

Detecting pan-Atlantic migration in salmon (*Salmo salar*) using ^{137}Cs

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Abstract: ^{137}Cs is a globally dispersed radioisotope that is transferred efficiently through the food chain. There is a strong east–west gradient of ^{137}Cs in the waters of the North Atlantic due to anthropogenic inputs from Europe, with levels exceeding $10 \text{ Bq}\cdot\text{m}^{-3}$ in the Irish Sea and concentrations $<1.5 \text{ Bq}\cdot\text{m}^{-3}$ in the West Atlantic. This range in values is subsequently reflected in fish, including Atlantic salmon (*Salmo salar*), caught in those waters. ^{137}Cs concentrations in adult salmon, which had returned to the Ste. Marguerite River, Canada, reflected the entire range of values seen previously across the North Atlantic. In fact, 43% of fish had concentrations characteristic of the Faroe, Norwegian, North, and Irish seas. These results are in sharp contrast with what is generally believed about the migration of salmon and suggest that their marine life history is more panoeceanic than previously thought.

Résumé : Le césium-137 (^{137}Cs) est un radio-isotope omniprésent qui se transmet efficacement le long de la chaîne alimentaire. On observe dans les eaux de l'Atlantique Nord un fort gradient est-ouest du ^{137}Cs , qui est dû à des apports anthropiques provenant d'Europe, les concentrations dépassant $10 \text{ Bq}\cdot\text{m}^{-3}$ en mer d'Irlande mais étant inférieures à $1,5 \text{ Bq}\cdot\text{m}^{-3}$ dans l'Atlantique Ouest. Cette gamme de concentrations se retrouve chez les poissons, notamment le saumon atlantique (*Salmo salar*), capturés dans ces eaux. Les concentrations de ^{137}Cs chez des saumons adultes revenus à la rivière Sainte-Marguerite, au Canada, représentaient l'ensemble des valeurs observées d'une façade à l'autre de l'Atlantique Nord. En fait, 43 % des poissons présentaient des concentrations caractéristiques des eaux des îles Féroé, de la Norvège, de la mer du Nord et de la mer d'Irlande. Ces résultats contredisent nettement les idées reçues sur la migration du saumon et semblent indiquer que la phase marine est plus panocéanique qu'on ne le croyait jusque-là.

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Total abundance of North American origin Atlantic salmon (*Salmo salar*) has recently declined to approximately 45% of average numbers from previous decades (Anonymous 1998). This has occurred despite increases in spawning escapements, high smolt production in many rivers, and reduced harvests. With the general failure of river management schemes to maintain or enhance the abundance of salmon, interest has shifted to their marine life and the variability of ocean conditions that may influence migration and survival (Bisbal and McConnaha 1998). However, progress has been limited due to the difficulty of sampling over vast distances at sea. Sources of marine mortality are poorly understood, since there is a lack of basic knowledge about the distribution of salmon in the ocean (Friedland 1998). It is generally thought that Atlantic salmon originating from North American rivers feed on the Grand Banks, in the Labrador Sea, and along the coast of Greenland, with only a small percentage ($<1\%$) ranging as far east as Iceland and the Faroe Islands (Mills 1993). However, these are infer-

ences based on the recapture of very few tagged individuals and information from limited surveys of salmon abundance in the North Atlantic. These results are potentially biased by small sample sizes and uneven fishing effort to recapture marked fish (Hansen and Quinn 1998). Tremendous effort is required to tag a sufficiently high number of salmon to attain a statistically satisfying number of recaptures. Recapture rates are approximately 2% on average of individuals tagged on the high seas. Thus, information derived from other tracers such as radioisotopes can provide valuable independent information that will be particularly useful, since a much larger number of fish can potentially be analyzed. In theory, information could be generated for all fish.

^{137}Cs is a nuclear fission product that is rapidly taken up by biota, transferred efficiently through the food chain, and retained with a biological half-life of several years in large fish (Rowan and Rasmussen 1994, 1996). It can easily be detected at low levels with modern gamma spectrometry (Rowan and Rasmussen 1996). There is a pronounced east–west gradient of ^{137}Cs in the waters of the North Atlantic (Aarkrog et al. 1992; Kershaw et al. 1992; IAEA 1998) due to the combined effect of the Sellafield (United Kingdom) nuclear reprocessing plant on the Irish Sea and the Chernobyl nuclear accident (Fig. 1a). Thus, concentrations are highest in the Irish, North, and Norwegian seas, with values ranging from 10 to $150 \text{ Bq}\cdot\text{m}^{-3}$, whereas on the Grand Banks and Labrador Sea, concentrations are $<1.5 \text{ Bq}\cdot\text{m}^{-3}$. This range is subsequently reflected in prey items of salmon. In aquatic food webs, ^{137}Cs bioconcentrates in phytoplankton, approximately 10- to 1000-fold over environmental concentrations, and is transferred up the food chain into

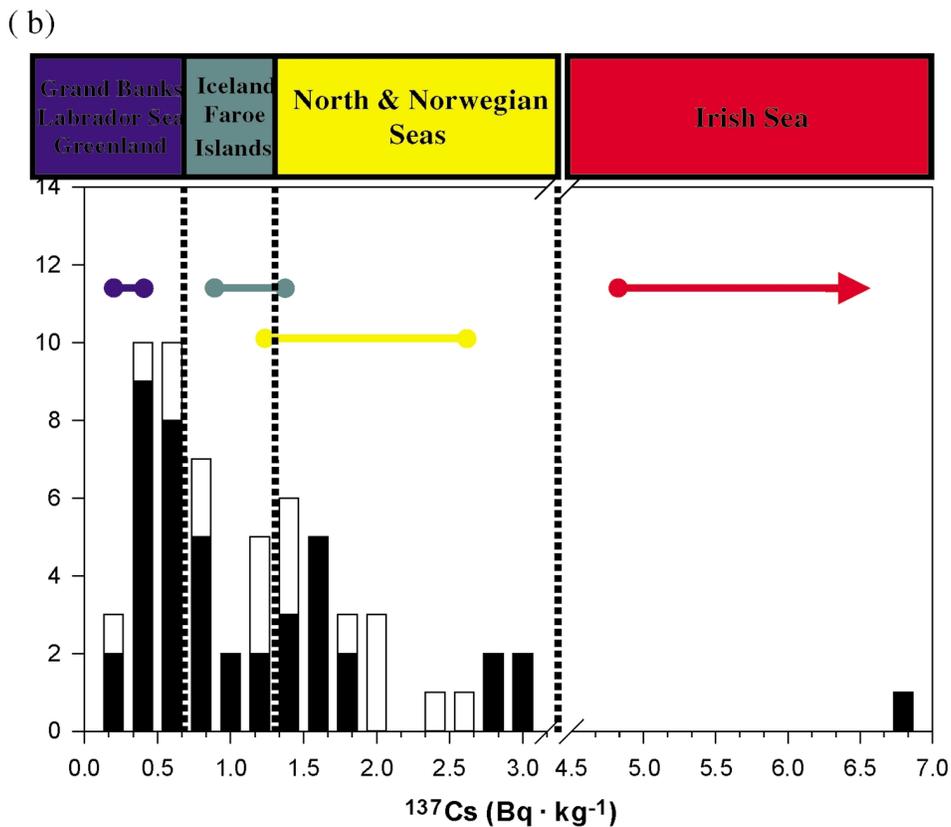
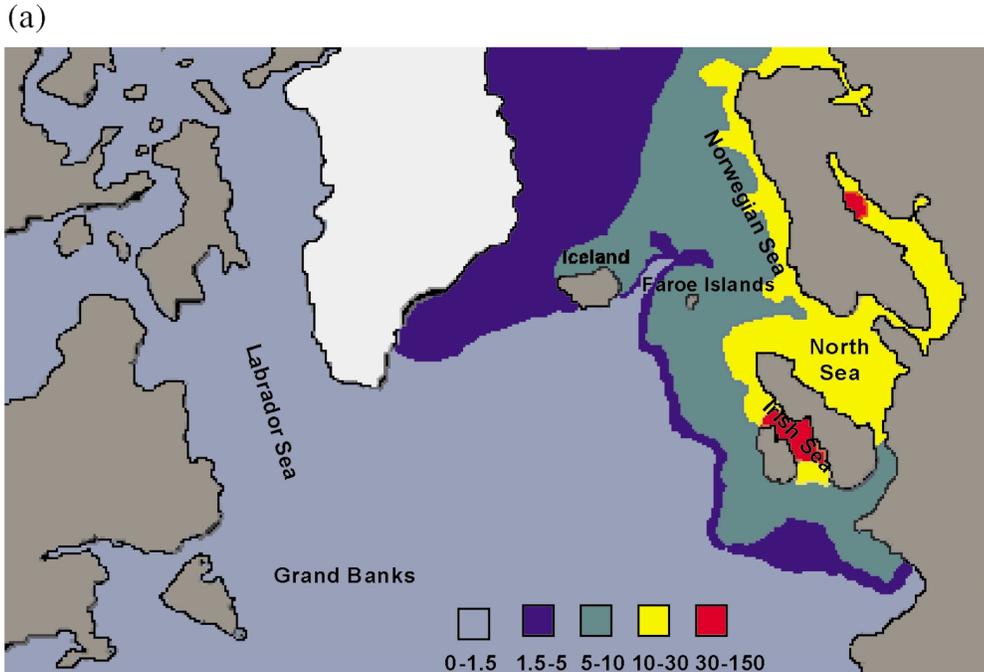
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Fig. 1. (a) ^{137}Cs distribution ($\text{mBq}\cdot\text{L}^{-3}$) in waters of the North Atlantic (Aarkrog et al. 1992; Kershaw et al. 1992; IAEA 1998). (b) Frequency distribution of ^{137}Cs concentrations ($\text{Bq}\cdot\text{kg}^{-1}$) in 1SW (open bars) and 2SW (solid bars) Atlantic salmon from the Ste. Marguerite River, Que. Tissue samples were obtained from the heads and tails of fish caught in the sport fishery during the summers of 1995 ($n = 33$ (28 2SW, five 1SW)) and 1996 ($n = 28$ (16 2SW, 12 1SW)) and measured by gamma spectrometry. Dashed vertical lines denote the expected range in ^{137}Cs concentrations in salmon based on a mean bioaccumulation factor of 130 from waters in the North Atlantic outlined in the color bar above (water ^{137}Cs concentrations color coded as a). Horizontal lines denote the observed ranges in ^{137}Cs concentrations in salmon and other fish (cod, whiting, haddock, hake, mackerel, and plaice) caught in those same waters (Aarkrog et al. 1992; Kershaw et al. 1992).



fish through ingestion with a twofold increase with each trophic level. There is therefore a general relationship between water and fish ¹³⁷Cs concentrations. A large, marine, piscivorous fish like salmon bioaccumulates ¹³⁷Cs by a factor of approximately 130 relative to seawater concentrations (Rowan and Rasmussen 1994). Thus, we can make predictions about ¹³⁷Cs concentrations in fish based on the observed values in the waters of the North Atlantic. Therefore, salmon that have fed exclusively in the North Sea would be expected to have ¹³⁷Cs concentrations of 1.3–4.0 Bq·kg⁻¹, whereas fish from the Northwest Atlantic would have concentrations of 0.15–0.65 Bq·kg⁻¹. Salmon that have spent all their marine life feeding in the vicinity of Iceland or the Faroe Islands would be expected to have concentrations of 0.65–1.3 Bq·kg⁻¹, whereas salmon from the Irish sea would have levels exceeding 4.5 Bq·kg⁻¹. These expectations are consistent with the results of marine monitoring surveys of piscivorous fish (Fig. 1b), including salmon, carried out by agencies in Denmark and Great Britain (Aarkrog et al. 1992; Kershaw et al. 1992). The ¹³⁷Cs concentrations in fish from different regions of the North Atlantic are discrete and match concentrations of ¹³⁷Cs in water in a predictable fashion.

Based on our present ideas on migration patterns of salmon, most returning North American fish would be expected to have levels from 0.15 to 0.65 Bq·kg⁻¹, with only a few specimens reaching 1 Bq·kg⁻¹. Our observed range of ¹³⁷Cs values for returning two-sea-winter (2SW) and 1SW salmon from the Ste. Marguerite River, Quebec, caught during the summers of 1995 and 1996 was very different from what we expected, as there was a 66-fold difference in ¹³⁷Cs levels (0.10–6.6 Bq·kg⁻¹) (Table 1). This range would suggest that these salmon had consumed prey with different ¹³⁷Cs levels and subsequently fed in different areas of the ocean. As mentioned previously, the bioaccumulation of ¹³⁷Cs has been reviewed explicitly (Rowan and Rasmussen 1994) and applied extensively to obtain consumption rates for all types of fish, including salmonids (e.g., Rowan and Rasmussen 1996; Tucker and Rasmussen 1999). We can therefore generate some expectations about the range in levels for fish feeding on the same or different prey as well. The maximum range in ¹³⁷Cs observed previously for salmonids within closed freshwater systems (same prey contamination levels) is a 14-fold difference (Table 1). This within-system variation in ¹³⁷Cs integrates large differences in consumption rates, as well as different trophic levels, among different age-classes, life history variants, and sex of fish (Rowan and Rasmussen 1996; Tucker and Rasmussen 1999). Among freshwater systems, however, the same salmonid species have very different ¹³⁷Cs levels. For example, lake trout (*Salvelinus namaycush*) vary 50-fold in ¹³⁷Cs concentrations amongst lakes (Table 1). This is not due to widely different consumption rates or trophic positions, but rather to differences in ¹³⁷Cs levels in water and subsequently in prey (Rowan and Rasmussen 1994). All else being equal, a 10-fold difference in consumption will result in approximately a 10-fold difference in ¹³⁷Cs body concentration. Therefore, if fish had all been feeding on the same prey ¹³⁷Cs, say 0.10 Bq·kg⁻¹ from the Northwest Atlantic, it would require a 60-fold difference in consumption rates among fish to obtain the range observed for our salmon. Considering that these fish have similar growth rates (same

Table 1. Mean ¹³⁷Cs concentrations for different salmonids and their prey from various systems.

Species	System	Mean (±SD) ¹³⁷ Cs (Bq·kg ⁻¹)	¹³⁷ Cs range (Bq·kg ⁻¹)	Maximum/ minimum	¹³⁷ Cs in diet (Bq·kg ⁻¹)	Reference
Atlantic salmon (<i>Salmo salar</i>)	Atlantic Ocean	1.14±1.03	0.10–6.62	66.2	—	Present study
Arctic grayling (<i>Thymallus arcticus</i>)	Reservoir: Joe Wright	0.21±0.04	0.16–0.30	1.9	—	D. Rowan (unpublished data)
Atlantic salmon: juvenile	Stream: Xavier	10.19±2.45	4.89–16.17	3.3	5.0	Tucker and Rasmussen 1999
Atlantic salmon: juvenile	Stream: Morin	5.35±1.39	2.37–8.95	3.8	6.0	Tucker and Rasmussen 1999
Atlantic salmon: juvenile	River: Ste. Marguerite	7.21±2.23	3.06–14.06	4.6	2.3	Tucker and Rasmussen 1999
Atlantic salmon: juvenile	Stream: Allaire	11.79±3.18	2.50–19.99	8.0	4.5	Tucker and Rasmussen 1999
Brook trout (<i>Salvelinus fontinalis</i>)	Stream: Allaire	5.63±1.33	2.95–9.94	3.4	4.5	Tucker and Rasmussen 1999
Brook trout	Stream: Xavier	5.91±1.92	1.23–9.37	7.6	5.0	Tucker and Rasmussen 1999
Brook trout	Stream: Little Beaver	0.19±0.10	0.03–0.42	13.9	0.04	D. Rowan (unpublished data)
Brown trout (<i>Salmo trutta</i>)	Stream: Little Beaver	0.14±0.07	0.06–0.31	5.1	0.04	D. Rowan (unpublished data)
Brown trout	River: La Poudre	0.13±0.03	0.08–0.19	2.3	0.08	D. Rowan (unpublished data)
Chinook salmon (<i>Oncorhynchus tshawytscha</i>)	Lake: Lake Michigan	12.88±3.35	9.56–16.43	1.7	6.2	Rowan and Rasmussen 1996
Cisco (<i>Coregonus artedii</i>)	Lake: Opeongo	4.98±1.74	2.67–12.84	4.8	2.5	I. Pazzia et al. (unpublished data)
Lake trout (<i>Salvelinus namaycush</i>)	Lake: Great Slave	6.04±1.83	1.92–10.47	5.4	3.1	Rowan and Rasmussen 1996
Lake trout	Lake: Memphramagog	1.58±0.43	0.35–2.90	8.3	0.7	M. Trudel et al. (unpublished data)
Lake trout	Lake: Opeongo	7.24±2.14	2.07–13.79	6.9	5.0	I. Pazzia et al. (unpublished data)
Lake trout	Lake: Happy Isle	6.51±3.71	2.92–16.55	5.7	1.5	I. Pazzia et al. (unpublished data)
Lake trout	Lake: Source	6.39±3.34	2.69–17.36	6.5	1.0	I. Pazzia et al. (unpublished data)
Lake whitefish (<i>Coregonus clupeaformis</i>)	River: Ottawa	8.14±1.14	6.82–9.47	1.4	1.8	Rowan and Rasmussen 1996

Table 2. ^{137}Cs concentrations in water of various zones in the North Atlantic, predicted ^{137}Cs concentrations in Atlantic salmon in those zones, the proportion of salmon observed in those ^{137}Cs ranges, and, the proportional area of the high-production continental shelf zone in the North Atlantic delineated by ^{137}Cs water concentrations.

Zone	Water ^{137}Cs (mBq·L ⁻¹)	Predicted salmon ^{137}Cs (Bq·kg ⁻¹)	Observed salmon ^{137}Cs (% total)	Area of zone (% of North Atlantic)
Grand Banks/Labrador Sea	0–1.5	0–0.20	6.6	14.5
Greenland	1.5–5	0.2–0.65	32.8	28.5
Iceland/Faroe Islands	5–10	0.65–1.3	23	29.9
North and Norwegian seas	10–30	1.3–4.0	36.1	25.1
Irish Sea	30–150	4.5+	1.6	2.0

Note: The proportion of salmon from various ^{137}Cs zones generally matches the proportional area of those feeding zones.

size range), this is highly improbable and would likely represent an excessive, and unheard of, consumption rate. Different diets would only account for a twofold difference in ^{137}Cs among trophic levels. However, salmon are considered opportunistic, generalist feeders, exploiting many different prey items (Mills 1993). Moreover, salmon caught in different regions of the Atlantic all have similar diets (Hansen and Quinn 1998), yet the ^{137}Cs values for these same prey types have been shown to be different and their distribution discrete. It is unlikely, therefore, that the 66-fold difference observed in Atlantic salmon feeding at sea could simply be obtained by feeding on prey with similar ^{137}Cs levels or by differences in feeding rate or trophic levels alone or even combined. In order to generate this range, it seems probable that fish were feeding on similar prey with different ^{137}Cs levels. Furthermore, there is a tendency in the ^{137}Cs distribution for multiple peaks (Fig. 1b), in contrast with the expected more uniform lognormal distribution typically observed in fish (Rowan and Rasmussen 1994). The data, then, also suggest that, individually, salmon spend most of their lives in one region, as opposed to moving about from one area to another, since the latter would bring about a smoothing effect and markedly reduce the range of variation. If prey were moving more than salmon, we would expect the range in variation to be reduced as well and more normally distributed for both our salmon and the fish surveyed at sea. Instead, we observe a range in ^{137}Cs values as might be expected from a composite sample of fish from different feeding grounds, each of which had fed most of its marine life in a single region.

The most frequently occurring values for returning salmon were in the 0.15–1.0 Bq·kg⁻¹ range (Fig. 1b) expected for fish feeding in the Northwest Atlantic to the Iceland region; however, a full 43% of the fish exceeded this range, and indeed, we obtained salmon with concentrations up to 6.6 Bq·kg⁻¹. As many as 28% of the fish had values >1.3 Bq·kg⁻¹, consistent with fish feeding beyond Iceland. In addition, 59% of ISW salmon had concentrations exceeding 1.3 Bq·kg⁻¹. Thus, fish returning to the Ste. Marguerite River exhibit virtually the entire range of ^{137}Cs concentrations seen previously across the entire North Atlantic. The data suggest that salmon of North American origin are using European feeding grounds much more than previously thought, as they exhibit ^{137}Cs values distinctly characteristic of the Faroe, North, Norwegian, and Irish seas (i.e., they match the values observed for fish caught in those waters from independent sampling and monitoring).

Ocean abundance of salmon is typically greatest in the high-production continental shelf areas of the North Atlantic (Mills 1993). The proportion of salmon returning to the Ste. Marguerite from particular feeding grounds (i.e., discrete ^{137}Cs ranges) generally matches the proportional area of those feeding zones (Table 2). This would suggest, then, that salmon are proportionately distributed in the Atlantic relative to the availability of food resources. Differences were noted in the range of ^{137}Cs values among salmon of different cohorts, suggesting that migration patterns of fish from the same river might differ from year to year. For example, the range observed for 1995 ISW salmon (0.21–1.92 Bq·kg⁻¹, mean 0.83 Bq·kg⁻¹) was lower than the range observed for 1996 ISW salmon (0.42–2.36 Bq·kg⁻¹, mean 1.39 Bq·kg⁻¹). In addition, same cohort fish (i.e., 1995 ISW and 1996 2SW salmon) displayed a reduced range in ^{137}Cs concentrations (0.89 Bq·kg⁻¹) compared with the other cohorts (1.36 Bq·kg⁻¹). Our sample of 61 salmon cumulatively represents approximately 2% of the returning stock to the Ste. Marguerite River over 2 years. This, as opposed to the small number of fish tagged at sea that might return to individual rivers. There is thus potential to examine a far greater number of fish. Comparing variations in fish movements among years and stocks using ^{137}Cs may lead to an understanding of the broad-scale oceanic processes influencing salmon migration and survival.

While it has been previously observed, although regarded as incidental, that a few fish tagged in waters around the Faroe Islands had been recaptured in Canadian rivers (Hansen and Quinn 1998), our results imply that the marine life history of Atlantic salmon is much more pan-oceanic than previously imagined, as is now known to be the case for Pacific salmon (Hansen and Quinn 1998). Analogous to the results presented here, recent satellite tagging of North Atlantic bluefin tuna (*Thunnus thynnus*) questions current assumptions about migration patterns, suggesting that their distribution in the ocean is much broader than presumed (Lutcavage et al. 1999). Although only limited monitoring of salmon for ^{137}Cs has been carried out in Europe (Kershaw et al. 1992), the few fish collected show a similar pattern to the one observed here (0.18–5.3 Bq·kg⁻¹), suggesting that fish returning to British rivers also use a wide range of feeding grounds across the North Atlantic. The implication of this pan-Atlantic marine history for the management and conservation of salmon stocks is dramatic, since it implies that salmon in most feeding grounds are of mixed origin. This, then, only emphasizes the importance of collective

management and conservation measures by all North Atlantic nations.

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