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Special Report: “Radioactivity in the Marine Environment and in Fisheries Products during the Five Years after the Fukushima Dai-ichi Nuclear Power Plant Accident”

Current Fishery Activities and Levels of Radioactivity in Fisheries Products from Fukushima Prefecture

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Abstract: We surveyed the levels of radioactivity in marine organisms from Fukushima Prefecture, where the Fukushima Daiichi Nuclear Power Plant accident occurred in March of 2011. In June of 2012, fishing trials were initiated for safe species to evaluate the commercial distribution of harvested fish. Over time, the number of targeted species, fishing methods, and fishing areas have increased, and in June of 2016 fishing trials were being conducted for 73 species along the shores of Fukushima Prefecture beyond a distance of 20 km from the Fukushima Daiichi Nuclear Power Plant. Immediately after the Fukushima accident, radioactive cesium (^{134}Cs and ^{137}Cs) activities of at least 100 Bq/kg-wet were detected in many species. However, those activities declined significantly during the five years following the accident. Since April of 2015, radioactive cesium activity has not exceeded the national standard limit (100 Bq/kg), and since July of 2015, the radioactive cesium activities of over 90% of the samples have been below the detection limit. Continuation of the fishing trials, collection and analysis of the scientific data, and sharing of information will all be necessary to reassure distributors and consumers of the safety of commercial fish. In addition, reconstruction of the production and distribution systems for commercially important marine fish is urgently needed to end the current suspension of fishing activities.

Keywords: Fukushima Prefecture, fishing trials, radioactivity

Introduction

Following the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident in March of 2011, radioactive substances were detected in commercial fish harvested from the coastal areas of the Fukushima Prefecture. As a result, the coastal fisheries of Fukushima Prefecture (including the offshore trawl fishery) voluntarily suspended fishing activities and were continuing to do so as of June 2016. Starting immediately after the accident, Fukushima Prefecture began monitoring the levels of radioactivity in commercially important marine fish and evaluating the extent of contamination. Based on the results, a fishing trial was initiated targeting fish species that had been confirmed to be safe. The impact of the accident decreased over time, and the targeted species, fishing methods, and fishing areas have been gradually expanded. As of June 2016, the number of targeted species had increased from the initial 3 to 73. Here, we report the levels of radioactivity in commercially important fish and discuss the efforts of Fukushima Prefecture and members of the fishing industry to restore the fishing industry. Finally, we discuss future challenges.

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Levels of radioactivity in commercial fish

Methods

The sampling of commercial fish from Fukushima Prefecture began on 7 April 2011. Widespread sampling was conducted under the auspices of the Fukushima Prefectural Federation of Fisheries Co-operative Associations (FPFFCA) with the support of fishermen from each coastal fishery cooperative. Periodic monthly sampling was conducted using a research vessel from the Fukushima Prefectural Fisheries Experimental Station (FPFES), and fishermen collected species of fish available throughout the entire region offshore of Fukushima Prefecture with fishing methods that had been in use before the earthquake that caused the accident. Meanwhile, an FPFES research vessel collected trawl samples once a month as a rule at survey locations. Until 30 September 2011, the area within 30 km of the FDNPP was designated an emergency evacuation preparation area, within which no samples could be collected. This restriction was subsequently withdrawn, and the survey areas were expanded accordingly. After April of 2013, sampling of commercial fish was conducted along the entire length of Fukushima Prefecture, except for the region within 5 km of the FDNPP. Within that 5-km radius, the Tokyo Electric Power Company monitored the state of environmental contamination and published the results.

Sampled marine organisms were brought to the FPFES, and after measuring the body size of individuals and recording the stomach contents of fish, the edible portions of each organism were collected as samples. For example, because whitebait and greeneyes *Chlorophthalmus albatrossis* are eaten whole, the surfaces of the fish were washed, and the whole bodies of the specimens, including their internal organs, were treated as samples. In contrast, fish such as Japanese flounder *Paralichthys olivaceus* are usually eaten as sashimi, and therefore only the muscle tissue of the specimens was used. To avoid underestimating contamination when samples were combined and to quantify the variability of contamination between individual specimens, individuals from which at least 100 g of muscle could be dissected were treated as separate samples. When 100 g of muscle could not be obtained from single individuals, equivalent proportions of tissue from multiple individuals were combined to obtain a total of at least 100 g of muscle tissue.

After collection, the samples were transported to a test facility*1, where the activities of ^{131}I, ^{134}Cs, and ^{137}Cs were measured using a germanium semiconductor detector. For each sample, about 100 g was placed in a U8 container, and the intensity of gamma radiation from each radionuclide was measured for 2000 seconds. Detection limits under these conditions ranged from 7 to 9 Bq/kg-wet for both ^{134}Cs and ^{137}Cs, and total radioactive cesium activities were equated to the sum of the ^{134}Cs and ^{137}Cs activities for each specimen.

Results

Figure 1 shows the number of samples of commercial fish collected each month in 2011, the percentage of samples with levels of radioactivity that exceeded the national standard limit of 100 Bq/kg, and the percentage of samples with levels of radioactivity below the detection limit. Immediately after the accident, analytical procedures were not yet firmly established, and only 100–200 samples were assayed each month. Subsequently, however, the number increased, and in 2016, around 700 samples were assayed each month. In 2011, the radioactivities of 39.8% of the samples exceeded 100 Bq/kg, but after April of 2015, no samples exceeded that limit. In 2011, the radioactivity of only 14.9% of the samples was below the limit of detection, but after July of 2015 the radioactivity of more than 90% of the samples was below the limit of detection. Thus, the impact of the nuclear accident on marine organisms was clearly decreasing.

We divided the coastal area of Fukushima Prefecture into 10 sections, which were oriented from east to west based on the position of the 50-m isobath and from north to south based on latitude. The radioactive cesium activities in marine organisms from each of the 10 sections were then summarized. From April to December of 2011, the samples were

*1 Until June of 2011, the Japan Chemical Analysis Center and Environmental Radioactivity Monitoring Center of Fukushima, Fukushima office, and subsequently the Fukushima Agricultural Technology Centre.

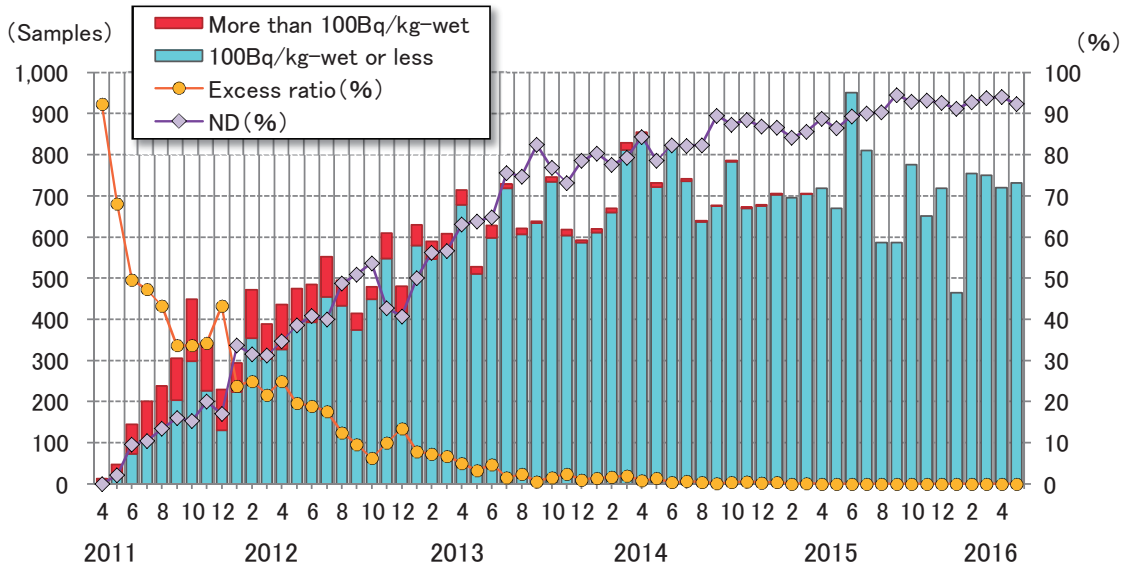

Fig.1 Monthly monitoring results.

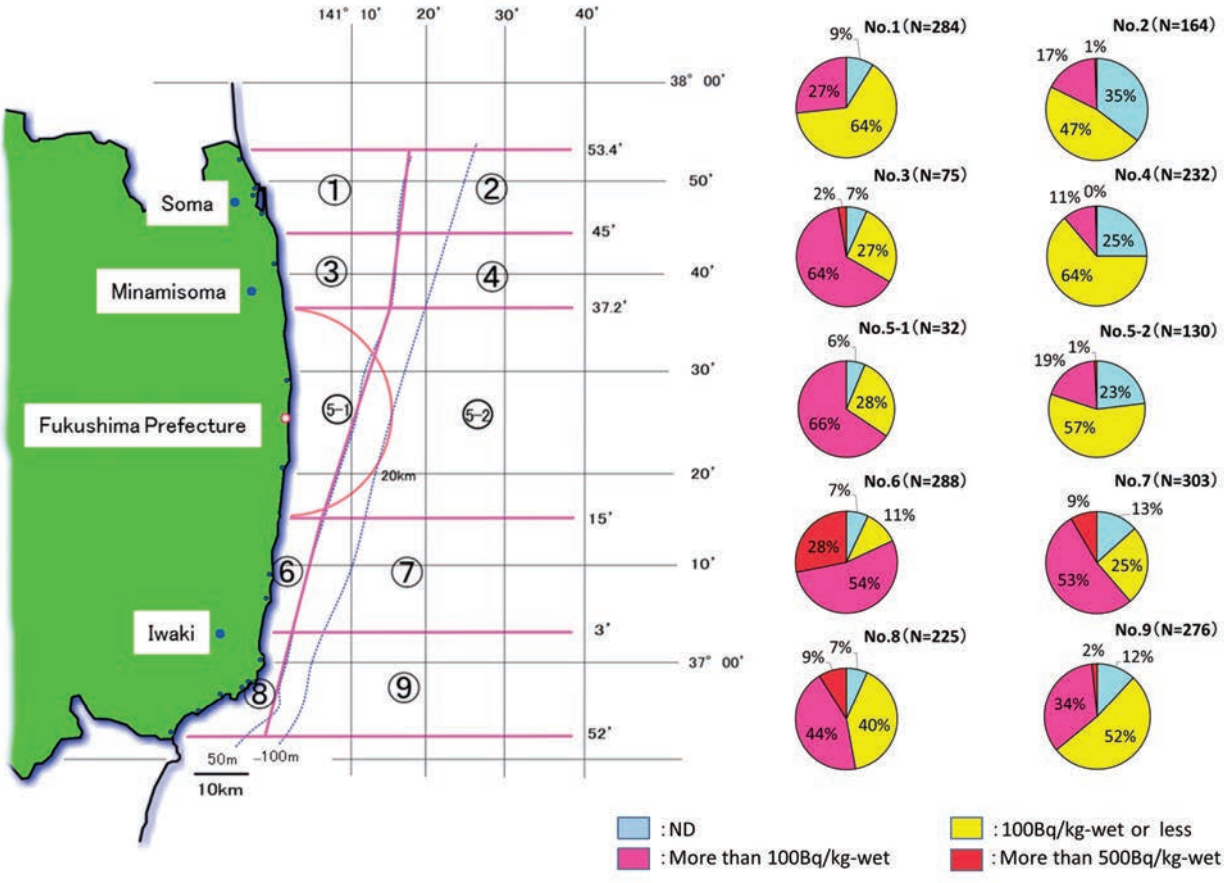

Fig.2 Radioactive cesium concentrations in each area (April to December, 2011).

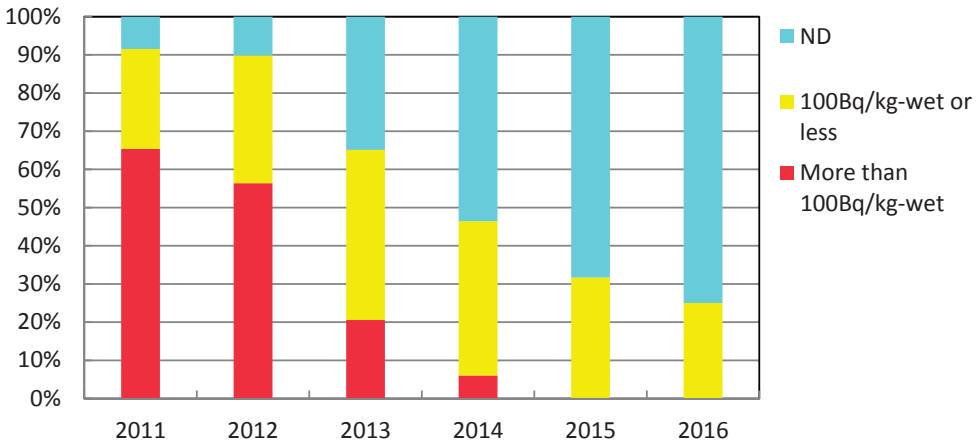

Fig.3 Radioactive cesium concentrations in each year in the area No.6.

categorized as >500 Bq/kg-wet, 100–500 Bq/kg-wet, ≤100 Bq/kg-wet, or below the limit of detection. Figure 2 shows the percentages of samples in each category for each of the 10 sampling areas. In marine area No. 6 (south of the FDNPP and in a water depth ≤50 m), the radioactivities of a high percentage of the samples exceeded 500 Bq/kg. However, the percentage of samples from the same depth interval (≤50 m) on the north side of FDNPP with radioactivities that exceeded 500 Bq/kg-wet was lower than on the south side. In addition, the percentage of radioactivities that exceeded 500 Bq/kg-wet was smaller for samples collected from water deeper than 50 m than from samples taken from shallower water. These results suggest that marine organisms from shallow water south of FDNPP were most contaminated by the accident. However, the activities of radioactive cesium tended to decrease over time, regardless of the area tested, even in area No. 6, where the percentage of samples with radioactivities exceeding 500 Bq/kg-wet was high. Furthermore, in 2016 there were no samples with radioactivities exceeding 100 Bq/kg-wet (Fig. 3).

The activities of radioactive cesium declined with time in all fish species. Cesium radioactivities, for example, were as high as 14,400 Bq/kg-wet in April 2011 in the juvenile of Japanese sand lance *Ammodytes personatus*, but they had decreased greatly by the fishing season of the following year, and after 2013 they were undetectable (Fig. 4). The cesium radioactivities in other fish, such as whitebait, also decreased rapidly with time. We suspect that this trend was related to the short generation times of the fish because less radioactive cesium accumulated in the generations of fish that were not exposed to the high levels of radioactivity immediately after the accident. In addition, the concentrations of radioactive cesium in migratory and offshore species of fish were relatively low or undetectable, even immediately after the accident (Fig, 5, 6). The cesium radioactivities in crustaceans and mollusks decreased rapidly, even in species for which the radioactivities exceeded the standard limits immediately after the accident (Fig. 7, 8).

As of 2016, the number of fish species with detectable (though low) cesium radioactivities was relatively small. The self-imposed criterion of the FPFFCA for shipment of fish is that the radioactivity be less than 50 Bq/kg-wet, which is lower than the national standard limit. In widespread sampling during 2016, the radioactive cesium activities of only rockfish

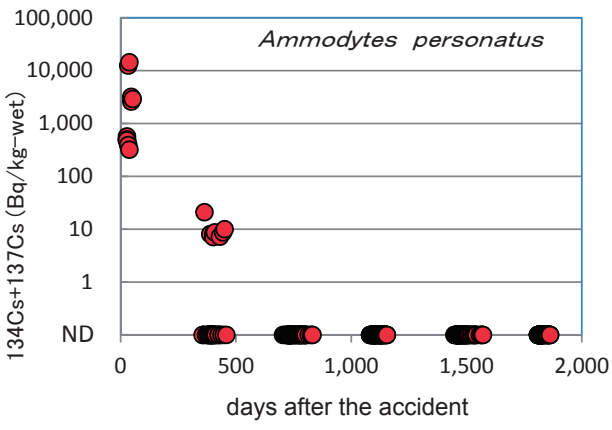

Fig.4 Changes in radioactive cesium concentrations of *Ammodytes personatus*.

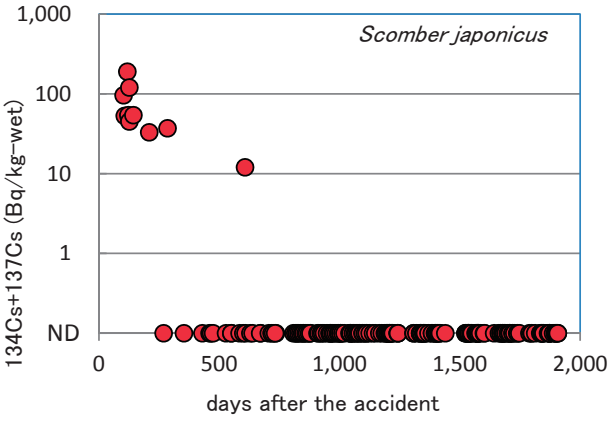

Fig.5 Changes in radioactive cesium concentrations of *Scomber japonicus*.

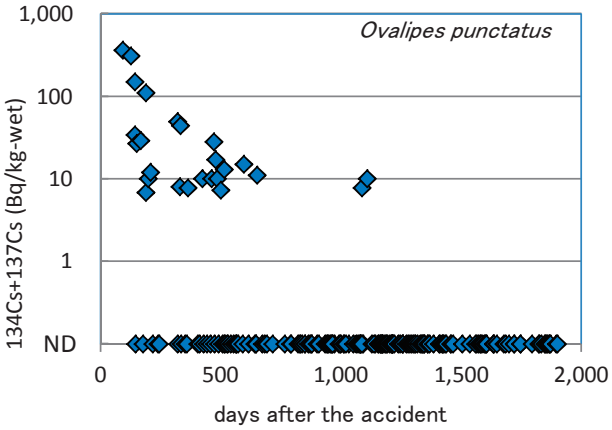

Fig.7 Changes in radioactive cesium concentrations of *Ovalipes punctatus*.

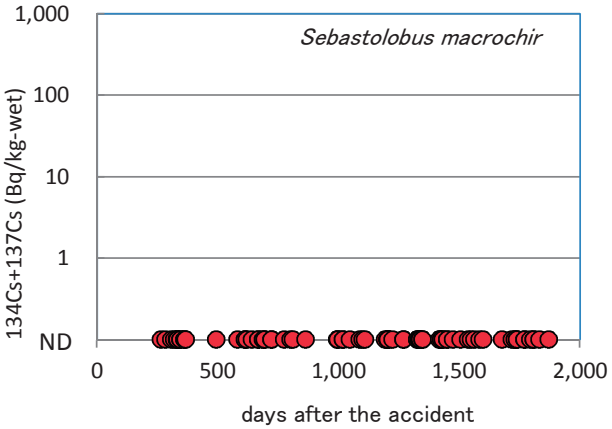

Fig.6 Changes in radioactive cesium concentrations of *Sebastolobus macrochir*.

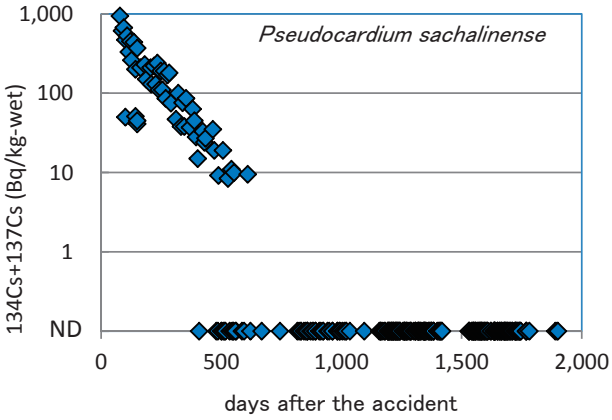

Fig.8 Changes in radioactive cesium concentrations of *Pseudocardium sachalinense*.

Table 1 Restriction on shipping and distribution (offshore Fukushima Prefecture, as of June 2016.)

Restriction on shipping and distribution					
No	Species	No	Species	No	Species
1	*Hexagrammos otakii*	10	*Sebastes schlegelii*	19	*Verasper variegatus*
2	*Cynoglossus joyneri*	11	*Acanthopagrus schlegelii*	20	*Pleuronectes yokohamae*
3	*Ammodytes personatus* （except juvenile）	12	*Okamejei kenojei*	21	*Platycephalus* sp.
4	*Kareius bicoloratus*	13	*Oncorhynchus masou*	22	*Sebastes pachycephalus pachycephalus*
5	*Sebastes thompsoni*	14	*Occella iburia*	23	*Mercenaria stimpsoni*
6	*Ditrema temminckii*	15	*Sebastes cheni*	24	*Stichaeus grigorjewi*
7	*Physiculus maximowiczi*	16	*Lateolabrax japonicus*	25	*Verasper moseri*
8	*Sebastes vulpes*	17	*Platichthys stellatus*	26	*Sebastiscus marmoratus*
9	*Paraplagusia japonica*	18	*Microstomus achne*		

Cancellation of restriction on shipping and distribution					
No	Species	Cancellation date	No	Species	Cancellation date
1	*Ammodytes personatus* （juvenile）	22 June 2012	10	*Gadus macrocephalus* ※	14 January 2015
2	*Hippoglossoides dubius*	9 October 2013	11	*Mustelus manazo*	18 February 2015
3	*Theragra chalcogramma*	17 December 2013	12	*Eopsetta grigorjewi*	24 February 2015
4	*Pleuronectes herzensteini*	16 April 2014	13	*Nibea mitsukurii*	2 April 2015
5	*Helicolenus hilgendorfi*	28 May 2014	14	*Pleuronichthys cornutus*	2 April 2015
6	*Chelidonichthys spinosus*	9 July 2014	15	*Hemitripterus villosus*	22 June 2015
7	*Strongylocentrotus nudus*	9 July 2014	16	*Takifugu pardalis*	3 December 2015
8	*Hyporhamphus sajori*	9 July 2014	17	*Paralichthys olivaceus*	9 June 2016
9	*Takifugu snyderi*	15 October 2014	18	*Conger myriaster*	9 June 2016

※ Limited area（The whole area cancellation was 24 May 2015）

Sebastes cheni, stone flounder *Kareius bicoloratus*, slime flounder *Microstomus achne*, and Japanese sea perch *Lateolabrax japonicus* exceeded the 50 Bq/kg-wet limit. Fish species that maintained detectable activities of radioactive cesium included species that inhabited areas that were severely affected by the accident and that did not move away from the areas afterward.

Future research challenges

As of late June 2016, national shipment restrictions remained for 26 commercially important marine species that occur in the coastal areas of Fukushima Prefecture (Table 1). Because many of these are important target species of coastal fisheries, shipping restrictions must be lifted to allow resumption of full-scale operations. Enhancement of the monitoring system and confirmation of the safety of these species can accelerate the lifting of these restrictions. Furthermore, in order for fishermen, distributors, and consumers to resume their respective activities with confidence, monitoring and scientific data will be needed to confirm the safety of target species, describe the phenomenon, and explain the cause. In the future, more detailed analyses should be added to current routine monitoring to assure the safety of commercial marine fish. The ecological and physiological characteristics of fish in which radioactive cesium is still detected should be quantified, and the rates of accumulation and excretion of radioactive cesium by each of these fish species should be determined.

Fig.9 Flow of decision making for the fishing trial.

Current state of fisheries

Fishing trials

Although the coastal fisheries of Fukushima Prefecture suspended their operations, a fishing trial and commercial distribution were initiated in June of 2012 for fish species that were confirmed to be safe by the prefecture's monitoring program. The main objective of the fishing trial was to determine how seafood from Fukushima Prefecture was evaluated in the distribution process. However, another objective was to assure the safety of fish from Fukushima Prefecture to consumers and brokers through distribution and sale.

Initially, the fishing trial involved an offshore trawl fishery boat that belonged to the Soma Futaba Fisheries Cooperative Association and was used to monitor North-Pacific giant octopus *Octopus* (*Enteroctopus*) *dofleini*, Chestnut octopus *Octopus* (*Paroctopus*) *conispadiceus*, and the whelk *Buccinum isaotakii*. The target area was limited to the coastal area of Soma, and to conserve resources, the bycatch of non-target species was limited by fishing at a depth >150 m. To conduct the fishing trial, which was based on the Shipment Policy of the Fishing Trial Target Species determined by the FPFFCA, the fishery cooperative of each district developed a plan for each area and fishing method. Then, after being approved by a fishing trial committee in each area (Soma, Futaba, and Iwaki), the plans were discussed by the Fukushima Prefecture Regional Fishery Recovery Council, which consists of experts from universities, distributors, and the federal and prefecture governments. Ultimately, the Prefectural Federation of Fisheries Co-operative Associations Chair Meeting approved the plans (Fig. 9).

In addition, marine commercial species that were captured during the fishing trial were gathered at (1) the Soma Haragama Regional Wholesale Market for the Soma Futaba Region and (2) the Iwaki City Regional Wholesale Market and Onahama Fish Market for the Iwaki area. At each market, each fish species was voluntarily tested on a daily basis for radioactivity

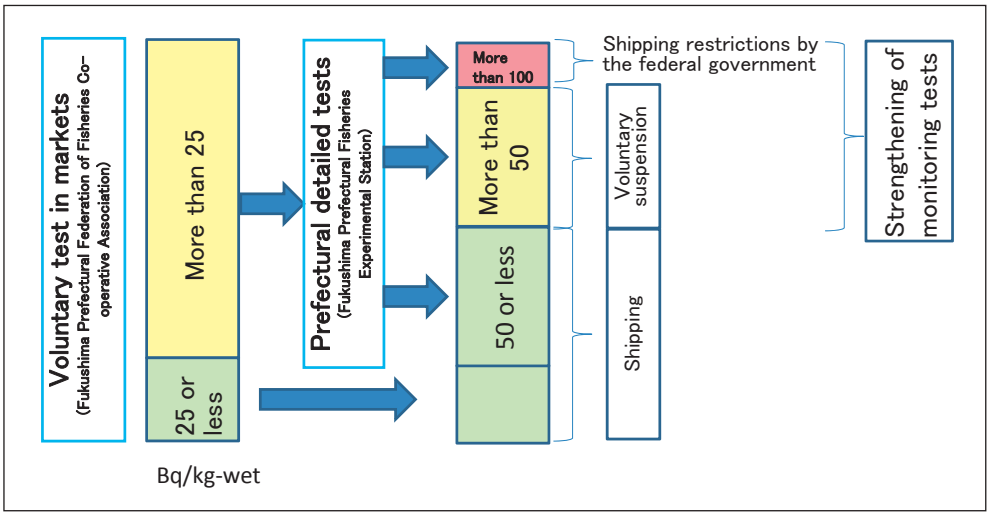

Fig.10 Voluntary test system of the Fishery Cooperative in the fishing trial.

Table 2 Sample number of voluntary test (as of March 2016)

		2012	2013	2014	2015	2016	Total
Iwaki	ND	0	71	489	812	364	1,736
	25Bq/kg-wet or less	0	2	25	23	2	52
	more than 25Bq/kg-wet	0	0	0	2	0	2
	more than 50Bq/kg-wet	0	0	1	0	0	1
	total	0	73	515	837	366	1,791
SomaFutaba	ND	149	543	1,150	1,931	548	4,321
	25Bq/kg-wet or less	1	3	6	10	1	21
	more than 25Bq/kg-wet	0	1	0	0	0	1
	more than 50Bq/kg-wet	0	0	1	0	0	1
	total	150	547	1,157	1,941	549	4,344
Total	ND	149	614	1,639	2,743	912	6,057
	25Bq/kg-wet or less	1	5	31	33	3	73
	more than 25Bq/kg-wet	0	1	0	2	0	3
	more than 50Bq/kg-wet	0	0	2	0	0	2
	total	150	620	1,672	2,778	915	6,135

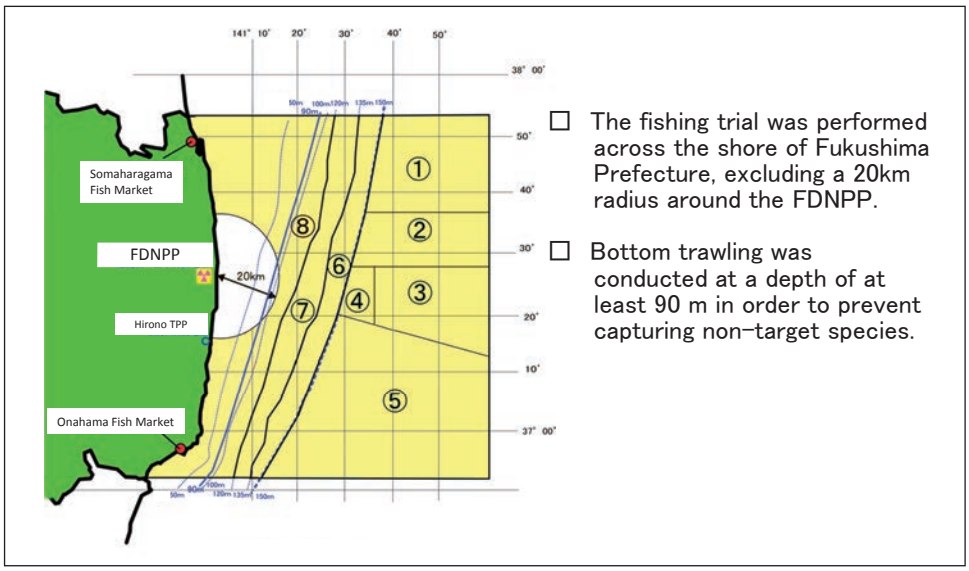

Fig.11 Trial fishing areas (as of June 2016). Numbers indicate the order of target area expansion for the bottom trawl fishery.

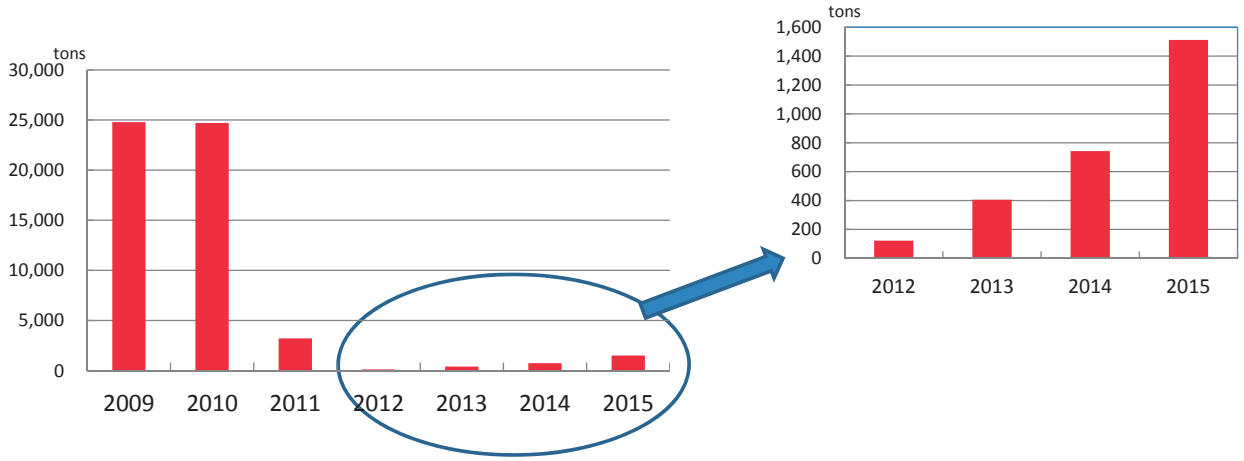

Fig.12 Catch by coastal fisheries in Fukushima Prefecture and in the fishing trial including offshore bottom trawl.

before shipping. The FPFFCA used 50 Bq/kg-wet as the self-imposed limit for shipping so that there was no chance of shipping any fish that exceeded the national standard limit of 100 Bq/kg-wet. Meanwhile, at each market, if a sample exceeded half of the self-imposed limit (i.e., 25 Bq/kg), it was shipped to the FPFES for a detailed analysis using a germanium semiconductor detector (Fig. 10). As of March 2016, 6135 samples had been voluntarily tested in the two markets. The majority of samples were below the detection limit of 12.5 Bq/kg-wet (Table 2); only five samples exceeded 25 Bq/kg-wet.

Over time, the number of fish species confirmed to be safe has increased, and as a result, the numbers of target species, target fishing methods, and target areas have gradually increased. As of June 2016, the number of target species was 73, and fishing trials were being conducted using many of the fishing methods that were used prior to the accident (e.g., trawl fishing, boat seine fishing, and gill-net fishing), but excluding angling and coastal longline fishing, which target restricted fish species. According to interviews with various fishermen's cooperatives, about 50% of the operating boats were participating in the fishing trial by the end of 2015, and 70% were participating as of June 2016. Meanwhile, the areas of the operation have been expanded to cover the whole nearshore area of Fukushima Prefecture, and although the operation has been voluntarily suspended within a 20-km radius of FDNPP (Fig. 11), discussion has begun about reducing the radius of that zone. The total catch of the fishing trial was 122 metric tons in 2012 and 1512 tons in 2015. However, this is a mere 5.8% of the 10-year average catch of 26,050 metric tons before the accident (Fig. 12).

At the beginning of 2012, harvested marine fish were shipped only to consumer markets and local retailers in urban areas of Fukushima Prefecture. Subsequently, they were shipped widely to the Tohoku, Kanto, Hokuriku, Chubu, and Kansai regions. According to a survey of local wholesalers by the Fishery Cooperative, the prices of marine fish from Fukushima Prefecture at the shipping destinations were similar to those of marine fish from other prefectures. However, the number of suppliers had decreased, and the sales of some fish species declined whenever there was a report of leakage of polluted water from FDNPP.

Challenges of resuming full-scale operation

To resume full-scale fishery operations, the safety of the 26 restricted species (as of June 2016) needs to be confirmed as soon as possible, and fishing restrictions must be lifted. In addition, the fisheries-related facilities that were damaged by the earthquake and nuclear power plant accident need to be rebuilt in a timely manner. Fisheries operations have been suspended for a long period. During that time, some of the older fishermen have retired, and some of the younger fishermen have found other jobs. The recovery of local suppliers has therefore been delayed. Thus, there are serious issues for the fishing industry from the standpoint of both human resources and the infrastructure needed for production, shipping, and distribution. In the future, it will be necessary to rebuild

the fishery by setting targets and schedules, including clear specification of the time when normal fishing operations will be resumed.

Summary

In the present study, we monitored the radioactivity of a large number of commercial fish to determine the impact of the Fukushima nuclear power plant accident and to identify commercial fish safe for human consumption based on fishing trials. Monitoring is important for guaranteeing the safety of fisheries products, determining when to lift shipping restrictions, and providing a scientific basis for a return to full-scale operations. It has been over five years since the Fukushima nuclear power plant accident, and the level of radioactivity in commercial fish is extremely low. However, to assure the public that consumption of commercial fish from Fukushima Prefecture is safe in the future, monitoring must be continued, and the results must be made public.

On 9 June 2016, shipping restrictions were lifted on Japanese flounder, a fish very much associated with commercial fishing off Fukushima. This action created high hopes of major progress towards full-scale resumption of commercial fishing operations. Scientific information, such as the results of monitoring levels of radioactivity in fish, should be provided to fishermen and consumers to accelerate progress towards full-scale resumption of fishery operations.