

Chapter 19

Assessment of Radiocesium Accumulation by Hatchery-Reared Salmonids After the Fukushima Nuclear Accident

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Abstract To understand the process of radiocesium uptake in salmonids after the Fukushima Dai-ichi Nuclear Power Plant (FNPP) accident, a lake caging experiment and two captive-rearing experiments with controlled radiocesium concentrations of water and feed were conducted in and around Lake Chuzenji, central Honshu Island, Japan (160 km from the station). Substantial accumulations of radiocesium were confirmed in muscle of hatchery-reared kokanee (*Oncorhynchus nerka*) and masu salmon (*Oncorhynchus masou*) after release into the cages, indicating that radionuclide contamination of fish is an ongoing process, 1.5 years after the nuclear accident. Two captive experiments, controlling water and feed radiocesium levels, showed that direct radiocesium transfer from water (43 mBq/l) in Lake Chuzenji to muscle tissue was undetected, at least during the approximately 90-day experimental period, whereas a rapid increase in radiocesium levels was observed when fish were cultured using radiocesium-contaminated pellets. The results revealed that radiocesium contamination in salmonids is mainly via the food chain, and that direct intake from water via the skin, gut, or gills has no major direct impact on muscle tissue concentrations.

Keywords Bioaccumulation • Caging experiments • Captive-rearing experiments • Kokanee • Lake Chuzenji • Masu salmon • Radiocesium

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19.1 Introduction

In the preceding chapters, we documented individual radiocesium concentrations in fish from a variety of locations, including in muscle and eggs of several salmonid fishes from the Lake Chuzenji system in central Honshu Island (Chap. 18), in muscle and internal organs of a herbivorous fish, the ayu *Plecoglossus altivelis*, from several rivers in Fukushima Prefecture (Chap. 17), and in muscle of lake-dwelling freshwater fishes from Lake Hayama in Fukushima Prefecture (Chap. 16). There is also a sizeable dataset of radiocesium concentrations in freshwater fishes from northern and central Honshu Island, Japan, an area that was affected by the Fukushima Dai-ichi Nuclear Power Plant (FNPP) accident (Mizuno and Kubo 2013; Arai 2014; Murakami et al. 2014).

Several preceding studies have demonstrated that radionuclide accumulation in freshwater fish results mainly from food intake (Forseth et al. 1991; Ugedal et al. 1995). Experimental studies under controlled laboratory conditions, conversely, have shown that high radiocesium concentrations in water can be transferred into the organs of freshwater fish (Hewett and Jefferies 1976; Man and Kwok 2000). In the recently affected areas of Japan, however, the nature of the processes underlying radionuclide intake by freshwater fish has not yet been explored in detail, despite the economic and biological importance of understanding radionuclide contamination of aquatic biota.

As an urgent investigation into the effects of the FNPP accident on salmonids by the Fisheries Agency of Japan, a caging experiment in Lake Chuzenji (central Honshu Island), and two captive-rearing experiments were conducted using controlled concentrations of radiocesium in water and food to understand radiocesium bioconcentration and bioaccumulation in salmonids. At present (Oct. 2013), most salmonid fishes in Lake Chuzenji still have radiocesium concentrations greater than 100 Bq/kg-wet, which is the Japanese standard limit for radiocesium in foods.

19.2 A Caging Experiment in Lake Chuzenji

To establish the radiocesium uptake rate of hatchery-reared fish released into Lake Chuzenji, two cages about 180 m³ (6×6×5 m in height) were placed about 50 m from the shore (Fig. 19.1). Each cage was covered on all sides in 4-mm plastic mesh. Five hundred juvenile kokanee (*Oncorhynchus nerka*) and masu salmon (*Oncorhynchus masou*), which were chosen from captive-bred fish in the Fisheries Research Agency (FRA), were selected randomly and released into the respective cages on 22 November 2012. Initial mean fork length and body weight (\pm SD) of kokanee and masu salmon were 150 \pm 13 (mm) and 30.5 \pm 8.4 (g), and 93 \pm 13 (mm) and 7.2 \pm 2.5 (g), respectively. During the experimental period, fish were not given any artificial food. Up until 10 April 2013, 20 fish from each cage were collected randomly at intervals of about 14 days. Sampled fish were frozen immediately, the



Fig. 19.1 Cages set in Lake Chuzenji

fork length and body weight of each fish recorded, and a sample of muscle tissue removed for measurement of radiocesium concentrations. During the experimental period, water temperature in the cages (1-m depth) had a range of 1.4 °C (27 February 2013) to 10.2 °C (29 March 2013).

The kokanee in cages showed little or no growth during the experimental period. Mean fork length and body weight (\pm SD) at the termination of the experiment (139 days after the start of the experiment) were 149 ± 8 (mm) and 30.0 ± 5.8 (g), respectively. There were no significant differences between initial and final fork lengths and body weights of kokanee (t tests; $P > 0.05$). Mean fork length and body weight (\pm SD) at the termination of the experiment (139 days after the start of the experiment) of masu salmon were 97 ± 11 (mm) and 9.0 ± 3.2 (g), respectively. Mean fork length and body weight of masu salmon at the termination of the experiment were significantly greater than those at the start of the experiment (t tests; $P < 0.05$). Substantial radiocesium concentrations ($^{134}\text{Cs} + ^{137}\text{Cs}$) in both kokanee and masu salmon muscle tissue from the cages were detected at first sampling (14 days after the start of the experiment), with 2.2 Bq/kg-wet for kokanee and 3.9 Bq/kg-wet for masu salmon (Fig. 19.2). Thereafter, radiocesium levels increased approximately linearly with the duration of the experiment (kokanee: $R^2 = 0.97$, $P < 0.001$; masu salmon: $R^2 = 0.89$, $P < 0.001$). The final radiocesium concentrations in kokanee and masu salmon were 19.2 Bq/kg-wet (ratio of $^{134}\text{Cs}/^{137}\text{Cs}$, 0.55) and

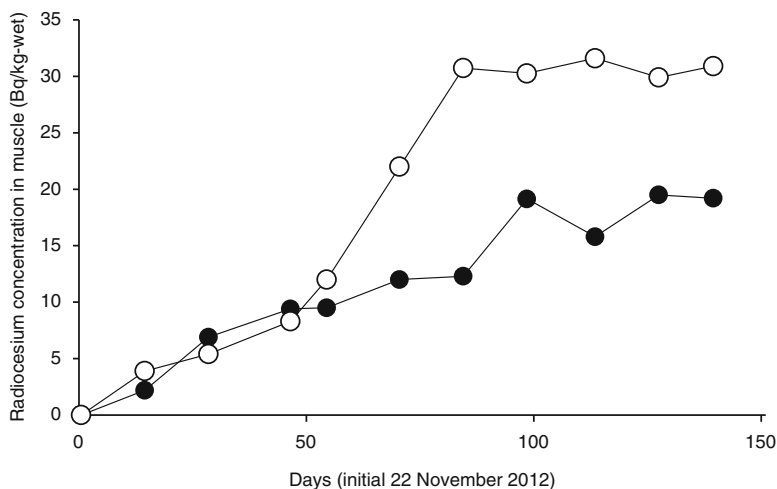


Fig. 19.2 Changes in radiocesium concentrations in kokanee (●) and masu salmon (○) in cages set up in Lake Chuzenji between 22 November 2012 and 10 April 2013

30.9 Bq/kg ($^{134}\text{Cs}/^{137}\text{Cs}$, 0.47), respectively. Daily radiocesium accumulation rates were estimated at 0.14 Bq/kg/day in kokanee and 0.22 Bq/kg/day in masu salmon, assuming linear relationships between radiocesium concentrations and experiment duration. During the experimental period, masu salmon had higher radiocesium concentrations than kokanee ($F=11.3$, $d.f.=1,21$, $P=0.007$).

In Lake Chuzenji, mean muscle radiocesium concentrations of wild salmonid fishes [kokanee, masu salmon, brown trout (*Salmo trutta*), and lake trout (*Salvelinus namaycush*)] collected during September to December, 2012, were in the range of 142.9 to 249.2 Bq/kg-wet (Chap. 18). Substantial accumulation of radiocesium was also confirmed in muscle tissue of hatchery-reared salmonids after release into cages set in Lake Chuzenji, indicating that radionuclide contamination of fish was an ongoing process, 1.5 years after the FNPP accident. Both kokanee and masu salmon juveniles in the cages were assumed to have fed mainly on zooplankton entering through the mesh. Radiocesium concentrations in plankton sampled over the same period in Lake Chuzenji (12.6 Bq/kg-dry; Fisheries Research Agency 2015) were much lower than the levels recorded in kokanee and masu salmon muscle tissue within the cages. The result provides strong evidence of in situ radiocesium bioaccumulation from food to fish muscle tissue in a natural lake in Japan. After the Chernobyl nuclear accident, radiocesium concentrations in crustacean zooplankton in Finnish lakes were significantly correlated with those in the water (Rask et al. 2012). During the experimental period of our study, planktivorous kokanee and masu salmon juveniles, with a short food chain, would closely track the environmental contamination of water and zooplankton in Lake Chuzenji.

19.3 Captive-Rearing Experiments with Controlled Radiocesium Concentrations of Water and Feed

To understand the process of radiocesium uptake in freshwater fish, two experiments were conducted on fish in captivity using known concentrations of radiocesium in water and feed. Two fiberglass circular tanks of 0.5 m³ (1,170 mm in diameter, 770 mm in depth) were set up in the FRA facility at Nikko. Throughout the experimental period, rearing water for this tank was drawn from Lake Chuzenji via an electronic pump. Before influx into the tank, the water was filtered through a 60- μ m mesh to remove any particles, including plankton. The discharge rate of filtered water into the tanks was controlled at about 1.24×10^{-4} m³/s. Into this tank, 200 juvenile kokanee, selected randomly from captive-bred fish in FRA, were released on 7 January 2013, and fed commercial food pellets of approximately 2 % body weight per day. Initial mean fork length and body weight (\pm SD) were 147 ± 10 (mm) and 27.9 ± 6.3 (g), respectively. Up until 10 April 2013, 20 fish from the tank were collected randomly at intervals of about 14 days. Collected fish were frozen immediately, the fork length and body weight of each fish recorded, and a sample of muscle tissue removed for measurement of radiocesium concentrations. During the experimental period, water temperature in the tank was in the range of 2.0 °C (26 February) to 12.5 °C (5 April). Dissolved radiocesium concentration of the surface water in Lake Chuzenji, collected on 28 November, 2012, was 43 mBq/l (Fisheries Research Agency 2015).

The other tank was filled with spring-fed water upwelling in the FRA facility (Fig. 19.3). Radiocesium concentrations of this water were below the limits of detection. The discharge rate of the spring-fed water into the tank was controlled at about 5.57×10^{-4} m³/s. Two hundred juveniles of kokanee, selected randomly from captive-bred fish in FRA, were released into the tank on 7 January 2013. Initial mean fork length and body weight (\pm SD) were 157 ± 10 (mm) and 37.0 ± 7.1 (g), respectively. Fifteen smallmouth bass (*Micropterus salmoides*), collected in Lake Hayama in Fukushima Prefecture (linear distance from the FNPP, ~17 km) in June 2012, were used to prepare food pellets for the experimental fish. Radiocesium concentrations in the muscle of smallmouth bass individuals had a range of 4,213 to 7,188 Bq/kg-wet (mean \pm SD, $5,777 \pm 891$ Bq/kg; median, 5,829 Bq/kg) (Chap. 16). The muscle tissue was carefully homogenized with commercial food pellets, the food pellets having been adjusted to contain an average radiocesium level of 445 Bq/kg-dry. Experimental fish were fed these commercial food pellets with radiocesium material of approximately 2 % body weight per day. Until 10 April 2013, 20 fish from the tank were sampled randomly at intervals of about 14 days. Collected fish were frozen immediately, the fork length and body weight of each fish recorded, and a sample of muscle tissue removed for measurement of radiocesium concentrations. During the experimental period, water temperature in the tank was in the range 8.8 °C (31 January) to 10.1 °C (5 April). All experimental fish used in this study were fed food pellets once or twice a day until used in the experiments but were not acclimated to the experimental tanks before the start of the experiments.



Fig. 19.3 An experimental facility in the Fisheries Research Agency for examining the process of radiocesium intake in salmonid fish

When fish were reared in water from Lake Chuzenji and a diet of commercial pellets, no radiocesium was detected in muscle tissue at any sampling period (detection limits, <1.74 Bq/kg) (Fig. 19.4). Final mean fork length and body weight (\pm SD) of kokanee in this experiment were 162 ± 12 (mm) and 49.5 ± 11.4 (g), respectively. When fish were reared using spring-fed water and pellets containing radiocesium, radiocesium concentrations in muscle tissue increased rapidly during the experiment. At 93 days after the start of the experiment, the radiocesium concentration increased to 126.2 Bq/kg-wet ($^{134}\text{Cs}/^{137}\text{Cs}$, 0.51). Final mean fork length (\pm SD) of kokanee in this experiment were 183 ± 68 (mm) and 67.8 ± 16.6 (g), respectively.

Two captive experiments with controlled water and feed radiocesium concentrations demonstrated that direct radiocesium transfer from water (43 mBq/l) in Lake Chuzenji to fish muscle tissue was undetected, at least during the approximately 90-day experimental period, whereas a rapid increase in radiocesium concentration was observed when fish were cultured using pellets contaminated with high concentrations of radiocesium. The results reinforce the evidence that radiocesium contamination of freshwater fish is mainly via the food chain, and that direct intake from the water via the skin, gut, or gills has little or no effect on muscle tissue levels. Previous experimental studies, however, showed that freshwater fish exposed to water with extremely high concentrations of radionuclides can accumulate the nuclides into their organs (Hewett and Jefferies 1976; Man and Kwok 2000). After the FNPP accident, Japanese governmental agencies initiated detailed sampling

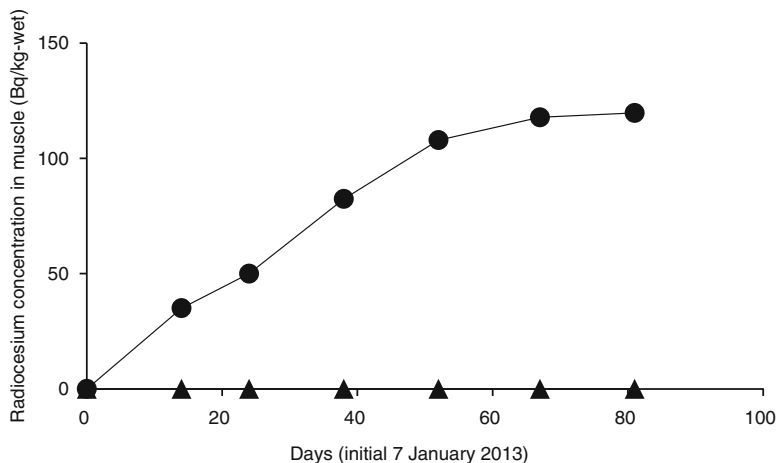


Fig. 19.4 Changes in radiocesium concentrations in kokanee in captivity between 7 January and 10 April 2013. *Circles and triangles* indicate the radiocesium concentrations in kokanee reared using spring-fed water with commercial pellets containing radiocesium material and in kokanee reared using water from Lake Chuzenji and fed with commercial pellets without any radionuclides, respectively

programs to establish the contamination levels of water in the affected area. Monitoring programs did not detect water with radiocesium concentrations greater than 1 Bq/l in any natural rivers or lakes during 2012–2013, with very few exceptions (Ministry of Environment 2015). Water itself, if it should contain radionuclides, is unlikely to have a significant direct impact on levels of radiocesium in fish muscle tissues, at least within current Japanese freshwater systems.

19.4 For Further Study

A meta-analysis of the relevant literature revealed that radiocesium concentrations in fish were a positive function of contamination concentrations in the water, particularly for nonpiscivorous fish species (Rowan and Rasmussen 1994). Although direct radiocesium transfer from water to fish muscle tissue seems to be negligible, water may act as a radiocesium source to planktivorous fish via the food chain (Elliott et al. 1992; Rask et al. 2012; Tuovinen et al. 2013). In many Japanese lakes and rivers, including the Lake Chuzenji system, the release of hatchery-reared fish enhances resources and supplements wild fish stocks, which are essential components of successful freshwater fisheries management programs (Kitada 2001; Yamamoto et al. 2011). Continued monitoring of radiocesium concentrations in water and zooplankton, as well as in fish, is crucial for estimating bioconcentration and bioaccumulation and, thus, for predicting contamination concentrations in released hatchery-reared fish within the affected area.

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