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Effects of the nuclear disaster on marine products in Fukushima: An update after five years

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ABSTRACT

Original data (^{134}Cs and ^{137}Cs, and sampling location) of marine products in Fukushima Prefecture monitored during 2011–2015 ($n = 32{,}492$) were analyzed to present an updated detailed description of radiocesium contamination after the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident and to examine taxon/habitat-specific decreasing trends in different areas. Furthermore, marine species data presented by the Tokyo Electric Power Company (TEPCO) during 2012–2015 ($n = 5458$) were analyzed to evaluate the decreasing trends of ^{137}Cs inside and outside (within a 20 km radius) of the FDNPP port. Monitoring results by Fukushima Prefecture show that percentages of samples higher than the Japanese regulatory limit of 100 Bq kg^{-1}-wet (>RL%) were higher, whereas those below the detection limit (<DL%) (mean 8.3 and 7.4 Bq kg^{-1}-wet for ^{134}Cs and ^{137}Cs, respectively) were lower in demersal fishes than in pelagic fish or other taxa. However, >RL% and <DL% of demersal fish respectively decreased dramatically and increased gradually to 0.06% and 86.3% in 2015, although slightly elevated radiocesium concentrations were still observed in shallow areas south of the FDNPP. The drastic decrease in radioactivity was supported by the spatiotemporal distribution of radiocesium concentrations in demersal fish, in which higher concentrations that were frequently observed in 2011 and 2012 were rarely detected in 2015, even within the 20 km radius area (maximum 220 Bq kg^{-1}-wet in Japanese rockfish *Sebastes cheni*). Statistical analyses of TEPCO data revealed that ^{137}Cs concentrations both inside and outside of the FDNPP port decreased exponentially with time: The respective geometric mean days of ecological half-lives were 218 d and 386 d. These results show clearly that the contamination level of marine products in Fukushima Prefecture, even within the 20 km radius area, has decreased drastically during the five years after the FDNPP accident, although ^{137}Cs concentrations higher than 10 kBq kg^{-1}-wet were still detected in some specimens of sedentary rockfishes (*S. cheni*, *Sebastes oblongus*, and *Sebastes pachycephalus*) in the FDNPP port. Fishing operations started on a trial basis in June 2012 have gradually expanded the target areas and species. Careful monitoring should be continued to accelerate the restoration of coastal fisheries in Fukushima Prefecture.

1. Introduction

The Great East Japan Earthquake (moment magnitude 9.0) and the gigantic tsunami waves that struck northeastern Japan on 11 March 2011 (Miura et al., 2011) caused a severe accident at Fukushima Dai-ichi Nuclear Power Plant (FDNPP), owned by the Tokyo Electric Power Company (TEPCO) (IAEA, 2011). As a consequence, large amounts of ^{134}Cs and ^{137}Cs (hereinafter radiocesium) were later released directly into the Pacific Ocean from the FDNPP (Tsumune et al., 2012). The released amount of ^{137}Cs was estimated as 3.5–5.9 PBq (Tsumune et al., 2013; Miyazawa et al., 2013; Aoyama et al., 2015). The leakage of extremely contaminated

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water from a cracked sidewall near the intake channel of Unit 2 in early April 2011 (Tsumune et al., 2012; IAEA, 2015) contributed greatly to radiocesium contamination of the surrounding coastal and offshore waters (Buesseler et al., 2011; Aoyama et al., 2013), although several other processes (e.g., atmospheric deposition to the ocean surface) have contributed to radiocesium contamination in the ocean as a result of the FDNPP accident (Morino et al., 2011; Tsumune et al., 2013; IAEA, 2015). Subsequently, radiocesium, with physical half-lives of 2.07 y for ^{134}Cs and of 30.17 y for ^{137}Cs, was detected continuously from marine biota collected in the waters off Fukushima Prefecture and its vicinity immediately after the FDNPP accident (Buesseler, 2012; Buesseler et al., 2012; Wada et al., 2013; Sohtome et al., 2014), although the radiocesium concentrations in surface seawater off the coast of Fukushima Prefecture dropped exponentially in 2012, with the exception of concentrations in the FDNPP port (Aoyama et al., 2013; Kanda, 2013; Kaeriyama, 2015). Higher levels of ^{137}Cs concentrations in seawater near the FDNPP continued until the end of 2015. The radiocesium contamination of marine biota and sediments was severer in shallow coastal waters south of the FDNPP (Kusakabe et al., 2013; Wada et al., 2013; Ambe et al., 2014), probably because the extremely contaminated water flowed mainly southward immediately after leakage from the FDNPP (Tsumune et al., 2012).

Wada et al. (2013) analyzed monitoring data of marine products obtained during April 2011–October 2012. Results showed species-specific declining trends and a wide geographical distribution of radiocesium concentrations in the waters off Fukushima Prefecture. Those results indicated that some specimens of demersal fishes (e.g., flatfishes, rockfishes) caught in coastal shallow waters after the FDNPP accident have often exceeded the Japanese regulatory limit of 100 Bq kg^{-1}-wet for foodstuffs (combined ^{134}Cs and ^{137}Cs). The results have also shown a more gradual declining trend of radiocesium concentration than those found for pelagic fish species, invertebrates (cephalopods, bivalves, gastropods, and crustaceans), and seaweed of various kinds. Results of several model studies for demersal fishes have implied that, along with the direct uptake of highly contaminated seawater, the gradual food chain transfer of radiocesium introduced to the ecosystem from the initial contamination of the seawater and continuous radiocesium uptake from the benthic food web, are the main causes of the lagged increase and gradual declining trend shown by these demersal fishes (Tateda et al., 2013, 2015, 2016; Kurita et al., 2015; Watanabe et al., 2015).

However, the exponential decreasing trends of ^{137}Cs concentrations in prey items (e.g., benthic invertebrates) and sediments (Sohtome et al., 2014), and the gradual alteration of generation in many fish species during the five years after the FDNPP accident explain the lowered radiocesium concentrations in marine products, including demersal fishes. Actually, substantially lower radiocesium concentrations in newly born generations that did not contact the extremely contaminated seawater immediately after the FDNPP accident were found in Japanese flounder *Paralichthys olivaceus* (Kurita et al., 2015) and in Pacific cod *Gadus macrocephalus* (Narimatsu et al., 2015). In contrast, much higher radiocesium concentrations in fish species collected inside the FDNPP port were reported from several studies using data publicized by TEPCO (Wada et al., 2013; Shigenobu et al., 2014; Fujimoto et al., 2015a, b). These results suggest the necessity of a comprehensive study addressing the time-series trend and recent radiocesium contamination levels in marine products based on the enormous volume of monitoring results. Nevertheless, no report in the relevant literature describes a study that has compiled multi-species data and which has elucidated area-specific and taxon-specific trends of radiocesium concentrations in the waters off Fukushima Prefecture. There, coastal gill net and trawl fisheries started since June 2012 on a trial basis (called "trial fishing operations" after Wada et al., 2013) have gradually expanded the target areas and species according to monitoring results (Shibata et al., 2015; Yagi, 2016). The marine products landed through trial fishing operations are sold through commercial markets and are consumed by the general public (Yagi, 2016).

In this study, to present an updated detailed description of the decreasing trend of radiocesium concentrations after the FDNPP accident, we compiled and analyzed the original detailed data of monitored marine products off Fukushima Prefecture during 2011–2015, which include published data presented by Wada et al. (2013) (169 species, $n = 6462$). Based on those results, we evaluated area-specific and taxon/habitat-specific decreasing trends of radiocesium concentrations for each category, and described the spatiotemporal distribution of radiocesium concentrations in demersal fishes. We also analyzed all marine species data released by TEPCO from 2012 to 2015 to clarify the radiocesium contamination level within a 20 km radius area from the FDNPP, where trial fishing by gill net, trawling, and other fishing methods were not operated as of December 2015. Subsequently, we calculated the ecological half-lives for the respective species to evaluate the decreasing trends inside and outside of the FDNPP port. Finally, we briefly introduce the restoration process and the present situation of trial fishing operations in Fukushima Prefecture and discuss the present obstacles, risk of seafood consumption, and potential benefits of restoring Fukushima's fisheries in the future.

2. Materials and methods

2.1. Sampling and measurement of radiocesium in marine products

Detailed sampling methods and radiocesium measurement procedures in marine products in Fukushima Prefecture were described by Wada et al. (2013). The sampling of marine products comprised two sampling frames: randomized sampling by fishing vessel and fixed sampling by research vessel. The fishing vessel samplings were performed weekly by fishery workers using various fishing methods (Table S1). The detailed locations for each fishing vessel sampling were chosen to cover a broad fishing area with a wide depth range for each fishing method. Fishery workers provided information related to sampling sites (latitude, longitude, and depth) immediately after sampling. Research vessel samplings (mainly by RV Kotaka, 59 t; RV Takusui, 30 t; and RV Iwakimaru, 189 t) were basically performed weekly by the staff of the Fukushima Prefectural Fisheries Experimental Station. They planned to collect samples from same sampling stations at the same depths (e.g., trawling depths of RV Iwakimaru: every 25, 50, or 100 m depth from 75 to 500 m depth) (Table S1). These randomized and fixed sampling frames contributed to coverage of all coastal fishing areas off Fukushima Prefecture. Less frequent samplings near the FDNPP were conducted in 2011 and 2012, when the evacuation zone with a 20 km radius from the FDNPP was set by the Japanese Government until August 2012. Samples were identified and processed at the Fukushima Prefectural Fisheries Experimental Station. During 2011–2015, 180 species ($n = 32{,}492$) were identified. Primarily, muscle tissues were used for radiocesium measurements, but whole bodies or other parts (gonads, muscle with skin without scales, and bodies without head and internal organs) were used in some cases (Table S1). Basically, one individual was used for radionuclide measurements for each species (70.1% of all samples), but several individuals were mixed and used as one sample if the volume of measured parts for each was small (Table S1).

Gamma rays from ^{134}Cs and ^{137}Cs were analyzed using a closed-end coaxial high-purity germanium (HPGe) detector at the