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Radioactive contamination of fishes in lake and streams impacted by the Fukushima nuclear power plant accident

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HIGHLIGHT

- Concentration of ^{137}Cs in brown trout was higher than in rainbow trout.
- ^{137}Cs concentration of brown trout in a lake was higher than in a stream.
- ^{137}Cs concentration of stream charr was higher in region with higher aerial activity.
- Concentration of ^{137}Cs in stream charr was higher in older fish.
- Difference of contamination among fishes was due to difference in diet and habitat.

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ABSTRACT

The Fukushima Daiichi Nuclear Power Plant (FDNPP) accident in March 2011 emitted radioactive substances into the environment, contaminating a wide array of organisms including fishes. We found higher concentrations of radioactive cesium (^{137}Cs) in brown trout (*Salmo trutta*) than in rainbow trout (*Oncorhynchus nerka*), and ^{137}Cs concentrations in brown trout were higher in a lake than in a stream. Our analyses indicated that these differences were primarily due to differences in diet, but that habitat also had an effect. Radiocesium concentrations (^{137}Cs) in stream charr (*Salvelinus leucomaenis*) were higher in regions with more concentrated aerial activity and in older fish. These results were also attributed to dietary and habitat differences. Preserving uncontaminated areas by remediating soils and releasing uncontaminated fish would help restore this popular fishing area but would require a significant effort, followed by a waiting period to allow activity concentrations to fall below the threshold limits for consumption.

1. Introduction

A massive earthquake occurred in eastern Japan on 11 March 2011, causing a tsunami that washed over the Fukushima Daiichi Nuclear Power Plant (FDNPP) on the east coast of Japan. Damage to the cooling system of the FDNPP resulted in several explosions, causing leakage of radioactive substances. The FDNPP accident released 1.6×10^{17} Bq of iodine-131 (^{131}I), 1.8×10^{16} Bq of cesium-134 (^{134}Cs) and 1.5×10^{16} Bq of cesium-137 (^{137}Cs) into the surrounding environment (Ohara et al., 2011). Most of these radionuclides, including ^{131}I, ^{134}Cs and ^{137}Cs, were unevenly deposited over large areas of land in eastern Japan, reaching sites hundreds of kilometers from the FDNPP. The dense radioactive plume spewing from the FDNPP moved north-westward, descending to ground level with precipitation and heavily contaminating large tracts of the landscape. A smaller plume drifted to the south-west and contaminated areas such as the Oku Nikko and Ashio regions in Tochigi Prefecture (Kinoshita et al., 2011; MEXT, 2011). Atmospheric dose rates 0.5 m above the ground exceeded 20 μSv/h in some hot spots >160 km from the FDNPP in May 2011 (Tochigi, 2011).

The first phase of investigation revealed that a large portion of the deposited ^{134}Cs and ^{137}Cs was trapped in the forest canopies and the soil litter layer (Hashimoto et al., 2012). Radiocesium is easily adsorbed onto clay minerals and soil organic matter (Kruyts and Delvaux, 2002) and can be transported to streams and rivers with eroded soils (Fukuyama et al., 2005; Kato et al., 2010; Wakiyama et al., 2010). Dissolved ^{134}Cs and ^{137}Cs in running waters that are not adsorbed to soil, are readily taken up by microbes, algae, plankton and plants. This

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pathway of ^{134}Cs and ^{137}Cs transport eventually leads to uptake by fishes at higher trophic levels.

Radioactive contamination of fish should be prevented because fishes may be taken by anglers and consumed as food. A safety threshold of 100 Bq/kg of radioactive Cs was introduced in April 2012, but activity concentrations greater than this have been detected in fishes hundreds of kilometers distant from the FDNPP. There is clearly a pressing imperative to reduce radioactive Cs contamination of food.

The Chernobyl accident released more than five million Tera Becquerel of radionuclides. Much radionuclides from the Chernobyl accident spread to Finland, Sweden and Norway, 2000 km to the northwest. Fish have been monitored for radioactivity Øvre Heimdalsvatn, a Norwegian subalpine lake (Brittain et al., 1991; Brittain and Gjerseth, 2010). Activity concentrations of ^{137}Cs in brown trout reached 8400 Bq/kg in 1987 and declined to 200–300 Bq/kg in 2008, but the contamination level has recently been constant and approached an asymptotic decline (Brittain and Gjerseth, 2010). The broad effects of the Chernobyl accident have been examined and management measures have been designed for large geographical areas (Report of the Chernobyl Forum Expert Group 'Environment', 2006; Yablokov et al., 2009). However, the ecological consequences of radioactive contamination in fishes are poorly understood.

To precisely describe the mechanisms of diffusion and export of ^{137}Cs deposited in freshwater fish, we measured concentrations of ^{137}Cs in the muscle tissue and stomachs of brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*) and kokanee (*Oncorhynchus nerka*) from a lake, that of brown trout (*Salmo trutta*) from a stream and that of charr (*Salvelinus leucomaenis*) from four streams. Here, we report the results of preliminary investigations 21 months after the FDNPP accident.

2. Materials and methods

2.1. Study site

The study was conducted in the Nikko area (Lake Chuzenji, Oku Nikko and Ashio regions) located approximately 160 km southwest of the FDNPP. According to an aircraft radioactivity survey reported by MEXT (2012), the air dose rate in this area was 0.1–0.25 μSv/h on 31 May 2012. The study area is mostly forested; the dominant tree species are broadleaf and deciduous. Other areas are forested with Japanese cedar and cypress plantations used for timber production. The field survey was conducted in Lake Chuzenji and two headwater tributaries (Toyamasawa and Yanagisawa streams) of the Kinu River in the Oku Nikko region and in two headwater tributaries (Kuzosawa and Asosawa streams) of the Watarase River in the Ashio region, which form the upper drainage component of the Tone River system, Honshu, Japan (Fig. 1).

2.2. Sampling

Fishes were captured in Lake Chuzenji and in the four streams in November and December, 2012 using fishing rod in the lake and battery-powered backpack electrofishing (Smith-Root Inc. LR-24) units operated at 300-V pulse-DC in the stream. In central Lake Chuzenji, three species of fishes, brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*) and kokanee (salmon) (*Oncorhynchus nerka*) were sampled. In Toyamasawa stream, two species of fish, brown trout (*Salmo trutta*) and charr (*Salvelinus leucomaenis*) were sampled at site B (200 m stream segments). In other three streams, only charr (*Salvelinus leucomaenis*) were sampled at sites E, G, and I (200 m stream segments). After capture, we recorded the body size (fork length) of each fish and sampled muscle tissue for the analysis of radioactive concentration. We then collected and froze the stomachs for the analysis of radiocesium concentrations in stomach tissue and for identification of stomach contents. The age of charr specimens was determined from sagittal otoliths using the surface reading method. The age of the other three fishes was not determined; folk length was used as a substitute metric.

In the four streams, air dose rates at 1-m above ground were measured with a γ survey meter adjacent to the stream (NaI scintillation counter; ALOKA TCS-172). Electrical conductivities (EC) of the streams were measured with a portable compact twin conductivity meter (B-173; Horiba); pH was measured with a portable compact twin pH meter (B-212; Horiba). Wetted stream widths (SW) were measured with a measuring tape; stream velocities were measured with a portable meter (V-303, VC-301, KENEK). All of these environmental parameters were measured in stream riffles at each site along Toyamasawa stream (sites A, B, and C), Yanagisawa stream (sites D, E, and F), Kuzosawa stream (sites G and H) and Asosawa stream (site I) in December, 2012.

2.3. Radiocesium analysis and identification

Samples of fish stomach and muscle tissue were directly packed into 100-ml polystyrene containers (U-8). The radioactive levels of ^{137}Cs (662 keV) were measured with an HPGe coaxial detector system (GEM40P4-76, GEM20-70, Seiko EG&G, Tokyo, Japan; GC4020, Canberra, Japan) for 36,000 s–63,000 s depending on the sample weight. Gamma-ray peaks of 622 keV were used to determine ^{137}Cs. The measurement system was calibrated using a standard gamma-ray source (MX033U8PP, Japan Radioisotope Association, Tokyo, Japan), and a standard soil sample (IAEA-444) was used to check accuracy. Fine adjustments to the measurements were made to correspond to the radiocesium concentration value for 1 December 2012. The radioactivity of lake and stream water was not measured because ^{137}Cs concentrations in several lakes and streams were reported to be below the detection level (1 Bq/l) (MOE 2013, Tochigi Prefecture, 2013).

The inner contents of the frozen stomach for the analysis of stomach contents were removed and identified under a 50× microscope (SMZ-U; Nikon). We identified specimens to the family level or higher following Merritt and Cummins (1996) and Kawai (1985).

2.4. Statistical analysis

Kruskal–Wallis tests or Mann–Whitney *U*-tests were used to compare the ^{137}Cs concentrations. The Kendall test was used to clarify the relationship between folk length and ^{137}Cs concentration. We conducted principal component analysis (PCA) on the presence or absence of each fish stomach content for three species in Lake Chuzenji, for brown trout in Lake Chuzenji and Toyamasawa stream, and for charr in the four streams. We examined the PCA axes among the three fish species and among the four streams using a Kruskal–Wallis multiple comparison test and between lake and stream habitats using a Mann–Whitney *U*-test.

It would be useful to compare samples of the same species or the same age at all sampling locations. However, the fishes sampled in this study differed between the stream and lake and it was not practical to collect specimens of equal size. Statistical analysis was performed using SYSTAT version 10 (SPSS Inc. 2000). Radiocesium concentrations that were below the detection level because of insufficient weight for radiocesium analysis were excluded from the statistical analysis.