Impact on Marine Biota in Fukushima by TEPCO Fukushima Daiichi Nuclear Power Plant Accident

−Is fish from Fukushima Good to Eat?−

National Research Institute of Fisheries Science,
Japan Fisheries Research and Education Agency, **Takami Morita**

The accident that occurred at the Fukushima Daiichi Nuclear Power Plant, which is operated by the Tokyo Electric Power Company (TEPCO), led to a massive release of radioactive materials into the ocean. The resultant devastation of the Japanese fishing industry continues to this day. A relatively high concentration of radioactive cesium was detected for some time after the accident. However, in the monitoring conducted subsequently by the prefectural government of Fukushima in FY2015, not a single fishery product sample exceeded 100 Bq/kg-wet, which is the national threshold for shipment restrictions. This commentary describes the current state of fishery product contamination in the waters off the coast of Fukushima Prefecture. It then explains how this contamination was reduced and examines why contamination was relatively prolonged for some fish species. It also mentions the rarely reported topic of the presence of strontium-90 in fishery products.

KEYWORDS: Fukushima accident, cesium, strontium, fishery, fishery product, reputational damage, monitoring research

I. Introduction

On March 11, 2011, an earthquake off the Pacific coast of Tohoku triggered a major tsunami that devastated TEPCO's Fukushima Daiichi Nuclear Power Plant (hereinafter referred to as the "Fukushima Daiichi NPP"). As a result, a large amount of artificial radioactive materials were released into the environment, thereby contaminating the marine biota along the Fukushima coast and in nearby waters. The devastation that this contamination has caused to the Japanese fishing industry continues to this day. In Fukushima Prefecture, a voluntary ban was imposed on all coastal fishing, except for trial fishing. From after the accident occurred until the end of February 2016, 33,753 samples of fishery products from Fukushima were examined [1]. During the period from April to June 2011, 57.7% of tested samples contained more radioactive cesium (Cs-134 and Cs-137) than the threshold of 100 Bq/kg-wet. This proportion gradually fell until eventually none of the 7,809 samples monitored between April 2015 and

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the end of February 2016 exceeded this threshold. However, given the repeated media coverage of contaminated water, concerns over the safety of local fishery products from Fukushima have yet to be dispelled. The resumption of fishing in Fukushima remains out of sight because of the lasting reputational damage caused by such coverage.

II. Radioactive Cesium in Fishery Products

1. Uptake and Elimination [2)]

Cesium is a water-soluble alkali metal element that behaves similarly to potassium, which is another type of alkali metal. Just like potassium, cesium is eliminated from the body so, after its uptake by fish, radioactive cesium does not accumulate in sufficient quantities to be detected in high concentrations years later. The uptake of radioactive cesium by fish takes place through two channels: the intake of food organisms and the uptake from ambient water. Different proportions have been reported for these two channels, with the uptake from ambient water ranging from 30 to 50%. The contribution from ambient water never exceeds that from food organisms. It is unclear whether radioactive cesium from food organisms and that from ambient water behave differently inside fish, but it is evident that radioactive cesium is dissolved in body fluids in an ionized form.

Osmoregulatory mechanism in fish significantly influences the uptake and elimination of radioactive cesium. Fish try to maintain a constant body environment within a certain physiological range to sustain their vital activities, and fish that regulate osmotic pressure are classified as osmoregulators. Marine fish live in seawater with a higher salt concentration than their body fluids, so they are passively deprived of water in their bodies due to osmotic pressure. To offset this loss, marine fish try to replenish their body water by swallowing seawater. They maintain a constant salt concentration in their bodies by actively pumping potassium and sodium out via chloride cells in their gills or by excreting them with a small amount of urine. Radioactive cesium is also eliminated during this process.

Some invertebrates that inhabit brackish waters or other changing environments are osmoregulators. However, most other marine invertebrates (e.g., squid, octopuses, shellfish, shrimps, and crabs) are osmoconformers, which keep their body fluids almost osmotic relative to the ambient seawater [2)]. Therefore, the radioactive cesium concentration in these species drops quickly following any reduction in the radioactive cesium concentration in seawater. Unlike terrestrial plants, seaweed absorbs nutrients from seawater, not from the marine soil. Accordingly, the radioactive cesium concentration in seaweed drops following any reduction in the radioactive cesium concentration in seawater.

2. Radioactive Cesium Concentration in Fishery Products

(1) Radioactive cesium concentration among species other than demersal fish

Sardines, saury, and other fish that always stay above the bottom of the sea are called pelagic fish. In contrast, demersal fish, such as righteye and lefteye flounders, maintain contact with the bottom of the sea.

The radioactive cesium concentration in pelagic fish depends on the concentration in the ambient seawater (because the concentration in their food organisms also depends on the ambient seawater). Therefore, any reduction in the radioactive cesium concentration in seawater gradually reduces the concentration in the bodies of pelagic fish. The leakage of highly contaminated water into the ocean due to the Fukushima Accident was relatively short time, so this water was quickly diluted and dispersed in the ocean. A major portion of the radioactive cesium dropped out of the element cycle in the surface seawater along with settling particles. As a result, the radioactive cesium concentration in seawater dropped sharply. On May 13, 2011, for example, swarms of whitebait (immature sardines) near the surface of the sea off the Fukushima coast contained 850 Bq/kg-wet of radioactive cesium, but this measurement had already dropped below the detection limit of 5 Bq/kg-wet by September 14, 2011 [1].

The radioactive cesium concentration in the bodies of invertebrates and seaweed also dropped quickly because the level depends on the ambient seawater, as explained earlier. These species are probably affected by radioactive cesium in marine soil similarly to demersal fish (discussed later). Unlike fish, however, they are osmoconformers that easily release radioactive cesium, so the concentration in their bodies probably dropped swiftly. The trial fishing for octopuses and shellfish described later was conducted in Fukushima based on the monitoring data and biological knowledge presented so far.

(2) Radioactive cesium concentration among demersal fish

The radioactive cesium concentration in demersal fish, such as righteye and lefteye flounders, tends to drop considerably slower compared to pelagic fish [1, 2]. This slower rate of reduction clearly indicates the continued uptake of radioactive cesium by demersal fish, but details of the uptake channels are not known. The discovery that lefteye flounders and black seabream kept in a tank with highly contaminated marine soil do not carry a high concentration of radioactive cesium demonstrates that demersal fish are not directly contaminated by marine soil. Even the food organisms raised in such a tank did not accumulate a high concentration of radioactive cesium [3]. The presumed reason for this is the scarce release of radioactive cesium adsorbed by clay minerals in marine soil. The presence of organic matter with a high concentration of radioactive cesium has also been confirmed for marine soil [3]. This organic matter is a likely source of contamination that slows down the reduction in the radioactive cesium concentration among demersal fish. However, the exact contamination mechanism has yet to be understood. In addition to the possible intake of such organic matter through food organisms, demersal fish may be directly taking in organic matter that drifts near the bottom of the sea due to sediment resuspension.

It is important to clarify here that the assumed continuous uptake by demersal fish does not increase the level of radioactive cesium concentration in their bodies. It simply slows down the reduction. Not long ago, misinformation claiming that the radioactive cesium concentration does not decrease was widespread. The source of this misinformation is believed to be an article published in a well-known scientific magazine that featured monitoring data from FY2011 [4]. The monitoring survey was not conducted within 30 km of the Fukushima Daiichi NPP until the designated emergency evacuation preparation zone was lifted (for a range of between 20 and 30 km) on September 30, 2011. The monitoring survey began after September 30, 2011 within a range of between 20 and 30 km from the plant. The survey sites gradually shifted to within 20 km, and this shift is most likely the reason why the concentration in demersal fish seemingly did not decrease (**Figure 1**).

A recent study has also found that fish born after the accident have a lower level of contamination [3]. This finding demonstrates that a major contributor to the contamination of fishery products from Fukushima was the release of highly contaminated water in the aftermath of the accident and that further contamination is no longer underway. The level of contamination of fishery products is expected to diminish further as the proportion of fish born after the accident increases.

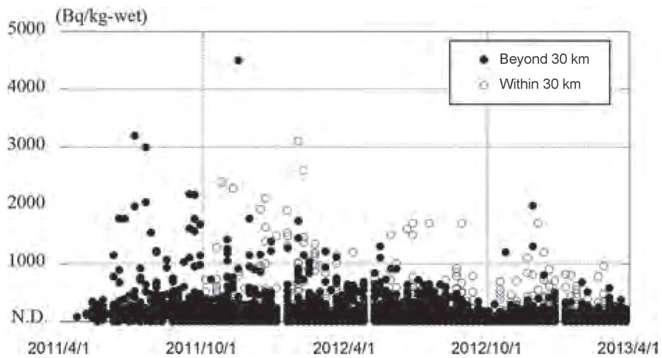

Figure 1 Concentration of radioactive cesium in demersal fish from Fukushima
The data cited here was obtained from a reference document [1]. N.D. denotes a level below the lower detection limit.

3. Characteristics of Radioactive Cesium Contamination of Fishery Products

(1) Behavior of radioactive cesium in an ecosystem

It is generally believed that contaminants become concentrated in a higher trophic level through food chains. However, a high level of concentration with a factor of 100 does not occur for radioactive cesium and other water-soluble substances because they are eliminated at each trophic level through the mechanisms explained earlier. Compared to the reported concentration factor of polychlorinated biphenyls (PCB), which is in the order of between tens of thousands to hundreds of thousands, radioactive cesium clearly presents a much lower level of concentration. Meanwhile, the Act on the Regulation of Manufacture and Evaluation of Chemical Substances defines the bioaccumulation of substances with a factor of 5,000 or more. Some claimed that tuna in a higher trophic level would be highly contaminated a few months after the Fukushima Accident. However, since the leakage of highly contaminated water had already been stopped, this claim was dismissed at an early stage [5]. In fact, the highest level of concentration in tuna caught off the Fukushima coast was 41 Bq/kg-wet according to information published in October 2011 [1]. In contrast, the nature of heavy metals with induced radioactivity from nuclear experiments (e.g., manganese-54, iron-55, iron-59, and zinc-65) means that they are known to bioaccumulate along food chains [6].

(2) Nonuniform contamination [6, 7]

The Fukushima Accident can be characterized by the nonuniformity of the resultant contamination. This can be attributed to the following three factors.

A. The contamination source is located in Japan.
B. Highly concentrated water leaked directly into the ocean.
C. The majority of the leakage was stopped relatively quickly.

Factor A resulted in different levels of contamination according to the distance from the source. Natural phenomena (i.e., ocean currents in this case) led people to make assumptions such as that rockfish off the northern coast of Fukushima would be contaminated to a similar degree as rockfish in the south, which were found to have a high concentration of radioactive cesium. It was also assumed that contaminated species from Fukushima had been contaminated in other prefectures, resulting in reputational damage.

Factor B brought some fish into direct contact with highly contaminated water. As a result, the concentration varied significantly among different bodies of fish in the same species caught in the same water areas. This fact raised widespread concerns that highly

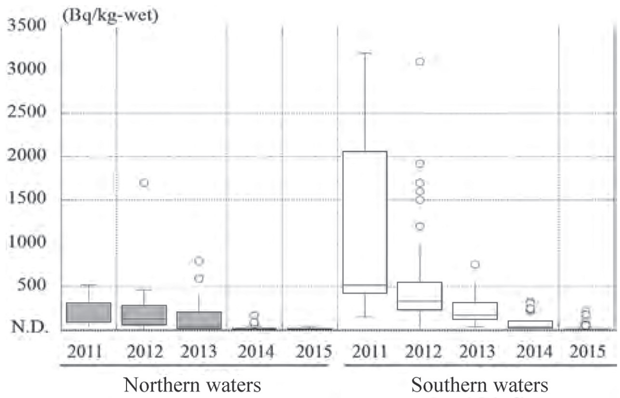

Figure 2 Radioactive cesium concentrations among rockfish in the north and south of the Fukushima Daiichi NPP
The data cited here was obtained from a reference document [1]. N.D. denotes a level below the lower detection limit.

contaminated fish may be overlooked in a sampling survey.

Factor C led to a sharp drop in the concentration of radioactive cesium owing to its swift dilution and dispersion in the ocean. Despite a steady drop in the concentration of radioactive cesium in fishery products under the mechanism mentioned earlier, the stigma of contamination lingers on. As an example of this, **Figure 2** presents the distribution of the levels of radioactive cesium concentration among rockfish off the Fukushima coast. This figure clearly indicates a higher concentration in the southern waters due to ocean currents carrying highly contaminated water southward (Factor A). Figure 2 also demonstrates a high degree of variance among samples. The degree of contamination in different places is not evened out by the mingling of fish, because rockfish and other fish that tend to dwell near rocks do not migrate over long distances. Therefore, the distribution of contamination levels in the immediate aftermath of the accident is believed to have remained unchanged (Factor B). Nonetheless, the radioactive cesium concentration is on the decline even among rockfish, a type of fish that is often mentioned as a notable example of contamination (Factor C).

III. Reputational Damage

1. Strontium-90

One of the most frequently raised concerns is that inspections of fishery products are conducted with respect to radioactive cesium but not with respect to strontium-90. It is certainly true that only the radioactive cesium concentration is indicated according to existing food safety standards. However, these standards are prepared by assuming the presence of a certain amount of radioactive materials with a half-life of 1 year or more (plutonium, strontium-90, and ruthenium-106) that were presumed to have been released in the Fukushima Accident [6, 8]. These standards are prepared based on the assumption of an equivalent dose of these nuclides as that of radioactive cesium in fishery products. The studies conducted to date have revealed that the assumed level is actually too high. Despite the fact that the standards give due consideration to strontium-90, there were reasonable concerns that a lack of measurements may cause unwarranted reputational damage. In response to a request from the

Fisheries Agency, the Japan Fisheries Research and Education Agency began measuring radioactive strontium in May 2011. These measurements are published online [9]. TEPCO also began measuring the concentration of strontium-90 within a range of 20 km from the Fukushima Daiichi NPP. So far, the measured dose ratios for strontium-90 and radioactive cesium fall within the range of between 0.00018 and 0.016. This finding proves that there is no need for concern over food safety since the ratio is much lower than that assumed in the setting of the existing standards [8].

2. Misconceptions about Contaminated Water

One other reason for lingering consumer concerns about the contamination of fishery products is the repeated media coverage of the leakage of contaminated water from the Fukushima Daiichi NPP. In August 2013, TEPCO announced that it had been continuously releasing radioactive cesium and other radioactive materials since the accident. The total amount of radioactive cesium (during a period of 850 days) was about one hundredth of the amount leaked over the course of 10 days in April 2011 in the immediate aftermath of the accident. This release was found to have had an impact only in the port exclusively reserved for the plant. Beyond this area, the release was found to have had no impact at all, even in the waters used for conducting trial fishing. The media also reported the leakage of contaminated water from an onshore tank and the leakage of contaminated rainwater into the ocean through drainage systems. However, none of these incidents has ever caused a rise in the concentration of radioactive cesium in fishery products caught off the Fukushima coast.

Radioactive materials are initially introduced into the food webs of an ecosystem through ambient water. The extent of the ultimate concentration of radioactive materials in living organisms compared to the concentration in ambient water is expressed by the concentration factor (concentration in the body / concentration in seawater) [2]. Since the Fukushima Accident, it has become widely known that the concentration factor of radioactive cesium in marine fish is about 100 at most. To correct a common misunderstanding, it is important to note that fish swimming in seawater with a radioactive cesium concentration of 1 Bq/L will not necessarily have a concentration of 100 Bq/kg-wet in their bodies. In this environment, a food chain with food organisms that have taken in radioactive cesium must exist in order for fish to eat them and thus gain a concentration level according to the given factor [8]. Some people have suggested that fish will have a radioactive cesium concentration of 100 Bq/kg-wet after simply swimming through the waters near the port for the Fukushima Daiichi NPP, which has a concentration of 1 Bq/L. Such people are mistaken. In some cases, even correct statements made by researchers can cause reputational damage. Researchers are keenly interested in the possible causes of any increase in the waterborne concentration of radioactive materials in the order of several hundreds of mBq/L from an original level of several Bq/L. However, changes of this type of magnitude do not change the concentration in fishery products significantly enough to affect our health. Comments made by presumably knowledgeable researchers that are published in newspapers or magazines with an apparently strong interest in such changes tend to be interpreted by the public as having critical implications for their health.

3. Insufficient Understanding of the Actual Situation

Some people believe that the leakage of contaminated water with a high concentration of radioactive materials led to the appearance of deformed fish. The author and his colleagues have regular access to the fish sampled as part of the expulsion in the port for the Fukushima

Daiichi NPP, but they have not identified any that are deformed. Calculations also indicate that such deformations are highly unlikely [2]. In fact, the only fish that the author has seen become deformed due to radioactive contamination is Blinky from the American animated sitcom The Simpsons. Furthermore, the author has also requested samples of fish caught in ports from some Japanese research institutes that are considered well informed about radiation damage, but none of them has offered to conduct any studies. Fish and shellfish lay a vast number of eggs, but only a few of them survive in natural marine waters. Even if some of them become deformed due to radiation during their early development, they are extremely unlikely to survive. Their contribution to the reproduction of their species is almost inconceivable. The voluntary ban on fishing in Fukushima has reportedly resulted in an increase in the fishery stocks.

A high concentration of radioactive cesium was detected in fat greenling caught in 2012. The author and his colleagues published a paper ascribing this high concentration to contamination in the immediate aftermath of the accident [3]. In its report published in October 2015, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) quoted our paper. In the English original, the report mentioned that the concentration of radioactive cesium remained high among fat greenling. However, the Japanese version that they published simultaneously stated the following: “The radioactive cesium concentration among fat greenling is still on the increase.” The author noticed this mistranslation and contacted the UNSCEAR Secretariat, which is based in Vienna, in November 2015 to request a correction. They eventually corrected this part of the report in February 2016 [10]. The mistranslation was reportedly made by a translation agency. However, the Japanese involved in preparing this report should also have felt uncomfortable with this discrepancy if they accurately understood the actual state of fishery product contamination. Those in charge of preparing such a report most probably have more information than the public, so it is extremely regrettable that even they were not well informed of the actual state of contamination. Because the use of the present tense in this kind of report can be misleading, it should be pointed out that the concentration of radioactive cesium in fat greenling monitored in Fukushima never exceeded 40 Bq/kg-wet in FY2015 [1].

IV. Current State and Future of the Fishing Industry

1. Survey of Fishery Products on the Market

The concentration of radioactive cesium in fishery products from Fukushima is on a steady decline. However, fishery products that satisfy the relevant safety standards must be traded among brokers, handled by processing companies, and ultimately purchased by consumers. Otherwise, the fishing industry is not viable. Although only trial fishing is being conducted in Fukushima Prefecture at present, monitoring inspections have been conducted with many samples and the results have been published. These results are often confused with those of inspections of fish on the market, but the fish were caught exclusively to conduct monitoring inspections. They are not put on the market. Foods on the market are regularly inspected by the Ministry of Health, Labour and Welfare. From the occurrence of the Fukushima Accident until the present day (end of March 2016), fishery products on the market that have exceeded the threshold were detected only twice in 2012. This is extremely rare compared to the 30 such cases among agricultural and livestock products, especially considering that most fishery products are wild caught [8, 9]. Fishing activities have been suspended for some time along the Pacific side of Eastern Japan, which was seriously affected by the Fukushima Accident on top of the devastation left by the tsunami that was triggered by the Great East Japan Earthquake. Fishing activities have been resumed one by one after first confirming their safety by conducting inspections for radioactive materials (positive list system). In contrast, shipments of agricultural products continued from inland areas less affected by the tsunami even after the Fukushima Accident. Shipment restrictions were imposed only on products that exceeded the safety limits (negative list system). Although the total amount is unknown, it is easy to imagine that many products that exceeded the safety limits were put on the market. The contamination of beef and shiitake was mostly caused by the distribution of contaminated rice straw and logs, respectively. Farmed fish are raised in similarly controlled environments, but the Fisheries Agency immediately provided guidance to aquaculturalists on how to prevent contamination and related groups stopped the distribution of feed that may be contaminated. For this reason, no inspected farmed fish (excluding extensively farmed ones) exceeded the safety limits [1).

2. Fishing Industry in Fukushima Prefecture

Immediately after the Fukushima Accident, the Fukushima Federation of Fisheries Cooperatives organized a meeting of cooperative leaders on March 15, 2011. At the meeting, they decided to impose a voluntary ban on fishing activities along and off the Fukushima coast. To date, marine fishing activities have remained suspended, except for trial fishing (discussed later). This voluntary ban was imposed purely based on the judgment of the fisheries industry without any instructions to that effect being issued by the national or local governments.

At present (i.e., the end of March 2016), shipment restrictions have been imposed on 28 types of fish from Fukushima. However, this does not necessarily mean that they still have a high concentration of radioactive cesium. Begun in Fukushima off the coast of Soma and Futaba (approx. depth: 150 m) in June 2012, trial fishing was conducted for several months for species whose radioactive cesium concentration was at or below the lower detection limit (2–3 Bq/kg). This trial fishing began with three species off the coast of Soma and Futaba, but the number of target species has increased (73 as of the end of March 2016) along with the expansion of the target waters to include an area off the coast of Iwaki. However, due to reputational damage and other difficulties, only a few businesses trade in fishery products from Fukushima and a return to full-scale fishing operations remains out of sight. Incidentally, the waters located within 20 km of the Fukushima Daiichi NPP are excluded from the trial fishing, but the monitoring survey did not identify any differences in concentration between the waters within and beyond the range of 20 km, except for in areas inside the port or very near the plant. These waters are not targeted in the trial fishing to ensure the safety of the fishery products caught during the trial fishing.

3. Future of the Fishing Industry in Fukushima Prefecture

As mentioned earlier, the concentration of radioactive cesium in fishery products is on a steady decline. Furthermore, the inspection system is fully functional. Nonetheless, consumers remain concerned about the contamination of fishery products, and some neighboring countries still impose rigorous import restrictions. Consumers have not received any updated information since they were made aware of the awful conditions that prevailed in the immediate aftermath of the Fukushima Accident. Perhaps the repeated media coverage on the leakage of contaminated water from the Fukushima Daiichi NPP has ingrained this outdated knowledge. Otherwise, they would find it hard to accept the actual situation in light of the noticeable gap between the severe contamination that existed in the immediate aftermath of the accident and the much lower level of contamination that prevails today.

In FY2015, significant progress was made in relation to measures for dealing with contaminated water. Examples of these measures include the removal of highly contaminated water from the trenches for seawater piping at the Fukushima Daiichi NPP, the performance of coating work for the seabed inside the port, the completion of a seaward impermeable wall, and the deployment of a frozen soil wall. The author hopes that the press will report such improvements.

Statistical calculations have already demonstrated that the chance of fishery products from Fukushima exceeding the safety limit is just one in ten thousand [9]. Furthermore, there is scientific evidence for the reduced level of contamination in fishery products. To counter the reputational damage, we believe it is important to not only monitor the concentration of radioactive materials in fishery products, but also offer a clear and scientific explanation of how they become contaminated and how such contamination can be mitigated. The Japan Fisheries Research and Education Agency strives to communicate accurate information through its website and publications [3, 8, 9]. We hope that you will refer to these resources.

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