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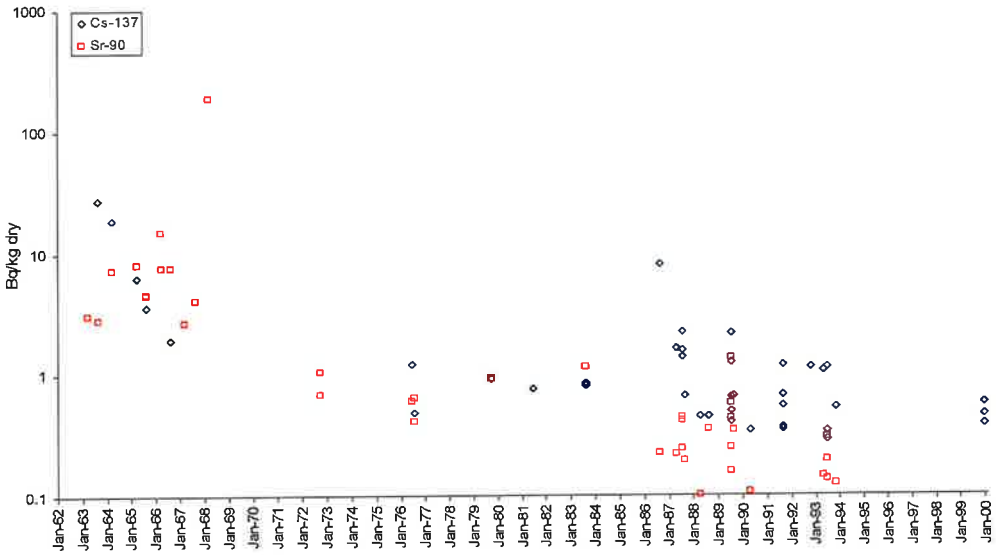
Indicator organisms for environmental radioactivity.
Final report on the Faroese contribution to the NKS-B INDOFERN project

Hans Pauli Joensen



^{137}Cs and ^{90}Sr in *Fucus sp.* from the Faroe Islands in the period 1963-2000.

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Indicator organisms for environmental radioactivity. Final report on the Faroese contribution to the NKS-B INDOFERN project.

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1. Introduction

Radioactive contamination of the Faroese environment derives mainly from nuclear weapons tests in the 1950's and 1960's and from the Chernobyl nuclear accident in April 1986. Radioactive discharges from Sellafield and La Hague are potential sources for anthropogenic radionuclides in the Faroese marine environment.

This paper presents results from the Faroese part of the INDOFERN project. The ^{137}Cs activity concentration has been measured in selected indicator organisms from the terrestrial, freshwater and marine environments in the years 2002-2004. Results from earlier measurements during the last four decades are also presented.

The indicator value of the organisms is discussed, and a ranking list is suggested in some cases.

2. Material and methods

Indicator organisms have been sampled for the INDOFERN project in the years 2002, 2003 and 2004. The radioactivity measurements have been carried out with a lead shielded Germanium detector. Data from previous measurements of relevance to INDOFERN have become available from earlier data archives and annual reports from Risø National Laboratory, Roskilde, Denmark (Sven P. Nielsen and Henning Dahlgaard, Risø, personal communication; Risø Reports, 1962-93).

The indicator organisms include *Empetrum sp., Moss sp., Lichen sp., Calluna vulgaris, Erica cinerea* from the terrestrial environment, trout sp. and water from freshwater lakes, and *Fucus sp.,* haddock and seawater from the marine environment. Trout and haddock samples constitute flesh, and were kept frozen before measurement. The terrestrial samples and fucus were dried at 105°C before measurement. Seawater and lake water were measured by Risø.

Grass and soil samples were sampled from four randomly chosen 50cm x 50cm plots at one site in 2002. The grass was cut from the area and dried at 105°C before measurement. Three soil cores, 5.7cm in diameter and 10cm in depth, were taken from each plot and divided into an upper and a lower 5cm layer. The soil material from the respective layers was mixed and dried at room temperature before measurement.

3. Results and Discussion

3.1. Terrestrial environment

Tables 1 and 2 present results from terrestrial samplings in the years 2002-2004. It should be noted that the sampling stations were not exactly the same every year. It is wellknown from other studies (Joensen, 1999) that there is large variability in the ^{137}Cs activity concentration in grass, both within and between pastures, and this is presumeably also the case for other vegetation.

Measurements prior to INDOFERN are presented in Tables 3 and 4. Measurements of ^{137}Cs and ^{90}Sr from April 1967 indicate a significant geographical variation of the activity concentrations in Moss sp. and Lichen sp. with lower activity in the southern part of the country (Tvøroyri) as compared with the central area (Tórshavn). The moss and lichen species are, however, not identified in the old data files, and there is neither any information about soil characteristics from the respective sampling sites that could assist to explain the observed differences. It can be noted that the ^{137}Cs activity concentration in moss at lake Toftavatn decreased from 270 Bq/kg dw in September 1999 to 77.5 Bq/kg dw in September 2002 and 58.9 Bq/kg dw in August 2003 (cf. Tables 3 and 1).

Cs-134 was measured in the moss and lichen samples from Tórshavn in 1987. The $^{134}Cs/^{137}Cs$ ratio was 0.532 and 0.585 for moss and lichen, respectively, as date corrected to 26 April 1986, indicating that practically all the radiocesium activity in 1987 derived from the Chernobyl accident.

Table 1. Cs-137 in terrestrial samples taken on the shores of lake Toftavatn and Leitisvatn on the islands Eysturoy and Streymoy, respectively. Values are given with 1 counting standard deviation. *: *Empetrum hermaphroditum*. **: *Empetrum nigrum*. NS: No Sample.

	Sampling date	Soil		Mixed Grass	*Empetrum sp.*	*Hyloconium splendens*
		0-5cm	5-10cm			
		Bq/m^2	Bq/m^2	Bq/kg dw	Bq/kg dw	Bq/kg dw
Toftavatn	9 Sept. 2002	1514±74	1619±66	97.8±9.49	17.8±1.66 *	77.5±4.37
Leitisvatn	6 Sept. 2002	2106±99	1940±112	75.4±4.90	NS	NS
Toftavatn	30 Aug. 2003	NS	NS	NS	26.3±2.31 **	58.9 ± 4.16

Table 2. Cs-137 in samples from 2003 and 2004. All activity concentrations are given as Bq/kg dry weight, together with 1 counting standard deviation. The samples were collected at the site **Norðoyri** on the island Borðoy 4 August both years, except *Parmelia saxatilis* which was sampled *17 July 2004* at the site **Trøllanes** on the island Kalsoy. (NS: Not Sampled).

Year	*Empetrum hermaphroditum* (Northern crowberry)	*Empetrum nigrum* (Crowberry)	*Erica cinerea* (Bell heather)	*Calluna vulgaris* (Heather)	*Racomitrium laniginosum*	*Potentella eracta* (Common tormentil)	*Parmelia saxatilis*
2003	NS	11.8 ± 2.21	11.2 ± 2.25	91.3 ± 5.33	31.9 ± 1.90	NS	NS
2004	6.13 ±0.34	NS	10.2 ± 0.86	29.3 ±0.82	46.1 ± 0.78	14.1 ± .76	49.5 ± 0.74

Table 3. Measurements of ^{137}Cs, ^{134}Cs and ^{90}Sr in **moss** from 1967, 1987 and 1999 (unspecified species). The unit for all data is Bq/kg fw.

1 April 1967			1 July 1987		1 Sept. 1999
Tvøroyri	Tórshavn		Tórshavn		Toftavatn
^{137}Cs	^{137}Cs	^{90}Sr	^{134}Cs	^{137}Cs	^{137}Cs
363	2479	220	219	600	270

Table 4. Measurements of ^{137}Cs and ^{90}Sr in **lichen** (unscpecified species) sampled in Tórshavn and Tvøroyri *1 April 1967* and "4-5km from *Tórshavn*" *1 July 1987*. (NS: No Sample)

	Tórshavn			Tvøroyri	
Year	^{134}Cs	^{137}Cs	^{90}Sr	^{137}Cs	^{90}Sr
	Bq/kg fw	Bq/kg fw	Bq/kg fw	Bq/kg fw	Bq/kg fw
1967	NS	3352	816	1221	89.0
1987	262	654	3.44	NS	NS

3.2. Freshwater environment

Samples have been taken from the three freshwater lakes Leitisvatn, Stóravatn and Toftavatn, in the islands Vágoy, Sandoy and Eysturoy, respectively. All three lakes have non-migratory stocks of brown trout (*Salmo trutta*). The trophic level of the lakes is decreasing in the order Stóravatn, Toftavatn, Leitisvatn. Information about the lakes are presented in Table 5. Some earlier samplings exist from lake Leynavatn in the island Streymoy.

Table 5. Topographic data about the lakes.

	Altitude, m a.s.l.	Surface area, km^2	Max depth, m	Volume, m^3
Toftavatn	15	0.509	22	$2.11 \cdot 10^6$
Leitisvatn	32	3.42	59	$81.6 \cdot 10^6$
Stóravatn	26	0.160	1.8	$0.150 \cdot 10^6$
Leynavatn	63	0.18	33	(No data)

Leitisvatn and Leynavatn are oblong relatively deep lakes, gradually descending towards a center line. Stóravatn is a shallow lake with an almost uniform depth. Toftavatn consists of a shallow northern part with maximum depth of 3.5m and a southern deeper part with almost circular isobaths and maximum depth 22m. Further description of the lakes can be found in Christoffersen *et.al.* (2002).

The results from 2002 are presented in the Table 6. Only two trouts were sampled in 2003, one from Leitisvatn (23 July) and one from Stóravatn (1 June) with the ^{137}Cs activity concentrations 1.26 Bq/kg fw and 16.2 Bq/kg fw, respectively. The significantly higher activity concentration in the trout from Stóravatn as compared to Leitisvatn may be a reflection of feeding habit of the trout, as trout in Stóravatn would be expected to feed more on benthic fauna than trout in Leitisvatn. The trout stomach contents were, however, not studied. But studies in July 1987 and July 1988 showed that trout from Stóravatn feed mainly on benthic fauna followed by diptera, while trout from Leitisvatn feed almost equally on dipteria and benthic animals (Joensen and Vestergaard, 1992).

The observed ^{137}Cs activity concentration in lake water in Toftavatn increased from 1999 to 2002 (cf. Tables 6 and 8). This should not be expected, but one reason may be that the samples have been collected from different parts of the lake these years, as it consists of a deeper and a shallower relatively separated parts. The higher ^{137}Cs concentration in water from Toftavatn as compared to Leitisvatn (Table 6) may be

explained by higher resuspension from sediments in Toftavatn, as this lake is much shallower and smaller than Leitisvatn.

Table 6. ^{137}Cs in Brown trout flesh (*Salmo trutta*) and lake water from Toftavatn and Leitisvatn in 2002. Trout were caught *15 August* in both lakes. Water samples (each 200 liter) were collected 3 September from Toftavatn and 6 September from Leitisvatn.

Lakes in 2002	*Salmo trutta*					Water
	Number of trout	Mean	St. dev	Min	Max	
		Bq/kg fw	Bq/kg fw	Bq/kg fw	Bq/kg fw	Bq/m^3
Toftavatn	9	9.88	4.20	5.85	19.8	5.51±0.32
Leitisvatn	10	5.31	1.99	4.02	10.7	3.45±0.27

Physical statistics about the trout from 2002 can be found in Table 7. The relationship between live weight and length of trout is given by the power function $W=K\cdot L^x$, where W is the live weight and L is the length. K is a proportionality constant. For trout from Leitisvatn we get $K=13.0\cdot10^{-3}$ and x=2.90. It was not possible to make the corresponding analyses for trout from Toftavatn, as no intestines were included with the trout samples.

Table 7. Length and live weight of Brown trout (*Salmo trutta*) from lakes Toftavatn and Leitisvatn. The trout are the same as in Table 11. (*) Without intestines.

		Mean	St. dev	Min	Max
Toftavatn	Length (cm)	25.9	2.27	23.0	29.7
	Weight (g) (*)	148.9	42.7	97.7	216.0
Leitisvatn	Length (cm)	24.3	2.16	20.9	28.9
	Weight (g)	131.2	38.8	89.6	232.4

Table 8. Measurements of radiocesium in lake water after the Chernobyl reactor accident. All values are given in Bq/m^3. (NS: No Samples).

	July 1987		July 1989		August 1991	June 1993	Sept. 1999
	^{134}Cs	^{137}Cs	^{134}Cs	^{137}Cs	^{137}Cs	^{137}Cs	^{137}Cs
Leitisvatn	1.60	9.94	0.63	6.23	6.24	6.24	NS
Leynavatn	0.90	3.74	NS	1.84	2.60	2.30	1.26
Toftavatn	NS	NS	NS	NS	NS	NS	4.17

Table 9. Measurements of ^{137}Cs and ^{90}Sr in rainbow trout flesh (*Salmo irideus*) in the Faroe Islands (no site specification). One trout from each of the years 1975 and 1976. In 1987, the data represent averages in flesh from 18 Brown trout (*Salmo trutta*) from the lake Leitisvatn.

1 August 1975				1 June 1976				July 1987	
^{137}Cs		^{90}Sr		^{137}Cs		^{90}Sr		^{134}Cs	^{137}Cs
Bq/ kg fw	Bq/ kg K	Bq/ kg fw	Bq/ kg Ca	Bq/ kg fw	Bq/ kg K	Bq/ kg fw	Bq/ kg Ca	Bq/ kg fw	Bq/ kg fw
0.78	196	0.17	207	0.45	126	0.22	207	42.4	115.4

Measurements from the 1970's, 1980's and 1990's are presented in Tables 8 and 9. Date correcting to 26 April 1986, the $^{134}Cs/^{137}Cs$ ratio for lake water in 1987 was 0.235 and 0.351 in Leitisvatn and Leynavatn, respectively, and 0.281 in Leitisvatn in 1989. The trouts from Leitisvatn in 1987 contained practically only radiocesium from

Chernobyl, as the average $^{134}Cs/^{137}Cs$ ratio was 0.536 (date corrected to 26 April 1986).

3.3. Marine environment

Seawater and Fucus sp. were sampled in 2002, 2003 and 2004. Measurements of ^{137}Cs are presented in Table 10. The ^{137}Cs activity in a sample of haddock flesh (*Melanogrammus aeglefinus*) from 15 March 2003 was 0.071±0.007 Bq/kg fw, i.e. about 27% of the dry weight concentration in *Fucus vesiculosus*, indicating that haddock is a relatively poor indicator organism.

Ascophyllum nodosum and *Fucus vesiculosus* were both sampled at the same site in March 2004 in order to compare their ^{137}Cs activity concentrations. The activity concentrations in the two species were the same within one standard deviation.

The **^{99}Tc** activity concentration was measured to 1.68±0.08 Bq/kg dw in the *Fucus vesiculosus* sample from 20 February 2003.

Table 10. Cs-137 in marine samples from Kirkjubøur. Concentrations are given with 1 counting std. deviation. (BDL: Below Detection Limit. NA: Not Analyzed. NS: No Sample). *) *Fucus vesiculosus* was sampled 15 June 2004

	Seawater	*Fucus vesiculosus*	*Ascophyllum nodosum*
Sampling date	Bq/m^3	Bq/kg dw	Bq/kg dw
27.06.2002	1.85 ± 0.14	BDL	NS
20.02.2003	1.70 ± 0.23	<0.3	NS
12.05.2003	2.04 ± 0.16	BDL	NS
25.09.2003	1.92 ± 0.34	0.262 ± 0.059	NS
05.03.2004	NA	0.175 ± 0.053	0.220 ± 0.050
26.05.2004	NA	*) 0.300 ± 0.063	NS
24.09.2004	NA	NA	NS

Ascophyllum nodosum has also been sampled in 1972, 1989 and 1991 (Table 11). It has not been possible to explain the increasing trends in the activity concentrations, but it may possibly be related to discharges from European reprocessing plants.

Table 11. ^{137}Cs and ^{90}Sr in *Ascophyllum nodosum*. Values are given with 1 counting standard deviation if available. (ND: No Data)

	^{137}Cs		^{90}Sr	
	Bq/kg dw	Bq/kg K	Bq/kg dw	Bq/kg Ca
1 Sept. 1972	ND	ND	0.68	50.0±16.5
1 April 1989	0.39±0.14	16.2	0.11±0.03	8.3±2.1
1 August 1989	0.60±0.09	23.8±3.40	ND	ND
1 May 1991	1.36±0.14	61.2	2.34±0.05	165.4±3.47

Measurements of soft tissue from *Mytilus edulis* have been reported on three occasions (Table 12). The relatively high activity concentration of ^{137}Cs in July 1987

is due to input from the Chernobyl accident. Cs-134 was measured to 0.160 Bq·kg^{-1}dw in this particular sample, giving a $^{134}Cs/^{137}Cs$ ratio of 0.235.

Table 12. ^{137}Cs and ^{90}Sr in *Mytilus edulis* soft tissue. Values are given with 1 counting standard deviation if available. (ND: No Data)

	^{137}Cs			^{90}Sr		
	Bq/kg fw	Bq/kg dw	Bq/kg K	Bq/kg fw	Bq/kg dw	Bq/kgCa
14 June 1981	0.0568±0.0170	ND	23.0	ND	ND	ND
1 July 1987	ND	0.6804±0.0782	86.2	0.0083±0.0035	0.0048±0.0020	5.68±2.39
7 Dec. 1999	0.0521±0.0164	0.1326±0.0418	21.6±6.79	ND	ND	ND

3.3.1. Time series for *Fucus* and *Laminaria*

3.3.1.1. Fucus species

Long-term measurements exist for ^{137}Cs and ^{90}Sr in *Fucus* since 1963. The time series are presented in Figure 1. The particular Fucus species have been recorded as *Fucus vesiculosus* since 1972, except for 1986 (*Fucus serratus)* and for September 1972 and April 1987 (*Fucus distichus*). The species are recorded as just *Fucus sp.* until 1968. The ^{137}Cs activity concentration in *Fucus sp.* decreased with short effective ecological half-life during the first tree years of measurements in the 1960's. The level was constant from the mid 1970's until 1986 when input from the Chernobyl nuclear accident caused the activity concentration to exceed the level from the mid 1960's. Exponential curve fitting to the ^{137}Cs data from March 1963 to August 1966 and from August 1986 to April 1988 resulted in half-lives of 271 days (R^2=0.986) and 142 days (R^2=0.883), respectively. The shorter post-Chernobyl half-life is explained by the fact that the input from Chernobyl came as a short pulse, while the input to the atmosphere in the 1960's was distributed over a longer time scale. The ^{90}Sr data do not show trends similar to ^{137}Cs in the early 1960's and after the Chernobyl nuclear accident, although the general decreasing pattern is similar (except for early 1960's and a maximum ^{90}Sr value in March 1968). There was no ^{90}Sr input from Chernobyl.

The highest ^{90}Sr activity concentration of 186 Bq·kg^{-1}dw was recorded in March 1968, while the second highest value of 15 Bq·kg^{-1}dw was recorded in March 1966; i.e. about a factor of 10 below the maximum. Cs-137 was not recorded for March 1966. The maximum ^{90}Sr value has been cross-checked with Aarkrog & Lippert (1969) who state that "the extreme value in March is difficult to explain. August was in agreement with last year's observations." It has still not been possible to find an explanation for the recorded maximum.

Cs-134 was measured in four Fucus samples after the Chernobyl accident, showing date corrected (to 26 April 1986) $^{134}Cs/^{137}Cs$ ratios of 0.491, 0.465, 0.681, 0.497 for samples collected 1 August 1986, 1 April 1987, 1 June 1987 and 17 July 1989, respectively. It shows that Fucus is an effective marine indicator organism for ^{137}Cs.

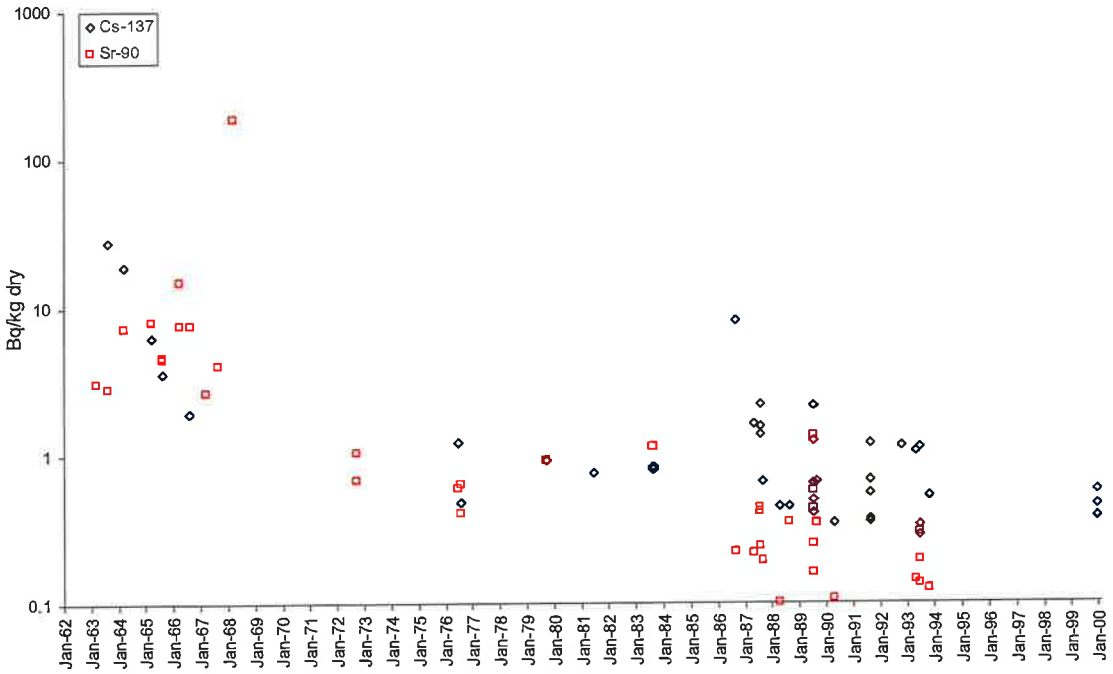

Figure 2. Measurements of ^{137}Cs and ^{90}Sr in *Fucus sp.* from the Faroe Islands in the period 1963-2000.

3.3.1.2. Laminaria species

Measurements of ^{137}Cs and ^{90}Sr in Laminaria species are presented in Figure 2. The Laminaria species was *Laminaria digitata* in April 1980 and since 1985 except for 1992, when it is recorded as just *Laminaria sp.* For the three years 1977-79 it was recorded as *Laminaria hyperboria*. In 1981 it was *Laminaria saccharina*. All other cases have been reported as just *Laminaria sp.*

The measurements of ^{137}Cs were reported as Bq·kg^{-1}K until 1981. After 1981, the values have been recorded in two units, Bq·kg^{-1}K and Bq·kg^{-1}dw, from which the ratio (Bq·kg^{-1}dw)/(Bq·kg^{-1}K) was determined to 0.0558±0.0157. The ^{137}Cs values in Figure 2 prior to 1983 have been calculated by using this ratio.

The ^{90}Sr values are reported in the database as Bq·kg^{-1}Ca until 1983, where-after they are given as both Bq·kg^{-1}Ca and Bq·kg^{-1}dw. The ratio (Bq·kg^{-1}dw)/(Bq·kg^{-1}Ca) was calculated to 0.1355±0.0020, and the ^{90}Sr data in Figure 2 prior to 1984 have been calculated by using this ratio.

Figure 2 shows an increase in the activity concentration from 1962 to 1965, but the maximum values are reported for 1971. It has not been possible to explain these maxima. As for *Fucus sp.*, the ^{137}Cs level in *Laminaria sp.* increased in 1986 due to input from the Chernobyl accident. The pre-Chernobyl ^{137}Cs activity concentration decreased with a half-life of 4.9 years (R^2=0.794). As mentioned earlier, there was no input of ^{90}Sr from the Chernobyl accident, and the ^{90}Sr activity concentration decreased with a half-life of 6.3 years (R^2=0.510) onwards from the early 1960's. The extreme activity concentrations for 1 March 1971 were excluded in the half-life calculation.

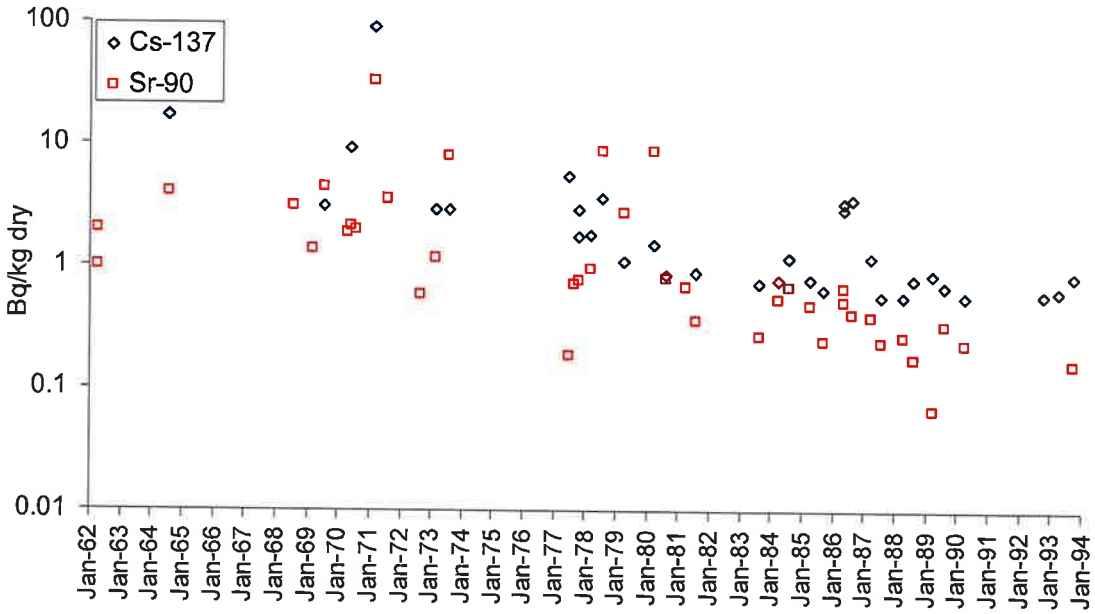

Figure 2. Measurements of ^{137}Cs and ^{90}Sr in *Laminaria sp.* from the Faroe Islands in the period 1962-1994.

Cs-134 was measured in three samples collected 1 May 1986, 1 August 1986 and 1 April 1989, and the $^{134}Cs/^{137}Cs$ ratio was 0.555, 0.381 and 0.145, respectively, as date corrected to 26 April 1986.

3.4. Transfer factors and concentration ratios

Estimates of transfer factors in the terrestrial environment are presented in Table 13. The value for mixed grass at Toftavatn in 2002 was calculated as the activity concentration (Bq/kg dw) in grass divided by the measured deposition (3133 Bq/m^2) in the uppermost 10cm of the soil. Grass and soil samples were collected at the same place. The transfer factors for other species than grass must be considered as more rough estimates, as they were collected some 100 meters away from the soil sampling station. The estimates at Toftavatn in 2003 were calculated from the deposition in 2002, and the values at Norðoyri in 2003 and 2004 were both years based on the deposition measured in 2003 (5455 Bq/m^2). The results show differences between species regarding uptake of ^{137}Cs, as well as a geographical variability.

Table 13. Transfer factors (m^2/10^3 kg dw) for ^{137}Cs.

	Mixed grass	*Empetrum herma-phroditum*	*Empetrum nigrum*	*Hyloconium splendens*	*Erica cinerea*	*Calluna vulgaris*	*Racomitrium laniginosum*	*Potentella erecta*
Toftavatn 9 Sep. 2002	31.2	5.68		24.7				
Toftavatn 30 Aug2003			8.39	18.8				
Norðoyri 4 Aug. 2003			2.16		2.05	16.7	5.85	
Norðoyri 4 Aug. 2004		1.12			1.86	5.37	8.44	2.58

Apart from mixed grass, the results indicate that *Hyloconium splendens* and *Calluna vulgaris* are the most suitable indicator organisms among the selected species. The transfer factors for *Racomitrium laniginosum* and *Calluna vulgaris* turn out in opposite order in 2003 and 2004. *Parmelia saxatilis* is also a suitable indicator organism (cf. Table 2).

The concentration ratio [(Bq/kg dw)/(Bq/m^3)] between ^{137}Cs activity in *Fucus vesiculosus* and seawater from Kirkjubøur 25 September 2003 vas 0.136 m^3/kg dw.

The concentration ratio [(Bq/kg ww)/(Bq/m^3)] between ^{137}Cs activity in haddock flesh (*Melanogrammus aeglefinus*) and seawater was 0.038 m^3/kg ww. The value is calculated from the concentration in the haddock sample from 15 March 2003 and the average seawater concentration in the samples from 20 February and 12 May 2003.

4. Conclusion

Hylocomium splendens and *Calluna vulgaris* are found to be good indicator organisms. *Racomitrium laniginosum* and *Parmelia saxatilis* are also found to be suitable indicator organisms. The results indicate, however, that mixed grass is one of the best terrestrial indicators. The highest transfer factor for ^{137}Cs was found for mixed grass.

Salmo trutta is a suitable indicator organism for the freshwater environment. It showed a ^{137}Cs signal soon after the Chernobyl accident.

Fucus vesiculosus is a good indicator organism for the marine environment. It showed a soon reaction to ^{137}Cs input from the Chernobyl accident. It was observed that the halflife for ^{137}Cs in *Fucus vesiculosus* was shorter after the Chernobyl accident as compared to the situation in the early 1960's.

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