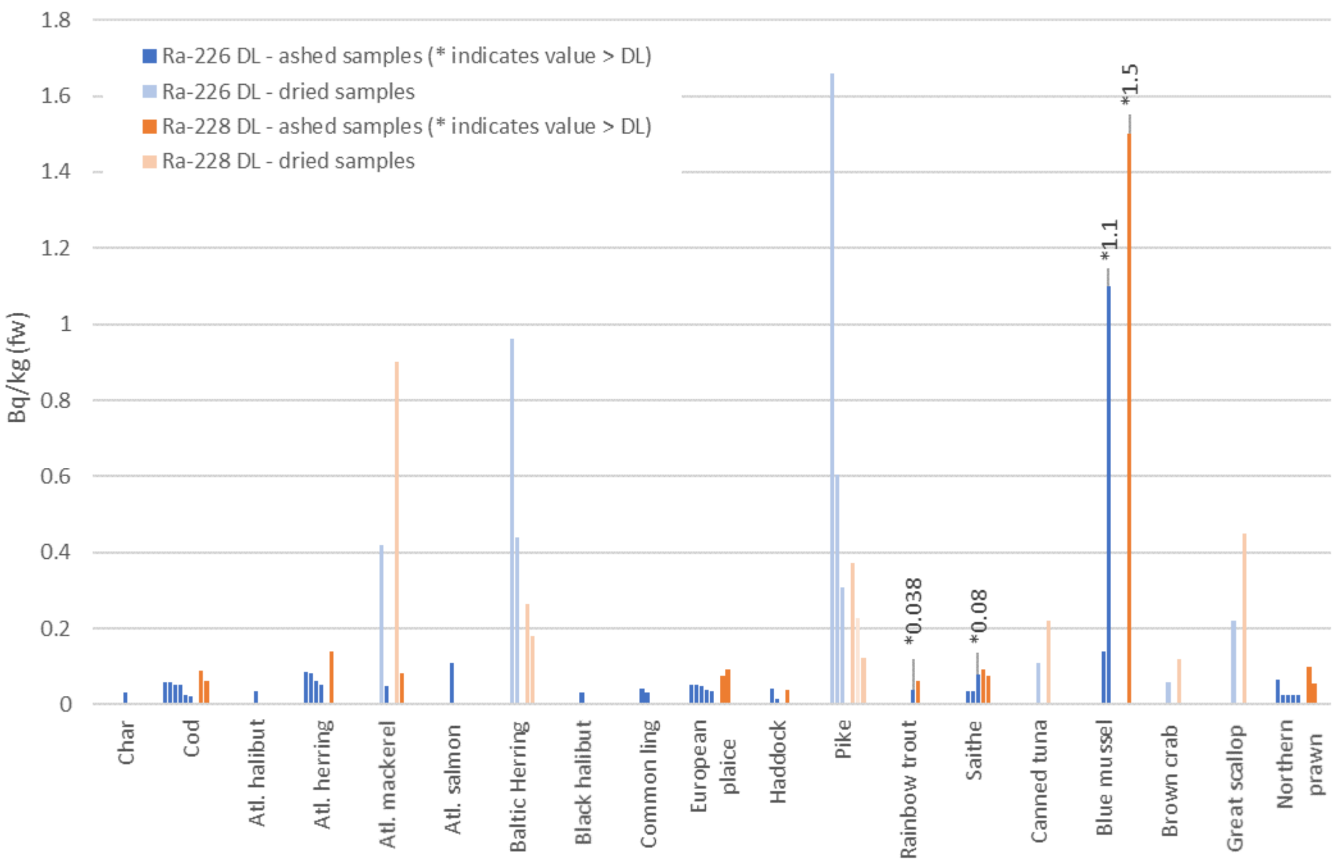

Figure 5.2-1. *Detection limits and measured activity concentrations (Bq/kg fw) for ^{226}Ra and ^{228}Ra. The four samples labelled with "*" and values indicate actual measured activity concentration, i.e., where the concentration is above the detection limit. For all other measurements, the activity concentrations were below detection limits.*

For fish, all ^{226}Ra and ^{228}Ra measurements of ashed samples had measured values or detection limits of approximately 0.1 Bq/kg or less. Most ^{226}Ra measurements were also below 0.05 Bq/kg.

Detection limits for edible parts of crab and shrimp indicate similarly low levels as fish. However, a sample of blue mussels was shown to contain 1.1 and 1.5 Bq/kg of ^{226}Ra and ^{228}Ra, respectively.

Two radium analyses for fish are also above detection limits – 0.038 Bq/kg of ^{226}Ra in farmed rainbow trout from Norway and 0.08 Bq/kg in a sample of saithe caught in Sweden.

5.3. Estimation of representative values for Nordic fish and shellfish

The objective of the NANOD project is to gather more data on the commonly consumed species in the Nordic countries and improve dose estimations. The results presented in this chapter contributes much needed new data towards this goal. However, the number of samples analysed in this project is still low for most species, and several species were not included due to limited resources. Therefore, results from previous work will also be taken into account with the goal of achieving the best possible representation of Nordic levels of naturally occurring radioactivity in seafood.

A set of so-called ‘representative values’ for ^{210}Po, ^{210}Pb, ^{226}Ra, and ^{228}Ra in Nordic seafood was therefore developed, based on results from this work as well as previously collected data from the Nordic region (Chapter 3). The approach to use set of general values for the Nordic region may be further supported by the significant seafood trade between Nordic countries and the fact that no clear geographical trend is apparent from the limited data available (see chapter 6). The estimated representative values are presented in Table 5.3-1. The intention is that these values may be used to represent the levels in the Nordic seafood, for example in other work or for estimating ingestion doses for the Nordic diets (Chapter 7).

A representative value for ^{210}Po and ^{210}Pb was estimated for each species by averaging each individual result from the NANOD study (Table 5-1) and the mean concentration from the other studies reviewed, combined (Appendix A). Using this approach, the data from the NANOD study overall contributes more than each of the previous studies in estimating the representative values. However, this has been considered appropriate for our purpose since in most cases, each NANOD sample represents a separate geographical region - similarly to how the individual studies from the previous studies considered usually also represents only one separate region.

Radium measurements are below detection limits in most cases, both in this work and previous projects. Since the variation in detection limits is dependent on the methods used in sample preparation and analysis, not the actual ^{226}Ra and ^{228}Ra activity concentrations in the sample, the approach used for averaging values for ^{210}Po and ^{210}Pb is not appropriate. In previous studies, many of the detection limits are considerably higher than obtained from ashed samples in this work. Moreover, several values appear very high compared to the findings in the NANOD study, and it may be possible that some of these are incorrectly presented as actual values when indeed they should refer to detection limits. Therefore, we choose to only rely upon radium values from the current study when estimating representative values.

Since all ashed samples of fish showed ^{226}Ra and ^{228}Ra concentrations below detection limits of approximately 0.1 Bq/kg or less, we assume that this also applies to all other analyses of fish consumed in the Nordic region (including the species for which only dried samples are measured and detection limits were higher). The same applies to crustaceans.

One blue mussel sample analysed for radium contained considerably more than 0.1 Bq/kg. The actual values and detection limits obtained for bivalves (blue mussels and scallops) where therefore used in the estimation of representative values for these species. For radium in blue mussels, the representative value was estimated as the mean of the measurement results (above detection limits) and detection limits divided by two. Only one data point was available for scallops, and this was below the detection limit. Also in this case, the detection limit divided by two was used as the value for dose calculations.

Table 5.3-1. *Assumed representative Nordic activity concentrations (Bq/kg fw) estimated from NANOD data as well as previous studies. For species with no radionuclide concentration data available, values for other species with similar types of diets were used (see footnotes).*

Species	Assumed representative values				Radium values used in dose calculations	
	^{210}Po	^{210}Pb	^{226}Ra	^{228}Ra	^{226}Ra	^{228}Ra
Alaska pollock[a]	0.81	0.06	<0.1	<0.1	0.05	0.05
Altantic salmon, farmed	0.01	0.05	<0.1	<0.1	0.05	0.05
Altantic salmon, wild[b]	0.16	0.05	<0.1	<0.1	0.05	0.05
Arctic char, farmed[b]	0.06	0.05	<0.1	<0.1	0.05	0.05
Blue mussels	45	5.0	0.85	1.5	0.85	1.5
Cod	0.81	0.06	<0.1	<0.1	0.05	0.05
Cod roe[a]	0.81	0.06	<0.1	<0.1	0.05	0.05
Crab	5.3	0.41	<0.1	<0.1	0.05	0.05
Greater argentine[c]	1.6	0.14	<0.1	<0.1	0.05	0.05
Haddock	1.01	0.04	<0.1	<0.1	0.05	0.05
Hake	1.15	0.03	<0.1	<0.1	0.05	0.05
Halibut[d]	0.11	0.05	<0.1	<0.1	0.05	0.05
Herring	2.2	0.35	<0.1	<0.1	0.05	0.05
Ling[b]	0.09	0.05	<0.1	<0.1	0.05	0.05
Mackerel	1.6	0.14	<0.1	<0.1	0.05	0.05
Northern pike	0.97	0.20	<0.1	<0.1	0.05	0.05
Norway lobster[e]	6.9	0.82	<0.1	<0.1	0.05	0.05
Pangasius[f]	0.11	0.05	<0.1	<0.1	0.05	0.05
Perch	0.31	0.06	<0.1	<0.1	0.05	0.05
Pike-perch	0.24	0.03	<0.1	<0.1	0.05	0.05
Plaice	2.2	0.05	<0.1	<0.1	0.05	0.05
Rainbow trout, farmed	0.02	0.03	<0.1	<0.1	0.05	0.05
Redfish[c]	0.16	0.14	<0.1	<0.1	0.05	0.05
Saithe	0.50	0.03	<0.1	<0.1	0.05	0.05
Scallops	0.93	0.16	<0.22	<0.45	0.11	0.23
Shrimp	6.9	0.82	<0.1	<0.1	0.05	0.05
Tuna, canned	10	0.18	<0.1	<0.1	0.05	0.05
Vendace	1.3	0.21	<0.1	<0.1	0.05	0.05
Whitefish[g]	3.2	0.07	<0.1	<0.1	0.05	0.05
Wolffish[f]	0.11	0.05	<0.1	<0.1	0.05	0.05

a. Cod activity concentrations assumed when missing data (one or more)
b. Farmed salmon activity concentrations assumed when missing data (one or more)
c. Mackerel activity concentrations assumed when missing data (one or more)
d. Plaice activity concentrations assumed when missing data (one or more)
e. Shrimp activity concentrations assumed when missing data (one or more)
f. Halibut activity concentrations assumed when missing data (one or more)
g. Herring activity concentrations assumed when missing data (one or more)

6. Discussion

Since radium results are mostly below detection limits, it is difficult to make many comparisons between species, regions and other potential influencing factors for these radionuclides. ^{210}Pb results are also fewer than planned due to unsuccessful analyses of Icelandic and Danish samples. Most data points are for ^{210}Po, which is also the radionuclide that generally causes the largest dose contributions. Therefore, most of the discussion will be concerned with ^{210}Po results, although the other radionuclides are also briefly discussed.

Results compared with previous work

For several of the species analysed in this work, no previously reported data for the Nordic region was found in the literature, and therefore there is no basis for comparison with previous work. A summary comparison between the results of the current and previous studies is presented in Table 6-1.

For the species where earlier data is available, the results from the NANOD project are generally within the range of activity concentrations reported in previously performed studies in the Nordic region. Minor exceptions are ^{210}Po concentrations for saithe and pike, which were somewhat lower than previous data, as well as the ^{210}Po level of 73 Bq/kg found in blue mussels from the Norwegian coast. This was somewhat higher than found in previous Nordic studies available, showing 7.5 Bq/kg in mussels from the Baltic Sea and 37 Bq/kg from the coast of Denmark. However, similar or higher concentrations have been reported from other regions, for example by Bustamante et al. (2002) from the French Atlantic coast or by Ryan et al. (1999) from the Irish coast. Therefore, the concentration still appear to be within the normal range.

^{210}Pb results are also within the same range as previous studies, although little data was available for comparison. One exception was for Baltic herring, in which NANOD samples contained somewhat more ^{210}Pb than the previous literature.

Most NANOD results for ^{226}Ra and ^{228}Ra were below the detection limits, and there is also little Nordic data available for comparison. In the previous studies, values shown are sometimes much higher than expected based on the work in this study. For example, values ranging from 0.042 to 4.9 Bq/kg have been reported in the HELCOM database for ^{226}Ra in cod, while the results obtained in the NANOD project were all below 0.06 Bq/kg. One possible explanation for such discrepancies is that detection levels have sometimes been reported as actual activity concentrations by mistake. Another possible explanation is that fragments of bones, skin or shell may have been analysed along with the muscle in some cases. In the NANOD study, great care was taken to make sure that no bones, skin or shell parts were included in the samples for radium analyses, as this can have great impact on the results.

Table 6-1. *Comparison of results in the current work with data from available previous studies (Appendix A). Grey cells denote instances where no previous data was found in the available literature. Both ranges and mean values (when individual measurements are not available) from previous studies were used to represent ranges in this overview. Previous radium activity concentration data that seem unreasonably high are shown in grey font (in which case cells under 'Current work' is also marked as grey).*

Species	Previous work				Current work			
	^{210}Po	^{210}Pb	^{226}Ra	^{228}Ra	^{210}Po	^{210}Pb	^{226}Ra	^{228}Ra
Arctic char (farmed)[a]					0.061		<0.030	
Atlantic cod	0.043 - 4	0.058-0.082	0.042 - 4.9		0.07-1.4	0.03-0.1	<0.022-<0.058	<0.062-0.090
Atlantic halibut					0.06		<0.034	
Atlantic herring	0.5-5	0.11			0.36-1.1	0.12	<0.052-<0.084	<0.138
Atlantic mackerel	1.29-2.5	0.068			0.76-1.9	0.07-0.25	<0.05-<0.42	<0.081-<0.90
Atlantic salmon (wild)					0.14-0.17		<0.11	
Baltic herring	0.19-23	0.076-0.45	0.02-0.055		1.3-3.4	0.3-0.83	<0.44-<0.96	<0.18-<0.26
Black halibut					0.16		<0.033	
Common ling					0.074-0.11		<0.033-<0.042	
European plaice	0.26-12	0.055-0.15			0.29-1.5	0.02	<0.034-<0.052	<0.076-<0.093
Haddock	1.35-1.45		0.19		0.31-1.2	0.04	<0.016-<0.042	<0.037
Hake					1.15	0.03		
Perch	0.038-0.37	0.010-<0.15	<0.95-<3.2	<0.54-<1.3	0.04	0.04		
Pike	0.94-3.8	0.092			0.01-1.1	0.14-0.35	<0.31-<1.7	<0.23-<0.37
Pike-perch					0.24	0.03		
Rainbow trout (farmed)	0.039-<0.26	0.013-<0.026	<0.73	<0.25	0.02	0.03	0.038	<0.061
Saithe	0.92				0.23-0.56	0.01-0.18	<0.035-0.08	<0.075-<0.091
Skipjack tuna[b]					10	0.18	<0.11	<0.22
Blue mussel	7.5-37	1.2-2.8	0.029-12	0.35-3.4	37-73	6.4-9.7	<0.14-1.1	1.5
Brown crab					5.3	0.41	<0.059	<0.12
Great scallop					0.93	0.16	<0.22	<0.45
Northern prawn					0.72-30	0.08-1.6	<0.025-<0.064	<0.054-<0.099

Usefulness of results below detection limits

Even when results are below detection limits, the information can be valuable in cases when detection limits are sufficiently low. The information obtained in this work could be more representative when assessing ingestion doses than some of the alternative references values available. For example, UNSCEAR (2000) provides a reference value of 0.1 Bq/kg for ^{226}Ra in fish products, and Brown et al. (2004) suggested a reference value of ^{226}Ra of 0.2 Bq/kg in fish and 0.7 Bq/kg in shellfish in the European region. Neither UNSCEAR nor Brown et al. found sufficient material to provide a reference level for ^{228}Ra. Hosseini et al. (2010) used a reference value of 1.8 Bq/kg for ^{228}Ra for use with ICRPs Reference Animals and Plants, although this was based on data from an area with enhanced levels of natural radioactivity. Representative data on ^{228}Ra in fish and shellfish are therefore in demand. Most detection limits in the present work suggest that actual ^{226}Ra and ^{228}Ra values in Nordic seafood are below reference values provided in these sources.

Variation between species

Differences in ^{210}Po concentrations between different species is believed to mainly be due to their different diets, as ^{210}Po enters the body primarily via ingestion (Carvalho & Fowler 1994, Carvalho 2011). Polonium is particle reactive, adhering to surfaces in the marine environment, and thus the majority of ^{210}Po in seawater is associated with suspended particles, including plankton (Wildgust et al. 1999; Carvalho et al. 2011; Ryan et al. 1999; Skwarzec & Bojanowski 1988). It has been shown that species like mackerel and herring, whose diet mainly consists of plankton or other small plankton consumers, generally have higher ^{210}Po concentrations than larger predators like cod and salmon (Carvalho 2011a, Fernando & Carvalho 2011). Similarly, ^{210}Po is expected to be higher in filter feeders feeding directly on particles, such as blue mussels, and also elevated in consumers of bottom feeders, such as plaice (Carvalho 2011; Carvalho et al. 2011; Dahlgaard 1995).

Our data partly support such earlier findings. The fish species feeding on the lower trophic levels, like herring and mackerel, are among those with the highest mean activity concentrations of ^{210}Po. However, the levels are not markedly and consistently higher compared to fish species feeding on higher trophic levels in the same geographical areas, and activity concentration ranges are in most cases overlapping between the individual samples of low and high trophic level feeders.

The filter feeding shellfish and bottom dwelling crustaceans show higher activity concentrations of ^{210}Po, with the exception of great scallop. In the current study, edible parts from all organisms are analysed. However, edible parts from great scallop only included the muscle, while in the blue mussel, all soft parts are included, also the gut and gonads. Likewise, the edible part of the brown crab includes not only the claws, but also the soft parts in the carapace and shrimp samples may be more or less cleaned for guts. Other studies have found higher activity concentrations in internal organs of shellfish compared to muscles (Bustamante et al. 2002; Carvalho 2011), The inclusion of inner organs is therefore likely to be one reason for the high ^{210}Po content observed in edible parts of blue mussels in this work. Nonetheless, earlier studies investigating the partitioning of ^{210}Po in various organs also suggests higher concentration in the muscle tissue of mussels than in fish muscle (Godoy et al. 2008; Wildgust et al. 1998). The inclusion of organs in the analyses is therefore not necessarily the only cause.

The highest ^{210}Po concentration in fish was found in the bulk sample of canned tuna, containing 10 Bq/kg. This was despite the fact that the reference data for the analysis was set to the date of purchase, in order to be more representative for Nordic consumption. It is likely that the tuna had been caught many months prior to purchase and that the original concentration was far higher. Khan & Wesley (2016) also found high ^{210}Po content in tuna, ranging from 41 to 93 Bq/kg, while lower levels were found in others (Carvalho et al. 2011; Társico et al. 2007). One reason for the discrepancies could be that many different species and genera fall within the category referred to as “tuna” as a food product. The labelling of the six brands of canned tuna used in this study indicated that skipjack tuna (*Katsuwonus pelamis)* is a common species used in canned tuna in the Nordic region.

Geographic variations

In addition to the differences between species, there can be large differences between samples of the same species caught in different regions. Dahlgaard (1995) examined geographical effect on ^{210}Po concentrations in cod, plaice, and herring caught in the Baltic Sea, Kattegat, and the North Sea, but observed no significant geographical differences. The concentrations in the various species were in the same range as in this work. Carvalho (2011) compared organisms of different ocean depths and found no apparent difference in radionuclide levels between organisms inhabiting the various depths. Instead, it was observed that the species inhabiting the same ecological niches tended to have comparable ^{210}Po and ^{210}Pb levels, despite different habitats. Neither did Pearson et al. (2016) find any significant differences between various species in the coastal regions of New Zealand.

Any variation in geographic region that may exist, could also be related to diet, as different foods may be available for the same species in different regions. For example, populations occupying a coastal environment may have a different diet than populations of the same species inhabiting the larger oceans.

In this work, no general pattern of geographical variation is observed for fish or shellfish (Figure 6-1 to 6-4). For example, somewhat higher levels of ^{210}Po were observed in cod from the North Sea and the Kattegat/Skagerrak regions than in the Baltic Sea. However, for herring, the highest levels were observed in the Baltic Sea – although it must also be considered that Baltic herring (*Clupea harengus membras*) is a separate subspecies of Atlantic herring (*Clupea harengus*)). In northern prawn, higher ^{210}Po concentrations were found in the Kattegat/Skagerrak area than on the Icelandic and Norwegian coasts; however, for blue mussels, the trend was reversed (Figure 6-4). Hence, it is difficult to draw any conclusions of any apparent geographical trends based on these results. If there is a trend, they would differ between species, but there are not enough samples to establish such a pattern in the current study.

One must also consider that the apparent differences between regions could be affected by other factors. For example, some studies have indicated seasonal variations in ^{210}Po concentrations. Since sampling could not be carried out at the same time by all countries, this and other potential influences should be considered as well.

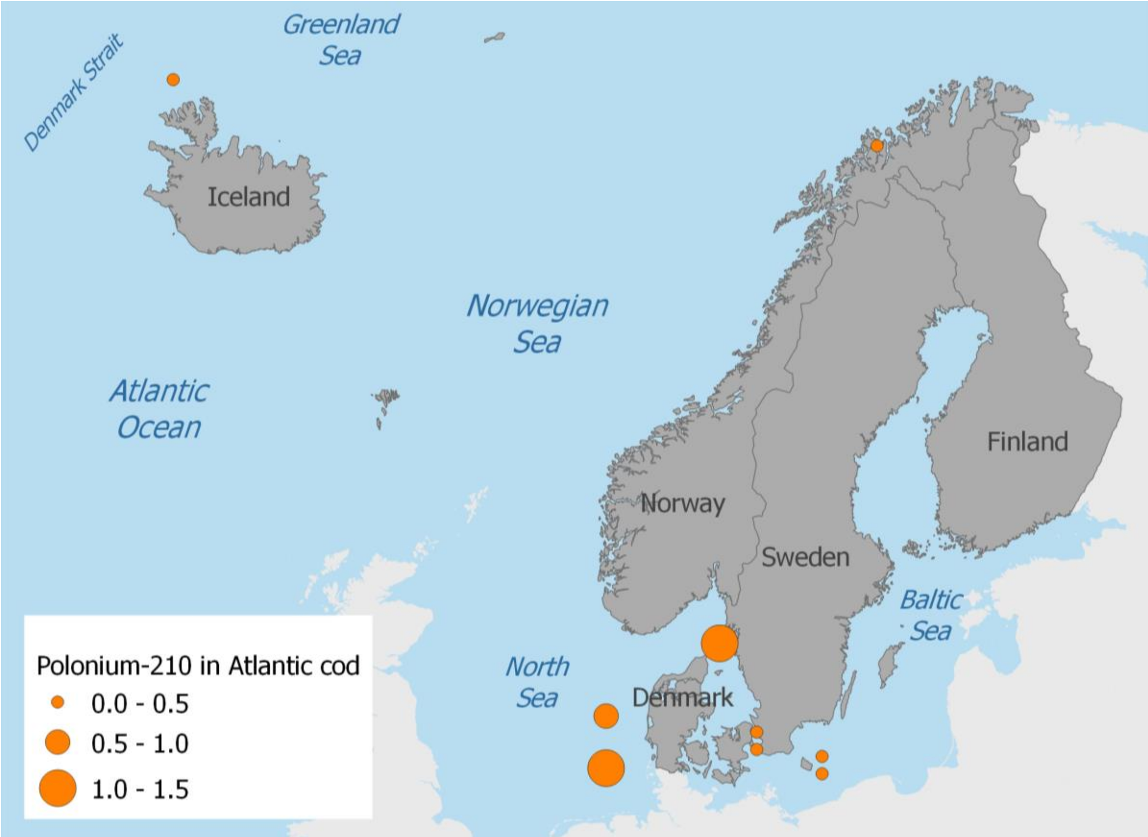

Figure 6-1. *^{210}Po concentration (Bq/kg freshweight) in Atlantic cod.*

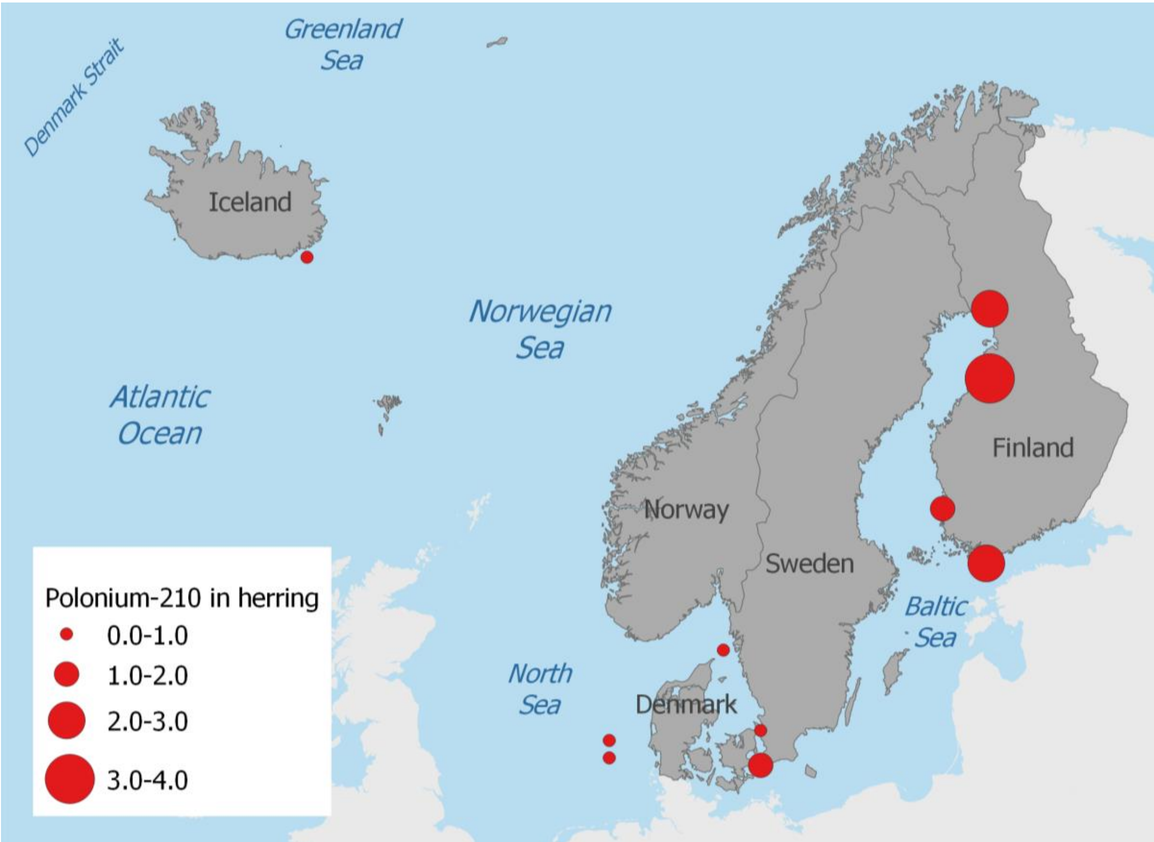

Figure 6-2. *^{210}Po concentration (Bq/kg freshweight) in Atlantic and Baltic herring.*

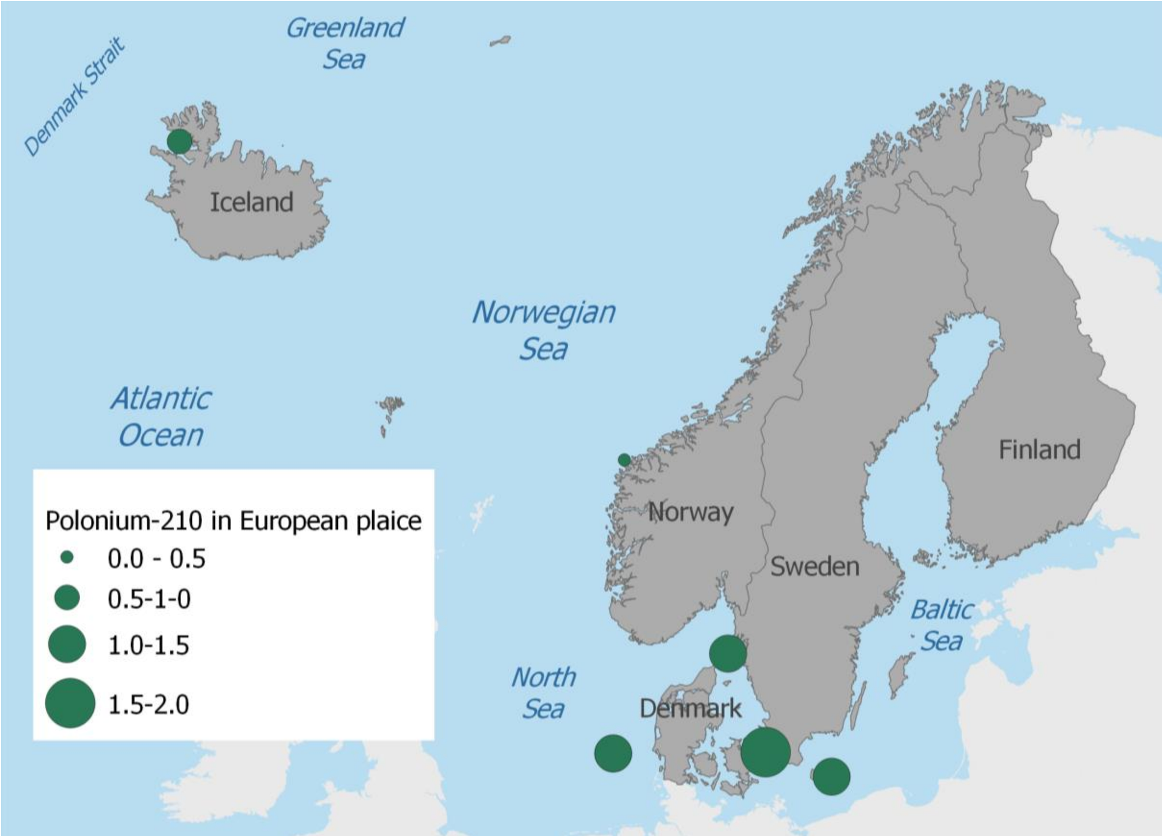

Figure 6-3. *^{210}Po concentration (Bq/kg freshweight) in European plaice.*

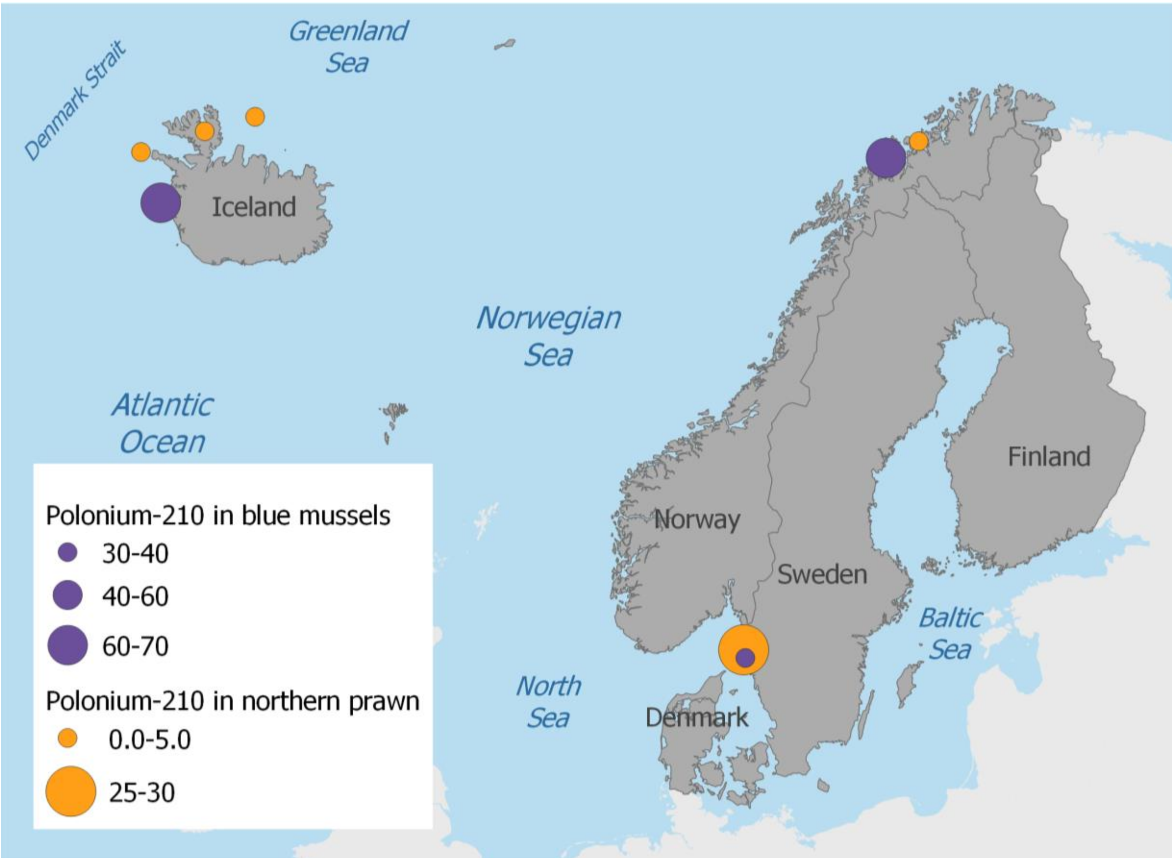

Figure 6-4. *^{210}Po concentration (Bq/kg freshweight) in blue mussels and northern prawn.*

Temporal effects

In the case of ^{210}Po, which is very particle bound, the bioavailability may vary with the seasonality in the primary production by the microalgae in the northern areas. In the wintertime, plenty of nutrients are available in the water masses due to mixing of water under windy conditions, but the primary production is limited by the low light attenuation at sea. During spring, most areas experience a spring bloom with a pronounced production which scavenge the nutrients available. With reduced levels of available nutrients, the production decrease over the summer all though the light levels are high. In autumn, nutrients may be provided again due to storm/wind events while there is still available light, and autumn blooms may occur. Depending on the seasonal and geographical differences in the microalgae productions, the ^{210}Po may be diluted or concentrated on the available particles.

Several studies have examined seasonal variations in molluscs, although with mixed outcomes. Carvalho et al. (2011) examined monthly variations in ^{210}Po and ^{210}Pb concentrations in the Mediterranean mussel on the coast of Portugal, also in relation to the physiological condition of the mussels. Despite no clear changes in seawater concentrations, the authors found an apparent seasonal fluctuation throughout the year. However, this was believed to be caused by changes in body weight due to storage of lipids. ^{210}Po generally binds to protein and amino acids, not fat, meaning the activity per mussel can remain fairly constant and that only variations in body mass affect the activity concentration. Similarly, Wildgust et al. (1999) found an increase in ^{210}Po levels in the common periwinkle on the Welsh coast in the summer, likely due to a drop in body weight due to spawning. Ryan et al. (1999) found significant temporal variability in blue mussels in several sites on the Irish coast, but no clear patterns. Germain et al. (1995), on the other hand, found no distinct seasonal changes in ^{210}Po concentrations in edible parts of blue mussels on the coast of France.

The temporal effect was examined for ^{210}Po concentrations in the present study, but no clear seasonal patterns were observed with the limited number of samples per species.

Ryan et al. (1999) also found strong correlation between ^{210}Po concentrations of suspended material in seawater and the turbidity of the seawater at the given site. Since this factor changes according to both place and time, it could serve as one possible explanation for both geographic and temporal variations that might be observed in some species.

Variation between individuals or populations of same species

Bulk samples were analysed in this work, as it was not within the scope of this study to analyse differences between individuals. However, some of the factors that affect individuals can also apply to whole populations and are therefore relevant to discuss. One such factor is that the exact ecological niche and individual feeding habits may affect differences in radionuclide concentrations within the same species (Carvalho et al. 2011; Cherry & Heyraud 1991). Individual body size or condition can also have an effect on radionuclide concentrations. Dahlgaard (1995) observed significantly higher ^{210}Po levels in blue mussel soft parts with low condition index[8]. Ryan et al. (1999) found no clear correlation with

[8] There are several methods of determining the 'condition index' (CI), although most rely on the relationship between weight of the mussel's soft parts (dry weight) vs. length, volume or weight of the shell. Dahlgaard

condition index, but found a strong linear dependency between ^{210}Po concentration and dry matter content of blue mussel soft tissues, with higher concentrations in smaller individuals. As a side note, studies of cod have also found that different populations of cod are genetically different, including having different growth rates (IMR 2018). It is possible that e.g. growth rates could also potentially influence radionuclide accumulation.

Large variability between individuals sampled at the same place and time has also been observed. For example, Dahlgaard (1995) found standard deviation values ranging from 70-100% in plaice, herring, and cod from the same catches. The significant variations between individuals emphasize the importance of analysing a large number of individuals, or bulk samples consisting of many individuals, in order to obtain representative values.

Potential effects of cooking on ^{210}Po concentrations

It is well documented that some radionuclides may be lost during the process of food preparation. For example, a significant portion of the anthropogenic radionuclide ^{137}Cs is removed through dilution when food is boiled (IAEA 2010). However, all such effects will vary according to the physical and chemical properties of the element.

^{210}Po volatizes at high temperatures and it has been hypothesized that some ^{210}Po also may be lost due to volatilization when food is grilled or baked at high temperatures. Due to the importance of ^{210}Po to ingestion doses from seafood, the available scientific literature was examined to see whether the effect of cooking on ^{210}Po levels should be taken into account. A very limited number of studies was found, and are summarised in Table 3.2-1. All represent muscle/edible parts of the fish and shellfish. The organisms have received slightly different treatments, but the main cooking methods and net gain or loss in ^{210}Po concentration are summarised.

The data varies dramatically and suggest that both increases and decreases in ^{210}Po concentrations may occur during food preparation. Increases likely represent a loss of water from the tissue, thereby increasing the concentration of remaining substances, whereas decreases could represent either loss via fluids, loss due to volatilisation, the added weight of e.g. oil, or a combination.

Due to the ambiguous results of the existing data, it was concluded that no adjustment in ^{210}Po concentrations due to cooking could be made in the dose assessments from fish and shellfish (chapter 7). Due to limited resources and the apparent complexity of the subject, it was not possible to make such studies within the scope of this project since producing data on the main consumed species in the Nordic countries was the main priority. However, studies on the effects of cooking may be the scope of later work.

(1995) defined CI in relation to length, CI = g dry soft parts · 10^6 mm^{-3}. Ryan et al. (1999) used CI = dry flesh weight / dry shell weight. It's possible that different methods used for determining CI influenced the contrasting outcomes.

Table 6-1. *Calculated changes in ^{210}Po concentrations in seafood based on levels observed in previous studies.*

Species	Cooking method	Change in ^{210}Po concentration (%)
Mackerel (*Scomber scombrus*)[a]	Grilled in pan	+5.9
Salmon (*Salmo salar*)[a]	Grilled in pan	> -80
Sardine (*Sardine pichardus*)[a]	Grilled in pan	-24
Blue whiting (*Micromesistius poutassou*)[a]	Grilled in pan	-81
Red mullet (*Mullus barbatus*)[a]	Grilled in pan	-70
Sword fish (*Xiphias gladius*) [a]	Baked in oven	-38
Cod (*Gadus morhua*)[a]	Grilled in pan	+13
Anchovy (*Engraulis encrasicolus*)[a]	Grilled in pan	-14
Sole (*Solea solea*)[a]	Grilled in pan	-20
Clam (*Camelea gallina*)[a]	Steamed	-38
Blue mussel (*Mytilus edilus*)[a]	Steamed	-51
European anchovy (*Engraulis encrasicolus*)[b]	Boiled in water	+4.5
Mediterranean mussel (*Mytilus galloprovincialis*)[b]	Boiled in water	+94
Cross-cut carpet shell (*Venerupis decussata*)[b]	Boiled in water	+59
Mediterranean shore crab (*Carcinus aestuarii*)[b]	Boiled in water	-47
Spot-tail mantis shrimp (*Squilla mantis*)[b]	Boiled in water	+1.1
Mediterranean mussel (*Mytilus galloprovincialis)*[c]	Boiled in hot oil	+3.2
Mediterranean mussel (*Mytilus galloprovincialis*)[c, d]	Boiled in hot oil	+2.3

a. Díaz-Francés et al. 2017
b. Roselli et al 2017
d. Kristan et al. 2015
c. Assumed 15% dry matter when converting dry weight to wet weight concentrations.

Farmed vs. wild fish

The share of farmed fish in the Nordic countries is relatively high. In Sweden, for example, an estimated 40% of seafood consumed is farmed (Ziegler & Bergman 2017). Therefore, it is important to also include farmed fish in studies of naturally occurring radionuclides.

Data from Norway, Finland and Sweden show that the salmon and rainbow trout consumed is usually farmed. Farming could have significant impact on the concentration of certain radionuclides in the fish muscle, due to different diet than its wild relatives.

The sample of Norwegian farmed rainbow trout analysed in this work contain a lower ^{210}Po concentration (0.020 Bq/kg) than what was generally found in the wild fish samples in this work, and the levels are similar to what Heldal et al. (2017) found in farmed salmon along the Norwegian coast (0.003-0.023 Bq/kg).

Rainbow trout and salmon are large predator fish that would be expected to contain relatively low ^{210}Po concentrations compared to fish lower on the food chain in a wild setting. However, the ^{210}Po concentrations in wild salmon from the Bornholm area analysed in this work (0.14-0.17 Bq/kg), are nonetheless about one order of magnitude higher than that of the farmed salmon. The observation of lower concentrations observed in farmed fish vs. wild fish is likely due to the different diets, as the fish feed used in farming consists of feed produced mainly from plant-based ingredients that is likely low in ^{210}Po. Also farmed Arctic char from freshwater contained only 0.06 Bq/kg of ^{210}Po. Wild arctic char feeds largely on plankton and bottom feeders and one might therefore expect more ^{210}Po; however, the farmed fish received plant-based fish feed, which could explain the low concentration. It is also uncertain whether its freshwater origin affects ^{210}Po content compared to saltwater species.

Nordic fish and shellfish in the global market

Nordic seafood makes up over 10% of worldwide exports in terms of trade value (FAO 2018). Norway is the biggest Nordic exporter, second only to China in the global market. This means that Nordic seafood is not only important to Nordic consumers, it is also an important part of global consumption, making it all the more relevant to have knowledge of radionuclide levels. Documentation of concentrations of anthropogenic radionuclides for exported species are already frequently requested by exporters. Requests for documentation of natural radioactivity is still relatively scarce; however, the IAEA, FAO and WHO currently have a joint project to examine the need for guidelines for naturally occurring radionuclides in food as well (IAEA 2017), including fisheries products. Such guidelines may increase the need for data on natural radioactivity in seafood.

7. Ingestion doses from fish and shellfish in the Nordic diet

7.1. Method

In this work, effective doses were calculated using ICRPs ingestion dose coefficients (2012) and the national dietary data presented in chapter 2.

Different approaches are possible for the choice of activity concentration data to use as the input in the calculations. The main question is whether country-specific data best represent the national intake, or whether to assume that averaging data from several countries and studies results in values that are more representative also for national intake because these are less affected by random variations and outliers. Such ‘representative values’ are presented in Chapter 5.3 and implies that the radionuclide levels of fish consumed in the different countries are similar within each species, or at least that any difference between countries is smaller than the random variations caused by other factors than geography.

For estimating doses from the Nordic diets, it is assumed that the values based on data from several countries and studies, are more likely to be representative of Nordic consumption. The ‘representative values’ are therefore used in the estimates presented in this chapter. Dose calculations and a brief discussion on dose estimates made from country-specific NANOD data is presented in Appendix D, as an alternative approach.

For more details on the dose calculations and doses from individual species and/or countries, see Appendix E.

7.2. Results and discussion

Overall findings

The population in Finland is estimated to receive the lowest dose from ^{210}Po, ^{210}Pb, ^{226}Ra, and ^{228}Ra in fish and shellfish with 31 µSv/y, followed by Iceland and Sweden with 34 and 37 µSv/y, respectively (Fig. 7.2-1). Estimated doses in Norway and Denmark are significantly higher at 51 and 59 µSv/y, respectively. Based on earlier assessments, it is not expected that the addition of anthropogenic radionuclides or the inclusion of other naturally occurring radionuclides would significantly impact the result[9] (Komperød & Skuterud 2018; Oatway et al. 2016; O’Connor et al. 2016; Renaud et al. 2015).

As shown in Figure 7.2-1, it is clear that ^{210}Po provides most the dose contribution with approximately 80-90% of the total dose. The ^{210}Pb dose is overall far lower and contributes one tenth or less than that of the ^{210}Po dose. Although the exact values of ^{226}Ra and ^{228}Ra are unknown for most species, it can be confidently established that the dose from radium isotopes in seafood is negligible.

[9] ^{40}K adds a significant overall ingestion dose; however, this dose is more or less constant regardless of what you eat and the concentration in food products due to the homeostatic control of ^{40}K in the body. Everyone also receives a certain dose from ^{14}C, although this dose is also assumed to be consistent regardless of diet.

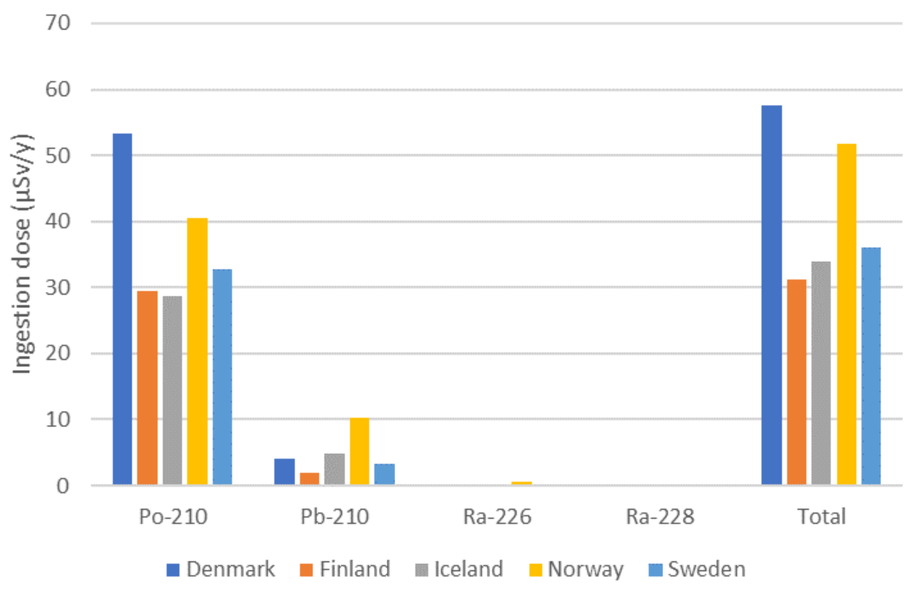

Figure 7.2-1. *Effective doses (µSv/y) calculated using ICRP dose coefficients (ICRP 2012), based on representative Nordic values (chapter 5.3). See Appendix E for details on dose contributions from the different species.*

Dose contributions from various species

An overview of estimated doses from each species is provided in Table 7.2-1. Canned tuna, blue mussels and shrimp account for a large portion of the ingestion doses from seafood to the Nordic population, despite their low consumption. This is due to the far higher ^{210}Po concentrations in these species.

Exposure for persons with high consumption

Ingestion doses associated with fish and shellfish will clearly vary depending on the individual intake, and it is also of interest to assess the dose to population groups with high fish consumption. The highest 95th percentile fish and shellfish consumption for the Nordic countries was found to be 248 g/d, including fish products, as reported for Norwegian adults (Totland et al. 2012). This results in an estimated dose of 229 µSv/y using the representative values. The Norwegian national survey shows higher fish consumption for men than women, and higher consumption with increasing age.

An assessment of how much high consumption of single products may affect the ingestion dose was also performed. The 95th percentile consumption for individual species is not available; however, based on the Norwegian dietary statistics for total fish and shellfish consumption, it has been assumed that the 95th percentile consumption is approximately 5 times higher than the mean intake also for individual species. This ratio was used to calculate ingestion doses from high intake of selected fish and shellfish species that were found to contribute significantly to the mean national doses (Table 7.2-2).

The calculations show that, although obviously increasing the ingestion dose, the exposure to persons with a very high overall intake of fish and shellfish is still moderate compared with the IAEA's general safety requirement that exposure from food should be no higher than approximately 1 mSv/y (IAEA 2014). Persons with a high intake of specific species containing high ^{210}Po levels, such as blue mussels or tuna, still receive only moderate exposure as well. Of course, a few persons with an extremely high intake will have an even higher ingestion dose than in the calculated example. For an actual assessment of compliance with the IAEA requirement of 1 mSv/y, the contribution from other foods must also be taken into account.

Table 7.2-1. *Ingestion dose estimate for each species and country (µSv/y). Empty cells denote that no dietary data is available for the respective species in the given country. Some consumption likely occurs for all species in all countries; however, it is assumed that consumption is low for the species that were not included in the available national dietary data. For the category "other fish" in Finnish dietary data, activity concentrations equal to the mean of Nordic fish species included in the dose estimate has been assumed.*

Species	Mean ingestion dose (µSv/y)				
	Denmark	Finland	Iceland	Norway	Sweden
Alaska pollock	0.61			1.22	0.18
Altantic salmon, farmed	0.02	0.06	0.01	0.07	0.03
Arctic char (farmed)			0.07		
Atlantic cod	0.74		3.49	5.04	3.10
Atlantic mackerel	3.90			2.84	3.97
Tuna, canned	28.93	19.13	4.20	9.33	4.67
Cod roe				0.36	0.43
Crab	0.18			1.02	
European perch		0.15			
European plaice	3.48		1.79	0.50	4.08
European whitefish		1.13			
Greater argentine				2.41	
Haddock			5.92	1.75	0.35
Halibut			0.09	0.05	
Herring	7.63	2.27	1.86	1.03	4.13
Mussels			4.82	14.46	
Northern pike		0.49			
Norway lobster			3.65		
Pangasius					0.01
Pike-perch		0.12			0.46
Rainbow trout (farmed)		0.05		0.01	
Redfish			0.06	0.07	
Saithe		0.24	0.20	0.66	
Scallops			0.42	0.04	
Shrimp	12.03	4.01	7.29	10.94	14.58
Vendace		0.95			
Wolffish			0.04	0.02	
Other fish		2.7			
Total	58	31	34	52	36

Table 7.2-2. Estimated ingestion doses (µSv/y) for high intake of fish and shellfish. For high consumption of selected species, it was assumed that the consumption was 5 times higher than the highest national mean intake among the Nordic countries. In these scenarios, only the dose associated with the species in question is shown (i.e., exposure from other species must be added for total dose from fish and shellfish). The selected species shown contributed to the mean dose either by high ^{210}Po concentration, as in the case of mussels or tuna, or by a high intake of a species with low or moderate activity concentration, as in the case of cod or haddock.

High consumption scenario	Associated ingestion dose (µSv/y)
95th percentile consumption of fish and shellfish for Norwegian adults (248 g/d)	229
Atlantic cod	25
Atlantic mackerel	20
Canned tuna	145
European plaice	17
Haddock	30
Herring	38
Blue mussels	72
Shrimp	60

Effect of delay prior to consumption

With the exception of the canned tuna, all samples collected for this project were fresh. However, in most cases, seafood undergoes some period of delay after it is caught, before consumption. The length of this period is likely to vary dramatically, and depends in large part on whether the product is frozen (or canned) and for how long. Because ^{210}Po has a half-life of only 138 days, while at the same time being the major contributor to the ingestion dose, we wished to examine whether this was expected to significantly affect the actual ingestion dose received.

It is not possible to give an accurate assessment of the delay effect for Nordic countries since data on representative delays for the various species consumed in the Nordic countries is not available. Instead, we choose to calculate examples to illustrate the effect of time delay. In one scenario, it is assumed that 50% of the fish and shellfish have been frozen prior to consumption, and that 50% are consumed fresh. In the second scenario, 100% of the fish and shellfish is assumed frozen prior to consumption. Estimates made by Jones and Sherwood (2009) in the UK were used to represent the time delays for the various states (frozen or fresh) of wild-caught fish, farmed fish, and shellfish.

As shown in Figure 7.2-2, the scenarios assessed show that the effect of time delay on the ^{210}Po dose is relatively moderate. The scenarios for 50% and 100% frozen fish and shellfish lead to dose reductions of 6-11% and 10-18%, respectively. The reason why the delay effect does not have a greater impact is because the largest ^{210}Po contributors are the least affected by delay: Firstly, canned tuna was not decay corrected, since the ^{210}Po activity concentration already referred to the time of purchase for this particular product. Secondly, the delay times suggested by Jones & Sherwood for frozen shellfish, another of the major dose contributors, was only 7 days, and therefore didn’t have significant impact on ^{210}Po concentrations. Frozen wild-caught fish had the longest expected delay time at 3 months, but was already a relatively minor contributor to the dose due to low ^{210}Po levels, leading to only a moderate effect on ingestion doses caused by the time delay. If actual delay times for seafood consumed in Nordic countries is longer than that estimated for the UK by Jones and Sherwood, this could naturally lead to a more significant effect.

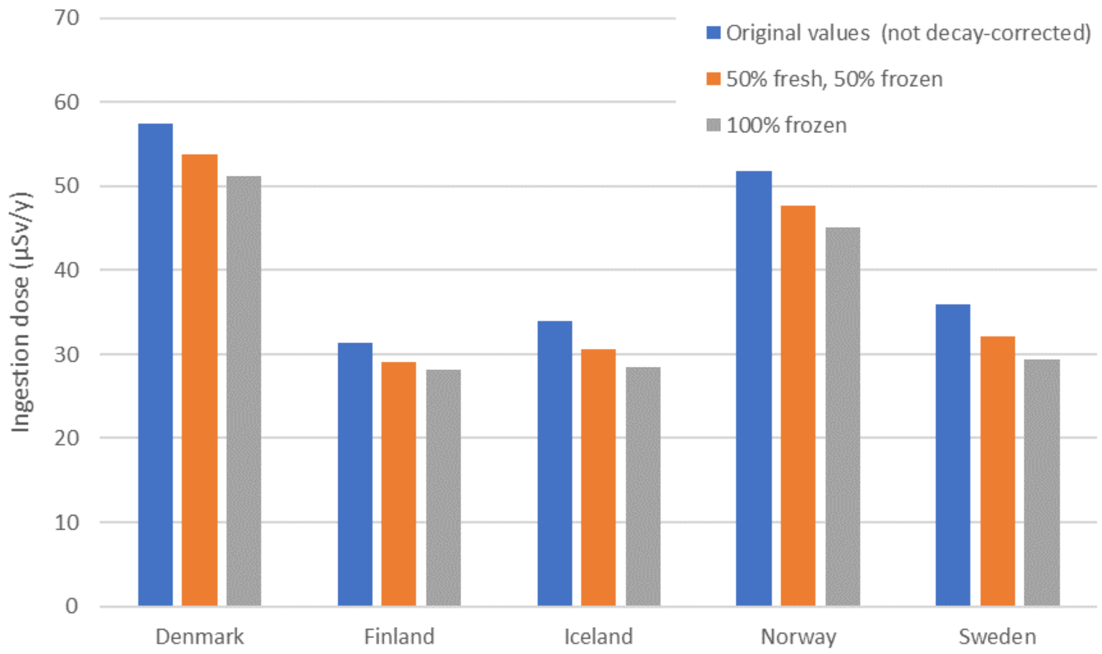

Figure 7.2-2. *Example of the effect on dose (µSv/y)) of time delay prior to consumption due to the decay of* ^{210}*Po. For canned tuna, no further reduction was calculated, as the activity concentration already represents the consumed form. Atlantic salmon, arctic char, and rainbow trout were assumed to be farmed, while other fish species were assumed to be wild-caught. Representative fresh and frozen delay times used were 8 and 90 days for wild-caught fish; 2 and 14 days for farmed fish, respectively, and 7 days for both fresh and frozen shellfish (Jones & Sherwood 2009).*

Uncertainties associated with dose calculations

As described in chapter 2, obtaining reliable species-specific consumption data for fish and shellfish has proved somewhat difficult. Differences between the consumption data provided by the countries are likely due both actual differences in the average national diet, as well as various the methods and sources used for collecting the national dietary data. Nonetheless, this is the best national consumption data available, and is used directly for dose calculations.

Data from NANOD and previous studies show that activity concentrations in fish and shellfish can be highly variable, sometimes ranging an order of magnitude or more within the same species and region. Moreover, radium data are usually below detection limits, leading to further uncertainties associated with values used in dose calculations. Some changes in radionuclide levels before consumption are also likely during cooking (chapter 3.2) and/or reduction as a result of radioactive decay during the delay between catch and consumption (chapter 7.2). Furthermore, there is significant uncertainty associated with the ICRP ingestion dose coefficients based on models.

In summary, there are considerable uncertainties associated with the dose calculations both through the dose coefficients, consumption data and radionuclide content. However, given the low doses estimated for the average populations, these uncertainties are not expected to affect the overall conclusions of this study.

8. Conclusions

All Nordic countries have a substantial fish and shellfish consumption; however, the dietary data indicates a substantial variation in species composition among the countries.

The results show that activity concentrations of ^{210}Po in wild fish caught in the Nordic region ranged from 0.01 to 3.4 Bq/kg in muscle tissue. The highest level in fish samples analysed was 10 Bq/kg, observed in a sample of imported canned tuna. The highest concentration of all samples was observed in blue mussels, containing up to 73 Bq/kg. Overall, the mean ^{210}Po concentrations were highest in species with a ^{210}Po-rich diet, such as plankton. This is in line with previous studies showing that ^{210}Po enters the organisms primarily via ingestion. However, ^{210}Po levels also varied considerably within the same species, and the pattern was not consistent between individual samples of the same species. Results of the present work and previous studies indicate that influences on ^{210}Po concentrations in fish and shellfish are complex, and several factors may play a role. Fewer results were available for ^{210}Pb; however, the data show an overall much lower content than for ^{210}Po, and concentrations ranged from 0.01 to 0.83 Bq/kg.

Most samples for radium analyses were ashed in order to obtain low detection limits. All ^{226}Ra and ^{228}Ra measurements of ashed samples of fish obtained measured values or detection limits of approximately 0.1 Bq/kg or less. Most ^{226}Ra measurements were also below 0.05 Bq/kg. Although almost all radium analyses showed results below detection limits, by ashing and achieving low detection limits, the analyses still provide highly valuable information and allow for more accurate dose estimates.

Ingestion dose estimates based on activity concentration data from this work as well as previous data for the Nordic region show average national doses ranging from 31 to 58 µSv/y from the radionuclides examined. ^{210}Po accounted for approximately 80-90% of this dose, while the dose from radium isotopes was negligible and below 2%. Despite their low consumption, canned tuna, blue mussels, and shrimp accounted for a large share of the dose due to their high ^{210}Po content relative to other species consumed in larger quantities. The large difference in ^{210}Po concentration between species, combined with variable consumption, explains why populations with the highest overall seafood consumption not necessarily receive the highest doses from seafood.

The estimated dose associated with high (95th percentile) consumption is still moderate compared with the recommendation that doses from food and drinking water should not exceed 1 mSv/y. Calculated examples of the effect of time delay between catch and consumption of seafood suggests only a moderate effect of the decay of ^{210}Po on ingestion doses.

Data on naturally occurring radionuclides in fish and shellfish is important not only due to the food group’s role in the Nordic diet, but also because the Nordic countries play an important role in the worldwide fishing industry.

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9. References

Amcoff, E, Edberg, A, Barbieri, HE, Lindroos, AK, Nälsén, C, Pearson, M & Lemming, EW. 2012. Riksmaten vuxna 2010-11. Livsmedels- och näringsinntag bland vuxna i Sverige. National Food Agency, Uppsala 2012.
Available at:
https://www.landlaeknir.is/servlet/file/store93/item14901/Hva%C3%B0%20bor%C3%B0a%20%C3%8Dslendingar_april%202012.pdf

Brown, JE, Jones, SR, Saxén, R, Thørring, H & Batlle JV. 2004. Radiation doses to aquatic organisms from natural radionuclides. Journal of Radiological Protection. 24(4A): A63 DOI: 10.1088/0952-4746/24/4A/004

Bustamante, P, Germain, P, Leclerc, G & Miramand, P. 2002. Concentration and distribution of 210Po in the tissues of the scallop *Chlamys varia* and the mussel *Mytilus edulis* from the coasts of Charente-Maritime (France). Marine Pollution Bulletin, 44(10): 997-1002.

Carvalho, FP. 2011a. Polonium (^{210}Po) and lead (^{210}Pb) in marine organisms and their transfer in marine food chains. Journal of environmental radioactivity. 102(5): 462-472.

Carvalho, FP, Oliveira, JM, Malta, M. 2011. Radionuclides in deep-sea fish and other organisms from the North Atlantic Ocean. ICES Journal of Marine Science. 68(2): 333-340. DOI: 10.1093/icesjms/fsq088.

Carvalho, FP & Fowler, SW. 1994. A double-tracer technique to determine the relative importance of water and food as sources of polonium-210 to marine prawns and fish. Marine ecology progress series. 103(3): 251-264.

Carvalho, FP, Oliveira, JM & Alberto, G. 2011. Factors affecting ^{210}Po and ^{210}Pb activity concentrations in mussels and implications for environmental bio-monitoring programmes. Journal of environmental radioactivity. 102(2): 128-137.

Chen, QJ, Aarkrog, A, Nielsen, SP, Dahlgaard, H, Lind, B, Kolstad, AK & Yu, Y. 2001. Procedures for determination of ^{239,240}Pu, ^{241}Am, ^{237}Np, ^{234,238}U, ^{228,230,232}Th, ^{99}Tc and ^{210}Pb-^{210}Po in environmental materials. Risø National Laboratory, Roskilde. Risø-R-1263.

Cherry, RD & Heyraud, M. 1991. Polonium-210 and lead-210 in marine organisms: allometric relationships and their significance. In Radionuclides in the Study of Marine Processes (pp. 309-318). Springer, Dordrecht.

Dahlgaard, H. 1996. Polonium-210 in mussels and fish from the Baltic-North sea estuary. Journal of Environmental Radioactivity. 32(1-2): 91-96.

Darnerud, PO, Becker, W, Öhrvik, W, Kollander, B, Sundström, B, Strandler, HS, et al. 2017. Swedish Market Basket Survey 2015. National Food Agency.

Díaz-Francés, I, García-Tenorio, R, Mantero, J & Manjón, G. 2013. Evaluation of the Amount of ^{210}Po Ingested by the Spanish Population and its Relation to their Diet Habits. IRPA13 Proceedings [online]. Available at: http://www.irpa.net/members/TS2b.7.pdf.

Díaz-Francés, I, Mantero, J, Díaz-Ruiz, J, Manjón, G & García-Tenorio, R. 2015. ^{210}Po in the diet at Seville (Spain) and its contribution to the dose by ingestion. Radiation protection dosimetry: 168(2): 271-276.
European Food Safety Authority (EFSA). 2018. The EFSA Comprehensive European Food Consumption Database. Updated 26.04.2018. Available online: https://www.efsa.europa.eu/en/food-consumption/comprehensive-database (Accessed 01.12.2018)

Food and Agriculture Organization of the United Nations (FAO). FAO Yearbook – Fishery and Aquaculture Statistics. Summary Tables. Table "Commodities 2014: International trade in fishery commodities by principal importers and expoerters". Available online: http://www.fao.org/fishery/docs/STAT/summary/default.htm (Accessed 04.11.2018)

García-Orellana, I & García-León, M. 2002. An easy method to determine ^{210}Po and ^{210}Pb by alpha spectrometry in marine environmental samples. Applied Radiation and isotopes: 56(4): 633-636.

Germain, P, Leclerc, G & Simon, S. 1995. Transfer of polonium-210 into *Mytilus edulis* (L.) and *Fucus vesiculosus* (L.) from the baie de Seine (Channel coast of France). Science of the Total Environment: 164(2): 109-123.

Gjelsvik, R, Brown, J, Holm, E, Roos, P, Saxen, R & Outola, I. 2009. Po-210 and other radionuclides in terrestrial and freshwater environments (No. NKS–181). Nordisk Kernesikkerhedsforskning.

Godoy, J M, de Oliveira, MS, de Almeida, CEB, de Carvalho, ZL, da Silva, ER, da Costa Fernandes, F ... & Danelon, OM. 2008. ^{210}Po concentration in Perna perna mussels: looking for radiation effects. Journal of environmental radioactivity: 99(4): 631-640.

Gunnarsdottir, I, Tryggvadottir, EA, Birgisdottir, BE, Halldorsson, TI, Medek, H & Geirsson, RT. 2016. Diet and nutrient intake of pregnant women in the capital area in Iceland. Laeknabladid: 102(9):378-84. DOI: 10.17992/lbl.2016.09.95.

HELCOM 2018. HELCOM MORS Environmental database. Available online: http://www.helcom.fi/Pages/MORS-Environmental-database.aspx (Accessed 01.12.2018)

Heldal HE, Brungot AL, Skjerdal H, Gäfvert T, Gwynn JP, Sværen I, Liebig PL & Rudjord AL. 2015. Radioaktiv forurensning i fisk og sjømat i perioden 1991-2011. Østerås: Norwegian Radiation Protection Authority; StrålevernRapport 2015:17 (in Norwegian).

Heldal HE, Volynkin A, Skjerdal HK, Komperød M, Naghchbandi P, Hannisdal R. 2017. Radioactive substances in Norwegian farmed Atlantic salmon (Salmo salar). Norwegian Institute of Marine Research. Available online: https://www.hi.no/filarkiv/2017/07/rapport_24-2017_lakseprosjekt_endelig.pdf/nb-no (Accessed 18.12.2018)

Holm, E. 1994. Polonium-210 and Radiocaesium in Muscle Tissue of Fish from Different Nordic Marine Areas. In Studies in Environmental Science. Elsevier. Vol. 62, pp. 119-126.

Hosseini A, Beresford NA, Brown JE, Jones DG, Phaneuf M, Thørring H &Yankovich T. 2010. Background dose-rates to reference animals and plants arising from exposure to naturally occurring radionuclides in aquatic environments. Journal of Radiological Protection. 30(2): 235. DOI: 10.1088/0952-4746/30/2/S03

Hrolfsdottir, L, Halldorsson, TI, Birgisdottir BE, Hreidarsdottir IT, Hardardottir H & Gunnarsdottir I. 2019. Development of a dietary screening questionnaire to predict excessive weight gain in pregnancy. Matern Child Nutr: Jan;15(1):e12639. DOI: 10.1111/mcn.12639

Insititute of Marine Research (IMR). Kysttorsk nord for 62ºN. Available online: https://www.hi.no/temasider/fisk/torsk/kysttorsk_nord_for_62_breddegrad/nb-no (in Norwegian). Accessed 01.12.2018.

International Atomic Energy Agency. 2014. Radiation protection and safety of radiation sources : international basic safety standards. General safety requirements part 3. Vienna: International Atomic Energy Agency. Available online: https://www-pub.iaea.org/MTCD/publications/PDF/Pub1578_web-57265295.pdf (Accessed 07.05.2020)

International Atomic Energy Agency. 2017. Natural Radioactivity in Food: Experts Discuss Harmonizing International Standards. Available online: https://www.iaea.org/newscenter/news/natural-radioactivity-in-food-experts-discuss-harmonizing-international-standards. Updated 14.05.2018. (Accessed 19.12.2018)

International Atomic Energy Agency. 2010. Technical Report Series No. 472. Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments. Vienna: International Atomic Energy Agency.

Jones, AL & Sherwood, JC. 2009. Delay times between harvesting or collection of food products and consumption for use in radiological assessments. Journal of Radiological Protection: 29(3): 377.

Khan MF & Wesley SG. 2016. Baseline concentration of Polonium-210 ((210)Po) in tuna fish. Mar Pollut Bull: 107(1):379-382 DOI: 10.1016/j.marpolbul.2016.03.056.

Komperød, M, Rudjord, AL, Skuterud, L & Dyve, JE. 2015. Stråledoser fra miljøet. Beregninger av befolkningens eksponering for stråling fra omgivelsene i Norge. Østerås: Norwegian Radiation Protection Authority; StrålevernRapport 2015:11 (in Norwegian).

Komperød, M & Skuterud, L. 2018. Radiation Doses From the Norwegian Diet. Health physics, 115(2), 195-202.

Komperød, M, García, FP, Guðnason, K, Kämäräinen, M, Roos, P, Jensen, LK & Skjerdal, HK. 2019 Natural Radioactivity in Nordic Fish and Shellfish – Summary report 2018. (No. NKS–416). Nordisk Kernesikkerhedsforskning.

Mársico, ET, Kelecom, A & Sérgio C. 2007. Levels of polonium-210 in highly consumed sea foods from a fish market of the city of Niteroi, RJ-Brazil. 2007 International Nuclear Atlantic Conference – INAC 2007. Available online: https://www.ipen.br/biblioteca/cd/inac/2007/pdf_dvd/E04_812.pdf

Mauring, A, Gäfvert, T & Aleksandersen, TB. 2014. Implications for analysis of 226Ra in a low-level gamma spectrometry laboratory due to variations in radon background levels. Applied Radiation and Isotopes: 94: 54-59.

Natural Resources Institute Finland. Fish consumption. Database: Luke/Tilastot. Available online: http://statdb.luke.fi/PXWeb/pxweb/en/LUKE/LUKE__06%20Kala%20ja%20riista__06%20Muut__02%20Kalan%20kulutus/2_Kalankulutus.px/table/tableViewLayout2/?rxid=40afc933-c1bb-4c7c-a4dd-0dae37076023. Accessed 05.12.2018.

Norwegian Broadcasting Company (NRK). Fiskematen som reiser jorda rundt. Available online: https://www.nrk.no/nordland/xl/fiskematen-som-reiser-jorda-rundt-1.14279783. Appendix with details available online: https://fido.nrk.no/517f751dd3cd33ed772e1c0fc0c76337dfc5e3762c032b8c057367401ffec7c9/NRK-kartlegging_fiskeprodukter.pdf (Accessed 12.12.2018.)

Oatway, WB, Jones, AL & Holmes, S. 2016. Ionising radiation exposure of the UK population, 2010 review. Centre for Radiation, Chemical and Environmental Hazards, Public Health England.

O'Connor, C, Currivan, L, Cunningham, N, Kelleher, K, Lewis, , Long, S, ... & McMahon, C. .2014. Radiation doses received by the Irish population 2014 (No. RPII--14-02). Radiological Protection Institute of Ireland (Ireland).

Ota, T, Sanada, T, Kashiwara, Y, Morimoto T & Sato K. 2009. Evaluation for committed effective dose due to dietary foods by the intake for Japanese adults. Japanese Journal of Health Physics. 44(1): 80-88. DOI: 10.5453/jhps.44.80

Pearson, AJ, Gaw, S, Hermanspahn, N & Glover, CN. 2016. Activity concentrations of ^{137}Caesium and ^{210}Polonium in seafood from fishing regions of New Zealand and the dose assessment for seafood consumers. Journal of environmental radioactivity. 151, 542-550.

Pedersen, AN, Christensen, T, Matthiessen, J, Knudsen, VK, Rosenlund-Sørensen, M, Biltoft-Jensen, A, et al. Dietary Habits in Denmark 2011-2013. Søborg: DTU Fødevareinstituttet, 2015 (in Danish). Available online: https://www.food.dtu.dk/-/media/Institutter/Foedevareinstituttet/Publikationer/Pub-2015/Rapport_Danskernes-Kostvaner-2011-2013.ashx?la=da&hash=6272131AA16D3E74CA5B7B3E770BD24C62DBB8B5

Renaud, P, Parache, V & Roussel-Debet, S. 2015. Internal doses of French adult population linked to the intake of radionuclides from the decay-chains of uranium and thorium by foodstuffs ingestion. Radioprotection 50(2): 117-121. DOI: 10.1051/radiopro/2014034

Ryan, TP, Dowdall, AM, McGarry, AT, Pollard, D & Cunningham, JD. 1999. ^{210}Po in *Mytilus edulis* in the Irish marine environment. Journal of Environmental radioactivity. 43(3): 325-342.

SEAFOODplus. 2016. On the average European fish consumption is below recommended levels. Available online: http://seafoodplus.org/project/european-fish-consumpt.411.0.html (Accessed 01.12.2018)

Skwarzec, B & Bojanowski, R. 1988. ^{210}Po content in sea water and its accumulation in southern Baltic plankton. Marine Biology, 97(2), 301-307.

Þorgeirsdóttir, H, Valgeirsdóttir, H, Gunnarsdóttir, I, Gísladóttir, E, Gunnarsdóttir, BE, Þórsdóttir, I, Stefánsdóttir, J & Steingrímsdóttir, L. 2013. Hvað borða Íslendingar? Könnun á mataræði Íslendinga 2010-2011. (Directorate of health, Icelandic Food and Veterinary Authority (MAST), Unit for Nutrition Research (UNR) of the University of Iceland, The National University Hospital of Iceland.

Totland, TH, Melnæs, BK, Lundberg-Hallén, N, Helland-Kigen, KM, Lund-Blix, NA, Myhre JB, et al. 2012. Norkost 3. En landsomfattende kostholdsundersøkelse blant menn og kvinner i Norge i alderen 18-70 år, 2010-11. Oslo: Norwegian Directorate of Health.

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). 2000. Volume I: Sources. Annex B. Exposures from natural radiation sources. New York, United Nations.

Vesterbacka, P (ed.). Surveillance of environmental radiation in Finland. Annual report 2017. STUK-B 226. Helsinki 2018. 105 pp.

VKM. 2014. Benefit-risk assessment of fish and fish products in the Norwegian diet – an update. Scientific Opinion of the Scientific Steering Committee. VKM, Oslo: 293 pp Oslo.

Watson, SJ, Jones, AL, Oatway & WB, Hughes, JS. 2005. Ionising radiation exposure of the UK population: 2005 review. Dixcot: Health Protection Agency; HPA-RPD-001.

Wildgust, MA, McDonald, P & White, KN. 1998. Temporal changes of ^{210}Po in temperate coastal waters. Science of the Total Environment. 214(1-3): 1-10.

Yamamoto, M, Abe, T, Kuwabara, J, Komura, K, Ueno, K & Takizawa, Y. 1994. Polonium-210 and lead-210 in marine organisms: intake levels for Japanese. Journal of Radioanalytical and Nuclear Chemistry. 178(1): 81-90.

Ziegler, F & Bergman, K. 2017. Svensk konsumtion av sjömat – en växande mångfold. SP rapport 2017:07. Gothenburg: Research Institutes of Sweden.

Appendix A – Previously collected data

Detailed overview of data from previous studies in the Nordic region.

Species	Region	Mean levels (min-max) in Bq/kg fw, and associated number of batches (and/or individuals in parentheses) analysed in the study								References
		^{210}Po		^{210}Pb		^{226}Ra		^{228}Ra		
		Bq/kg	n	**Bq/kg**	n	**Bq/kg**	n	**Bq/kg**	n	
Farmed salmon	Coast of Norway	0.013 (0.003-0.023)	7	0.03-0.07	7	<0.04 - <0.18	100	<0.006-<0.39	100	Heldal et al. 2017
Cod	Baltic Sea (Southern Baltic and Bay of Gdansk)	2.3 (0.9-3.3)	4 (9)							Cited in Holm 1994
	Coast of Norway	2.1 (0.9-4)	3 (75)							Holm 1994
	Coast of Sweden	3.5 (3.0-3.9)	2 (12)							Holm 1994
	Coast of Iceland	0.9	1 (10)							Holm 1994
	Baltic Sea	0.38 (0.043-1.5)	41	0.069 (0.062-0.082)	4	0.19* (0.042-4.9)	79			HELCOM 2018
	Barents Sea	0.518	2	0.058	2					DSA monitoring data
	Coast of Norway	0.26	23							Heldal et al. 2015
	North Sea	0.83	5							Heldal et al. 2015
	North Sea and Baltic Sea	0.35	1 (13)							Dahlgaard 1995
Haddock	Barents Sea					0.188	1			DSA monitoring data
	Coast of Norway	1.35	2							Heldal et al. 2015
	North Sea	1.45	2							Heldal et al. 2015
Atlantic mackerel	Barents Sea	1.29	1	0.068						DSA monitoring data

Species	Region	Mean levels (min-max) in Bq/kg fw, and associated number of batches (and/or individuals in parentheses) analysed in the study								References
		^{210}Po		^{210}Pb		^{226}Ra		^{228}Ra		
		Bq/kg	n	Bq/kg	n	Bq/kg	n	Bq/kg	n	
Saithe	North Sea	2.5	22							Heldal et al. 2015
	Coast of Norway	0.92	2							Heldal et al. 2015
Herring	Baltic Sea	8.3 (1.9-23)	4 (23)							Cited in Holm 1994
	Coast of Norway	2.8 (0.5-5)	2 (50)							Holm 1994
	Coast of Sweden (mainly Baltic Sea)	4.0 (1.6-9.6)	7 (105)							Holm 1994
	Baltic Sea	1.36 (0.19-8.5)	41	0.17 (0.076-0.3)	5	0.028 (0.02-0.055)				HELCOM 2018
	Barents Sea	2.91	1	0.108	1					DSA monitoring data
	North Sea	2.88	14							Heldal et al. 2015
	Baltic Sea	3.247	1	0.183						STUK monitoring data
	Baltic Sea	1.944	1	0.247						STUK monitoring data
	Baltic Sea	3.958	1	0.454						STUK monitoring data
	Baltic Sea	0.586	1	0.041						STUK monitoring data
	Baltic Sea	1.656	1	0.110						STUK monitoring data
	North and Baltic Sea	0.65	1 (14)							Dahlgaard 1995
Redfish	Coast of Norway	0.16	1							DSA monitoring data
European plaice	Coast of Norway	10.3 (8-12)	3 (75)							Holm 1994

Species	Region	Mean levels (min-max) in Bq/kg fw, and associated number of batches (and/or individuals in parentheses) analysed in the study								References
		^{210}Po		^{210}Pb		^{226}Ra		^{228}Ra		
		Bq/kg	n	Bq/kg	n	Bq/kg	n	Bq/kg	n	
	Coast of Iceland	6.4	1 (15)							Holm 1994
	Baltic Sea	1.1 (0.26-3.4)	42	0.1 (0.055-0.15)	4					HELCOM 2018
	North and Baltic Sea	0.96	1 (14)							Dahlgaard 1995
Pike	Coast of Finland	2.8 (1.7-3.8)	2							Holm 1994
	Baltic Sea	0.94	1	0.092	1					HELCOM 2018
Perch	Coast of Finland	0.2 (0.2-0.2)	2							Holm 1994
	Bothnian Sea	0.327 (0.28-0.37)	8	0.088	8					Gjelsvik et al. 2009
	Bothnian Sea	0.042 (0.038-0.048)	3	0.013 (0.010-0.018)	3					Gjelsvik et al. 2009
	Baltic Sea	<0.14-<0.15	2	<0.14-<0.15	2	<0.95-<1.8	2	<0.54-0.54	2	Vesterbacka 2018
	Unknown (Finland)	<0.15	1	<0.15	1	<3.2	1	<1.3		Vesterbacka 2018
Vendance	Unknown (Finland)	1.29 (0.79-1.64)	3	<0.38-<0.47	3	<2.2-<4	3	<0.64-<1.2		Vesterbacka 2018
Whitefish	Coast of Finland	1.9 (0.8-2.9)	2							Holm 1994
	Baltic Sea	0.244		0.018						STUK monitoring data
	Baltic Sea	0.380		0.022						STUK monitoring data
	Baltic Sea	13	1	<0.25	1	<0.96	1	<0.37	1	Vesterbacka 2018
	Unknown	0.40	3	<0.16-	3	<0.43-	3	<0.16-	3	Vesterbacka

Species	Region	Mean levels (min-max) in Bq/kg fw, and associated number of batches (and/or individuals in parentheses) analysed in the study								References
		^{210}Po		^{210}Pb		^{226}Ra		^{228}Ra		
		Bq/kg	n	Bq/kg	n	Bq/kg	n	Bq/kg	n	
	(Finland)	(<0.23-0.82)		<0.23		<0.79		<0.28		2018
Capelin	Coast of Iceland	5.3	1							Holm 1994
Sprat (brisling)	Baltic Sea					0.073 (0.05-0.11)	75			HELCOM 2018
Flounder	Baltic Sea	6.7 (2.7-16)	15							Cited in Holm 1994
	Baltic Sea					0.046 (0.026-0.075)	71			HELCOM 2018
Rainbow trout	Baltic Sea	0.039		0.013						STUK monitoring data
	Unknown (Finland)	<0.26	1	<0.26	1	<0.73	1	<0.25	1	Vesterbacka 2018
Blue mussel	Baltic Sea					1.4 (0.029-12)	11	1.5 (0.35-3.4)	3	HELCOM 2018
	Baltic Sea			2.186						STUK monitoring data
	Baltic Sea			2.821						STUK monitoring data
	Baltic Sea	7.541		1.172						STUK monitoring data
	Coast of Denmark (incl. East and West coasts)	37 (est. from 149 d.w.)	1 (72)							Dahlgaard (1995)
Cockle	Baltic Sea		1			0.71				HELCOM 2018
Baltic clam	Baltic Sea					2.5 (0.64-3.98)	3			HELCOM 2018

*The mean ^{226}Ra value of 0.19 Bq/kg in the HELCOM database appears to be strongly affected by two reported values from the 1980s that are so high that they appear to be erroneously registered. The median value registered in the database 0.08 Bq/kg, which seems more reasonable, although still somewhat higher than preliminary NANOD results. The HELCOM database only includes data from the Baltic Sea.

Appendix B – Sample overview

Details on samples collected in the NANOD project. All samples consist of fish muscle or edible parts of shellfish.

Country	Species	Catch date	Origin	Comment
Denmark	Atlantic cod	19.02.2018	Kattegat FAO 23	
	Atlantic cod	20.03.2019	Kattegat FAO 23	
	European plaice	19.02.2018	Kattegat FAO 23	
	European plaice	20.03.2019	Kattegat FAO 23	
	Atlantic herring	19.02.2018	Kattegat FAO 23	
	Atlantic herring	20.03.2019	Kattegat FAO 23	
	Atlantic cod	06.03.2018	North Sea FAO 27-A	
	Atlantic cod	04.03.2019	North Sea FAO 27-A	
	European plaice	06.03.2018	North Sea FAO 27-B	
	European plaice	04.03.2019	North Sea FAO 27-B	
	Atlantic herring	06.03.2018	North Sea FAO 27-A	
	Atlantic herring	02.03.2019	North Sea FAO 27-A	
	Atlantic cod	2018	Bornholm FAO 25	
	Atlantic cod	11.04.2019	Bornholm FAO 25	
	European plaice	2018	Bornholm FAO 25	
	Salmon	2018	Bornholm FAO 25	
	Salmon	11.04.2019	Bornholm FAO 25	
Finland	Baltic Herring	24.11.2017	Bothnian Bay, Hailuoto	
	Baltic Herring	21.10.2017	Bothnian Sea, Seili	
	Baltic Herring	20.11.2018	Bothnian Bay, Hailuoto	
	Baltic Herring	23.11.2018	Bothnian Bay, Olkiluoto	
	Baltic Herring	30.11.2018	Bothnian Bay, Seili	
	Baltic Herring	30.11.2018	Gulf of Finland, Tvärminne	
	Pike	12.11.2017	Bothnian Bay, Hailuoto	
	Pike	04.05.2017	Bothnian Sea, Seili	
	Pike	20.05.2017	Bothnian Sea, Vaasa	
	Pike	6.7.2018	Bothnian Sea, Seili	
	Pike	10.9.2018	Bothnian Sea, Olkiluoto	
	Pike	10.10.2018	Bothnian Sea, Vaasa	
	Pike	20.11.2018	Bothnian Bay, Hailuoto	
	Perch	23.11.2018	Bothnian Bay, Olkiluoto	
Iceland	Common ling	01.03.2018	Denmark Strait (West of Iceland)	
	Common ling	28.02.2018	South of Iceland	
	Atlantic cod	08.03.2018	Denmark Strait (West of Iceland)	
	Haddock	28.02.2018	South of Iceland	
	Saithe	12.03.2018	North of Iceland	
	Black halibut	02.03.2018	North of Iceland	
	Atlantic halibut	31.07.2018	South of Iceland	
	European plaice	31.07.2018	Breiðafjörður (West coast)	
	Arctic char	31.07.2018	Southern Iceland (inland)	Farmed, freshwater
	Atlantic herring	31.07.2018	South-East of Iceland	Salted
	Northern prawn	16-21.05.2018	West of Iceland	
	Northern prawn	07-11.04.2018	North of Iceland	
	Northern prawn	13.04.2018	Isafjarðardjúp (inner part of fjord, North-West coast)	
	Blue mussels	02.05.2018	South-Western coast of	

Country	Species	Catch date	Origin	Comment
			Iceland	
Norway	Atlantic mackerel	24.06.2018	Bremanger, Sogn og Fjordane	
	Great scallop[a]	08.08.2018	Hitra, Trøndelag	
	Brown crab	08.08.2018	Fosen, Trøndelag	
	Rainbow trout	08.08.2018	Stokmarknes, Nordland	Farmed
	European plaice	08.08.2018	Near Stadt, Sogn og Fjordane	
	Skipjack tuna	01.09.2017	Thailand/Vietnam	Canned
	Atlantic cod	17.08.2018	Troms	
	Haddock	17.08.2018	Troms	
	Saithe	17.08.2018	Troms	
	Northern prawn	05.09.2018	Troms	
	Blue mussel	20.08.2018	Troms	
Sweden	Atlantic mackerel	03.09.2018	Kattegat/Skagerrak	
	European plaice	06.09.2018	Kattegat/Skagerrak	
	Atlantic cod	18.08.2018	Kattegat/Skagerrak	
	Atlantic herring	30.08.2018	Kattegat/Skagerrak	
	Saithe	18.08.2018	Kattegat/Skagerrak	
	Hake	18.08.2018	Kattegat/Skagerrak	
	Pike-perch	30.08.2018	West coast region	Freshwater
	Blue mussel	08.06.2018	Mollösund	
	Northern prawn	30.08.2018	Lysekil	

[a.] Muscle only

Appendix C – List of English and Latin species names

English	**Latin**
Alaska pollock	*Gadus chalcogrammus*
Altantic salmon	*Salmo salar*
Arctic char	*Salvelinus alpinus*
Atlantic cod	*Gadus morhua*
Atlantic halibut	*Hippoglossus hippoglossus*
Atlantic herring	*Clupea harengus*
Atlantic mackerel	*Scomber scombrus*
Baltic clam	*Macoma balthica*
Baltic Herring	*Clupea harengus membras*
Black halibut	*Reinhardtius hippoglossoides*
Blue mussel	*Mytilus edulis*
Brown crab	*Cancer pagurus*
Brown trout	*Salmo trutta*
Cockle	*Cardiidae sp.*
Common ling	*Molva molva*
Common periwinkle	*Littorina littorea*
European hake	*Merluccius merluccius*
European perch	*Perca fluviatilis*
European plaice	*Pleuronectes platessa*
European whitefish	*Coregonus lavaretus*
Greater argentine	*Argentina silus*
Great scallop	*Pecten maximus*
Haddock	*Melanogrammus aeglefinus*
Mediterranean mussel	*Mytilus galloprovincialis*
Northern prawn	*Pandalus borealis*
Norway lobster	*Nephrops norvegicus*
Pangasius	*Pangasius* sp.
Pike	*Esox lucius*
Pike-perch	*Sander lucioperca*
Rainbow trout	*Oncorhynchus mykiss*
Redfish	*Sebastes* sp.
Saithe	*Pollachius virens*
Skipjack tuna	*Katsuvonus pelamis*
Vendace	*Coregonus albula*
Wolffish	*Anarhichas lupus*

Appendix D – Dose calculations based on national activity concentration data

The table shows the effective dose per country (µSv/y) calculated using ICRP (2012), based on national intake (g/d) and national activity concentration data (Bq/kg fresh weight) from the NANOD project, when available. (If national concentration data were not available, the mean of other NANOD results for the same species were used. If no NANOD data was available for the species, the mean value for a species with similar type of diet was used. For cases in which measurements were below the detection limit (DL), the lowest DL was assumed to apply to all samples. In the dose calculations, 1/2 the value of the DL was used when measurements were below DL.)

		Intake	Activity concentration (Bq/kg)				Effective dose (µSv/y)				
Country	Species	g/d	^{210}Po	^{210}Pb	^{226}Ra	^{228}Ra	^{210}Po	^{210}Pb	^{226}Ra	^{228}Ra	Total
Denmark	Alaska pollock[a]	1.7	0.42	0.065	<0.045	<0.062	0.31	0.03	0.00	0.01	0.36
	Altantic salmon[b]	3.6	0.013	0.05	<0.05	<0.09	0.02	0.05	0.01	0.04	0.12
	Atlantic cod[a]	2.05	0.37	0.065	<0.052	<0.062	0.33	0.03	0.01	0.02	0.39
	Atlantic mackerel[c]	5.5	1.35	0.16	<0.05	<0.081	3.25	0.22	0.01	0.06	3.54
	Tuna, canned	6.2	10.19	0.18	<0.11	<0.22	27.67	0.28	0.03	0.17	28.16
	Crab	0.07	5.27	0.41	<0.059	<0.12	0.16	0.01	0.00	0.00	0.17
	European plaice	3.5	1.37	0.02	<0.052	<0.076	2.10	0.02	0.01	0.03	2.16
	Herring	7.4	0.7	0.53	<0.052	<0.14	2.27	0.99	0.02	0.13	3.41
	Shrimp	3.3	6.9	0.82	<0.025	<0.054	9.97	0.68	0.00	0.02	10.68
	Total dose (µSv/y)						46.09	2.30	0.10	0.49	**48.98**
Iceland	Altantic salmon[b]	2.6	0.013	0.05	<0.05	<0.09	0.01	0.03	0.01	0.03	0.08
	Arctic char[b]	2.6	0.061	0.05	<0.030	<0.09	0.07	0.03	0.00	0.03	0.14
	Atlantic cod	9.7	0.16	0.065	<0.026	<0.062	0.68	0.16	0.01	0.08	0.93
	Tuna, canned	0.9	10.19	0.18	<0.11	<0.22	4.02	0.04	0.01	0.02	4.09
	European plaice	1.8	0.81	0.02	<0.034	<0.076	0.64	0.01	0.00	0.02	0.67
	Haddock	13.2	1.2	0.04	<0.042	<0.037	6.94	0.13	0.03	0.06	7.16
	Halibut[d]	1.8	0.11	0.02	<0.033	<0.076	0.09	0.01	0.00	0.02	0.12
	Herring	1.8	0.97	0.53	<0.063	<0.138	0.76	0.24	0.01	0.31	1.32
	Mussels	0.1	61	8	<0.14	1.5	2.67	0.20	0.00	0.00	2.87
	Norway lobster[e]	1	0.78	0.82	<0.026	<0.054	0.34	0.21	0.00	0.01	0.56
	Redfish[c]	0.9	1.35	0.16	<0.05	<0.081	0.53	0.04	0.00	0.09	0.66
	Saithe	0.9	0.23	0.025	<0.035	<0.075	0.09	0.01	0.00	0.01	0.11
	Scallops	1	0.93	0.16	<0.22	<0.45	0.41	0.04	0.01	0.06	0.52
	Shrimp	2	0.78	0.82	<0.026	<0.054	0.68	0.41	0.00	0.01	1.11
	Wolffish[f]	0.9	0.11	0.02	<0.033	<0.076	0.04	0.00	0.00	0.01	0.06
	Total dose (µSv/y)						17.98	1.56	0.09	0.76	**20.39**
Finland	Altantic salmon[b]	11	0.013	0.05	<0.05	<0.09	0.06	0.14	0.03	0.12	0.35
	Rainbow trout	5.5	0.02	0.03	0.038	<0.061	0.05	0.04	0.02	0.04	0.15
	Tuna, canned	4.1	10.19	0.18	<0.11	<0.22	18.30	0.19	0.02	0.11	18.62
	Herring	2.2	2.35	0.64	<0.439	<0.179	2.26	0.35	0.05	0.05	2.72
	Vendace[c]	1.6	1.35	0.16	<0.05	<0.081	0.95	0.06	0.00	0.02	1.03
	European perch[c]	1.1	0.04	0.04	<0.05	<0.081	0.02	0.01	0.00	0.01	0.04
	Northern pike	1.1	0.61	0.23	<0.31	<0.12	0.29	0.06	0.02	0.02	0.39

	Pike-perch	1.1	0.24	0.03	<0.31	<0.12	0.12	0.01	0.02	0.02	0.16
	Saithe	1.1	0.39	0.025	0.038	<0.075	0.19	0.01	0.00	0.01	0.21
	Shrimp	1.1	6.9	0.82	<0.025	<0.054	3.32	0.23	0.00	0.01	3.56
	European whitefish[g]	0.8	2.35	0.64	<0.439	<0.179	0.82	0.13	0.02	0.02	0.99
	Other fish	7.4	0.81	0.09	<0.01	<0.01	2.63	0.06	0.00	0.00	2.69
	Total dose (µSv/y)						26.39	1.23	0.19	0.43	**28.23**
Norway	Alaska pollock[a]	3.4	0.42	0.065	<0.045	<0.076	0.63	0.06	0.01	0.03	0.72
	Altantic salmon[b]	12.5	0.013	0.05	<0.05	<0.09	0.07	0.16	0.03	0.14	0.40
	Atlantic cod	14	0.07	0.03	<0.022	<0.062	0.43	0.11	0.02	0.11	0.66
	Atlantic mackerel	4	0.76	0.07	<0.42	<0.90	1.33	0.07	0.09	0.45	1.94
	Tuna, canned	2	10.19	0.18	<0.11	<0.22	8.93	0.09	0.01	0.06	9.08
	Cod roe[a]	1	0.07	0.03	<0.022	<0.062	0.03	0.01	0.00	0.01	0.05
	Crab	0.4	5.27	0.41	<0.059	<0.12	0.92	0.04	0.00	0.01	0.97
	European plaice	0.5	0.29	0.02	<0.038	<0.093	0.06	0.00	0.00	0.01	0.07
	Greater argentine[c]	3.4	0.76	0.07	<0.42	<0.90	1.13	0.06	0.07	0.39	1.65
	Haddock	3.9	0.31	0.04	<0.016	<0.037	0.53	0.04	0.00	0.02	0.59
	Halibut	1	0.06	0.02	<0.034	<0.093	0.03	0.01	0.00	0.01	0.04
	Herring	1	0.78	0.12	<0.071	<0.14	0.34	0.03	0.00	0.02	0.39
	Mussels	0.3	73	9.7	1.07	1.5	9.59	0.73	0.03	0.11	10.47
	Rainbow trout (farmed)	1	0.02	0.03	0.038	<0.061	0.01	0.01	0.00	0.01	0.03
	Redfish[c]	1	0.76	0.07	<0.42	<0.90	0.33	0.02	0.02	0.11	0.49
	Saithe	3	0.39	0.04	<0.034	<0.091	0.51	0.03	0.01	0.03	0.58
	Scallops	0.1	0.93	0.16	<0.22	<0.45	0.04	0.00	0.00	0.01	0.05
	Shrimp	3	2.12	0.08	<0.025	<0.054	2.79	0.06	0.00	0.02	2.87
	Wolffish[f]	0.5	0.06	0.02	<0.034	<0.093	0.01	0.00	0.00	0.01	0.02
	Total dose (µSv/y)						27.72	1.52	0.31	1.55	**31.09**
Sweden	Alaska pollock[a]	0.5	0.42	0.065	<0.045	<0.076	0.09	0.01	0.00	0.00	0.11
	Altantic salmon[b]	4.9	0.013	0.05	<0.05	<0.09	0.03	0.06	0.01	0.06	0.16
	Atlantic cod	8.6	1.37	0.1	<0.057	<0.090	5.16	0.22	0.03	0.10	5.50
	Atlantic mackerel	5.6	1.93	0.25	<0.05	<0.081	4.73	0.35	0.01	0.06	5.16
	Tuna, canned	1	10.19	0.18	<0.11	<0.22	4.46	0.05	0.01	0.03	4.54
	Cod roe[a]	1.2	1.37	0.1	<0.057	<0.090	0.72	0.03	0.00	0.01	0.77
	European plaice	4.1	1.3	0.02	<0.049	<0.076	2.33	0.02	0.01	0.04	2.40
	Haddock	0.78	0.76	0.04	<0.016	<0.037	0.26	0.01	0.00	0.00	0.27
	Herring	4	0.92	0.12	<0.084	<0.138	1.61	0.12	0.02	0.07	1.82
	Pangasius[f]	0.3	0.11	0.02	<0.033	<0.076	0.01	0.00	0.00	0.00	0.02
	Pike-perch[h]	4.3	0.24	0.03	<0.31	<0.12	0.45	0.03	0.07	0.06	0.62
	Shrimp	4	30	1.56	<0.064	<0.099	52.56	1.57	0.01	0.05	54.19
	Total dose (µSv/y)						72.43	2.47	0.17	0.49	**75.56**

a. Assuming same activity concentration as cod when missing data (all or some)
b. Salmon is assumed farmed. Data for Norwegian farmed salmon used (Heldal et al. 2017)
c. Assuming same activity concentration as mackerel when missing data (all or some)
d. Assuming same activity concentration as plaice when missing data (all or some)
e. Assuming same activity concentration as shrimp when missing data (all or some)
f. Assuming same activity concentration as halibut when missing data (all or some)
g. Assuming same activity concentration as herring when missing data (all or some)
h. Assuming same activity concentration as pike when missing data (all or some)

Discussion of dose estimates based on country-specific NANOD data

Dose estimations made based on activity concentrations in nationally collected samples in the NANOD project (when available), are summarised in Figure D-1. Details regarding the calculations are provided in Appendix D. In this dose estimate, any geographical differences in radionuclide levels present in the data will affect the dose estimation for each country. However, any random differences between countries' samples will also be of consequence to the calculated dose.

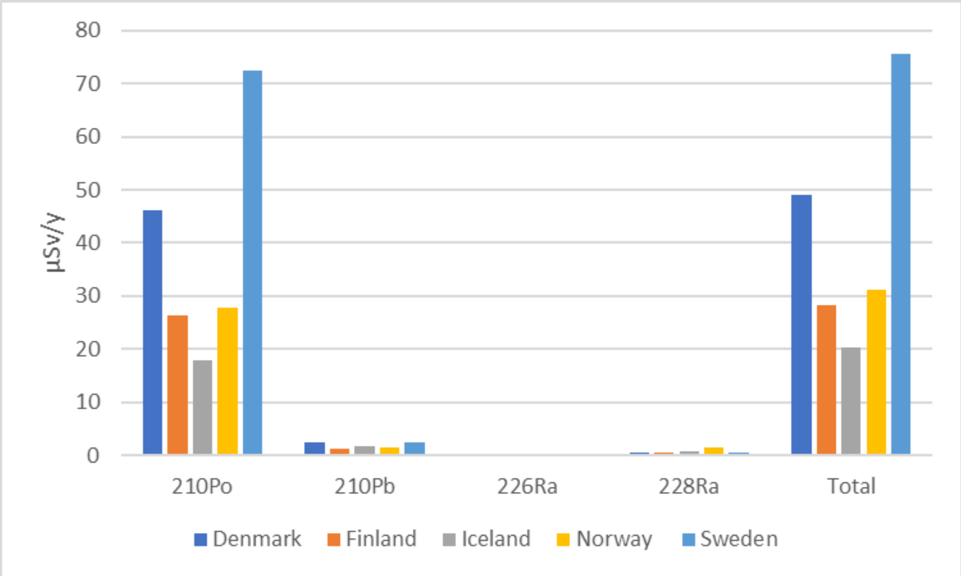

Figure D-1. *Effective doses calculated using ICRP dose coefficients (ICRP 2012), based on national consumption (Table 2.2-1) and nationally collected samples in the NANOD project, when available.*

Dose estimates based on country-specific NANOD results indicate a total annual effective dose from seafood to the average population varied from approximately 20 µSv in Iceland to 75 µSv in Sweden.

The higher dose estimate for Sweden in this case is mainly due to the higher ^{210}Po concentration measured in Swedish shrimp collected in the Kattegat area than in Icelandic and Norwegian samples. A shrimp intake of 4 g/d containing 30 Bq/kg of ^{210}Po resulted in an estimated 54 µSv/y alone. If it is the case that higher ^{210}Po levels are indeed typical for Swedish shrimp consumption, this represents an actual difference between doses received by the populations. On the other hand, if the high levels in Swedish shrimp are a random instance, this is an example of how using single/few national data points for the dose assessment could give more arbitrary results than a larger data set.

Appendix E – Dose calculations based on representative Nordic data

The table shows the effective dose per country (µSv/y) calculated using ICRP (2012), based on national intake (g/d) (Table 2.2-1) and Nordic 'representative values' for activity concentration data (Bq/kg fresh weight), as provided in Table 5.3-1. A comparison between the estimated ingestion dose per radionuclide from national activity concentration data and representative values (Chapter 5.3) is shown below in Figure E-1 below. As expected, the use of this approach causes less variation between the various Nordic countries than the use of national data only, as presented in Appendix D.

Country	Species	Intake	Effective dose (µSv/y)				
		g/d	^{210}Po	^{210}Pb	^{226}Ra	^{228}Ra	Total
Denmark	Alaska pollock	1.7	0.60	0.01	0.00	0.00	0.61
	Altantic salmon, farmed	3.6	0.02	0.00	0.00	0.00	0.02
	Atlantic cod	2.05	0.73	0.01	0.00	0.00	0.74
	Atlantic mackerel	5.5	3.77	0.13	0.00	0.00	3.90
	Tuna, canned	6.2	27.67	1.25	0.01	0.00	28.93
	Crab	0.07	0.16	0.02	0.00	0.00	0.18
	European plaice	3.5	3.44	0.04	0.00	0.00	3.48
	Herring	7.4	7.02	0.61	0.00	0.00	7.63
	Shrimp	3.3	9.96	2.06	0.01	0.00	12.03
	Total dose (µSv/y)		53.37	4.13	0.02	0.00	57.52
Finland	Altantic salmon, farmed	11	0.06	0.00	0.00	0.00	0.06
	Tuna, canned	4.1	18.30	0.83	0.00	0.00	19.13
	European perch	1.1	0.15	0.00	0.00	0.00	0.15
	European whitefish	0.8	1.12	0.02	0.00	0.00	1.13
	Herring	2.2	2.09	0.18	0.00	0.00	2.27
	Northern pike	1.1	0.47	0.02	0.00	0.00	0.49
	Pike-perch	1.1	0.12	0.00	0.00	0.00	0.12
	Rainbow trout (farmed)	5.5	0.05	0.00	0.00	0.00	0.05
	Saithe	1.1	0.24	0.00	0.00	0.00	0.24
	Shrimp	1.1	3.32	0.69	0.00	0.00	4.01
	Vendace	1.6	0.90	0.05	0.00	0.00	0.95
	Other species[a]	7.4	2.63	0.06	0.00	0.00	2.69
	Total dose (µSv/y)		29.43	1.85	0.01	0.00	31.30
Iceland	Altantic salmon, farmed	2.6	0.01	0.00	0.00	0.00	0.01
	Arctic char (farmed)	2.6	0.07	0.00	0.00	0.00	0.07
	Atlantic cod	9.7	3.44	0.06	0.00	0.00	3.49
	Tuna, canned	0.9	4.02	0.18	0.00	0.00	4.20
	European plaice	1.8	1.77	0.02	0.00	0.00	1.79
	Haddock	13.2	5.86	0.06	0.00	0.00	5.92
	Halibut	1.8	0.09	0.00	0.00	0.00	0.09
	Herring	1.8	1.71	0.15	0.00	0.00	1.86
	Mussels	0.1	1.99	2.53	0.22	0.08	4.82
	Norway lobster	1	3.02	0.62	0.00	0.00	3.65
	Saithe	0.9	0.20	0.00	0.00	0.00	0.20
	Scallops	1	0.41	0.02	0.00	0.00	0.42

	Shrimp	2	6.04	1.25	0.01	0.00	7.29
	Wolffish	0.9	0.04	0.00	0.00	0.00	0.04
	Total dose (µSv/y)		28.71	4.88	0.23	0.08	33.91
Norway	Alaska pollock	3.4	1.20	0.02	0.00	0.00	1.22
	Altantic salmon, farmed	12.5	0.07	0.00	0.00	0.00	0.07
	Atlantic cod	14	4.96	0.08	0.00	0.00	5.04
	Atlantic mackerel	4	2.74	0.09	0.00	0.00	2.84
	Tuna, canned	2	8.93	0.40	0.00	0.00	9.33
	Cod roe	1	0.35	0.01	0.00	0.00	0.36
	Crab	0.4	0.92	0.10	0.00	0.00	1.02
	European plaice	0.5	0.49	0.01	0.00	0.00	0.50
	Greater argentine	3.4	2.33	0.08	0.00	0.00	2.41
	Haddock	3.9	1.73	0.02	0.00	0.00	1.75
	Halibut	1	0.05	0.00	0.00	0.00	0.05
	Herring	1	0.95	0.08	0.00	0.00	1.03
	Mussels	0.3	5.97	7.58	0.66	0.25	14.46
	Rainbow trout (farmed)	1	0.01	0.00	0.00	0.00	0.01
	Saithe	3	0.66	0.00	0.00	0.00	0.66
	Scallops	0.1	0.04	0.00	0.00	0.00	0.04
	Shrimp	3	9.06	1.87	0.01	0.00	10.94
	Wolffish	0.5	0.02	0.00	0.00	0.00	0.02
	Total dose (µSv/y)		40.55	10.34	0.67	0.25	51.82
Sweden	Alaska pollock	0.5	0.18	0.00	0.00	0.00	0.18
	Altantic salmon, farmed	4.9	0.03	0.00	0.00	0.00	0.03
	Atlantic cod	8.6	3.05	0.05	0.00	0.00	3.10
	Atlantic mackerel	5.6	3.84	0.13	0.00	0.00	3.97
	Tuna, canned	1	4.46	0.20	0.00	0.00	4.67
	Cod roe	1.2	0.43	0.01	0.00	0.00	0.43
	European plaice	4.1	4.03	0.05	0.00	0.00	4.08
	Haddock	0.78	0.35	0.00	0.00	0.00	0.35
	Herring	4	3.79	0.33	0.00	0.00	4.13
	Pangasius	0.3	0.01	0.00	0.00	0.00	0.01
	Pike-perch	4.3	0.45	0.00	0.00	0.00	0.46
	Shrimp	4	12.07	2.49	0.01	0.00	14.58
	Total dose (µSv/y)		32.69	3.27	0.02	0.00	35.98

[a]For the category “other fish” in the Finnish dietary data, the mean activity concentration of other Nordic fish species was assumed.

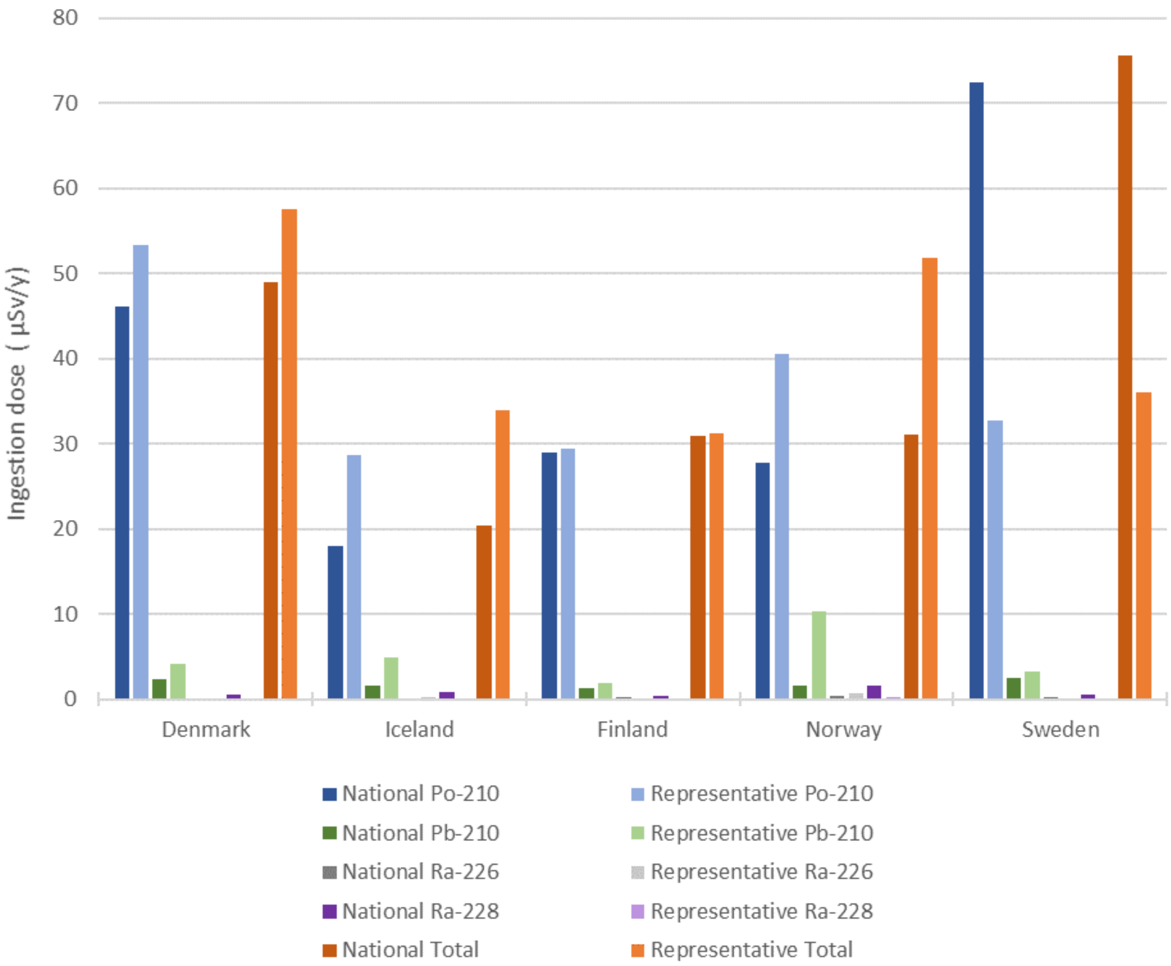

Figure E-1. Comparison of effective ingestion doses calculated using national activity concentration data obtained from the NANOD project and doses calculated from the ‘representative values’ as presented above and in Chapter 5.3.

Bibliographic Data Sheet **NKS-435**

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Abstract
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The objective of the NANOD project is to fill knowledge gaps related to the concentration of naturally occurring radionuclides in the fish and shellfish species commonly consumed in the Nordic region, in order to enable more accurate dose assessments for seafood and the total diet in the Nordic countries.

^{210}Po concentrations in the samples of wild fish caught in the Nordic region ranged from 0.01 to 3.4 Bq/kg (fw). The highest concentration of all samples was observed in blue mussels, containing up to 73 Bq/kg. Results of the present and previous work indicate that influences on ^{210}Po concentrations in fish and shellfish are complex, and several factors may play a role. Analyses of ^{210}Pb show an overall lower content. Most ^{226}Ra and ^{228}Ra results were below detection limits of approximately 0.1 Bq/kg or less.

Ingestion dose estimates for the Nordic countries show average national doses ranging from 31 to 58 µSv/y from the examined radionuclides. ^{210}Po accounted for approximately 80-90% of this dose, while the dose from radium isotopes was negligible and below 2%. Despite their low consumption, canned tuna, blue mussels and shrimp accounted for a large share of the dose due to their high ^{210}Po content relative to other species consumed in larger quantities.

Key words seafood, radioecology, fish, shellfish, natural radioactivity, ingestion dose, diet, polonium

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