



# **Environmental and Economic Recovery Post-Fukushima Daiichi Nuclear Disaster: Isotope Characteristics and the Recovery of a Crippled Fisheries Industry**

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## **Authors' contributions**

*This work was carried out in collaboration among all authors. Author PWW wrote the final draft. Author TLP supervised the study. Authors BHD, DH, LN, MR and SI designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. All authors read and approved the final manuscript.*

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## **ABSTRACT**

The 2011 Tohoku earthquake and subsequent tsunami had a catastrophic effect on the aquaculture industry of the North-East Japanese coast. Ten years on, this paper examines the environmental and economic impacts of this disaster within the context of the Fukushima nuclear

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meltdown. Following structural damage to the Tokyo Electric Power Company Fukushima Daiichi plant, fisheries and aquaculture industries were suspended, given the initially high radio caesium output into the coastal water column. Daily radiation testing began on all fisheries products, with tentative industry resuming within the Fukushima prefecture once radiation had dropped below the 50 Bq/kg, as stipulated by the Fukushima Fisheries Association. Routine testing continues biweekly (at least until March 2021). As of May 2016, 73 fish species were passed for consumption. The rapid functional recovery of the fisheries industry has been mediated by two factors, the sedimentation characteristics of the caesium isotopes and deposition of isotopes out to sea in an Easterly direction, given the interaction of oceanic currents. While the aquaculture industry may have recovered and food reduced to safe radiation levels, the disaster continues to exert a domestic and international economic impact given the stigma of Fukushima radiation.

*Keywords: Cs<sup>137</sup>; radioisotope; sediment sequestration; Kuroshio; Oyashio.*

## 1. INTRODUCTION

Japan sits on the convergence of the Eurasian, North American, Pacific and Philippines tectonic plates. With consistent plate interactions, numerous active fault lines trace throughout the Japanese islands and seismic activity causes frequent earthquakes of varying significance [1]. The East coast of Japan, particularly Miyagi Prefecture, which borders the active Japan Trench, is prone to earthquake activity. Prior to the 2011 Tohoku earthquake and tsunami, earthquakes were regularly documented, with significant seismic activity of up to magnitude 7 (Japan Meteorological Agency Seismic Intensity Scale) occurring every 30-40 years [2,3,4]. Since the 11<sup>th</sup> century however, no earthquakes had been recorded in this region greater than magnitude 8.5 [3]. The earthquake that occurred off the Pacific coast of Tohoku, Japan, at 14.46 Japan Standard Time on the 11<sup>th</sup> of March 2011 was classified as magnitude 9 [5]. Alongside the significant damage that the earthquake itself caused, the resulting seafloor disturbance triggered one of the largest tsunamis in Japanese history [6].

Given its seismic history, Japan has invested significant infrastructure and finance into the preparation for earthquake and tsunami evacuation. The unprecedented size of this earthquake and the subsequent tsunami, however, were beyond the abilities of these recommended procedures. The earthquake/tsunami resulted in the catastrophic loss of life and widespread damage to infrastructure. Impacting over 600 km of Sanriku coastline, the disaster had a profoundly devastating effect on the population, economy and environment of Japan, particularly within the epicentre of the disaster, Tohoku.

While the majority of the coastline of Miyagi and surrounding prefectures experienced some degree of devastation from the earthquake and tsunami, the city of Fukushima drew global attention given the damage to its nuclear power facility and subsequent radiation pollution caused by the disaster. As a result of the earthquake and tsunami, structural damage to the Fukushima Daiichi ("Fukushima the First") power plant (FDNPP), owned by TEPCO (Tokyo Electric Power Co), caused the cooling systems of the reactors to be disabled [7]. In use since its commission in 1971, the reactor was in the top 15 largest nuclear power facilities globally and used six boiling water reactors reliant on nuclear fission to facilitate a steam driven electrical energy system [7]. The structural damage to these reactors resulted in the distribution of radionuclides into the atmosphere and, given the proximity of the reactor to the coastline of Japan, to the marine environment.

Topsoil around the radiation zone was able to be excavated from arable and urban land to minimize radiation to human populations, but the millions of tons of water used in the cooling of the damaged reactor were more difficult to contain. The constant release of water containing caesium, iodine, plutonium and strontium isotopes presented a clear threat to marine systems [8]. Over 80% of the released radiation (particles, rather than gamma radiation) ended up in the ocean, either blown offshore by wind or in radioactive water directly released into the sea [9]. This radiation predominantly occurred in the form of highly soluble radio-caesium isotopes Cs<sup>137</sup> and Cs<sup>134</sup> [10].

The meltdown of the Fukushima Daiichi reactor resulted in the immediate evacuation of over 200,000 inhabitants from surrounding areas,

triggering immediate food, water and health monitoring for the impacts of radiation. In addition, this coastline supported one of the most dense aquaculture industries globally. This disaster had a catastrophic impact on aquaculture and fisheries given the outflow of radio-caesium into the marine environment, resulting in the suspension of a key primary industry.

This paper examines the effects of the Fukushima Daiichi meltdown on the environmental and economic recovery of the northern Honshu coastline ten years on from the catastrophic earthquake and tsunami.

## 2. MATERIALS AND METHODS

Given the logistical difficulties of sampling methodologies and variability of the ocean environment, achieving definitive models of oceanic movement of caesium has been difficult. Upon release into the marine environment, the distribution of radioactive particles was determined by ocean geophysical and biological processes. Numeration of radioactive material yielded the following estimations, 17.5 PBq of Cs<sup>134</sup>, 15 PBq of Cs<sup>137</sup> through atmospheric fallout and 5 PBq into the immediate surroundings [10]. However, radioactive pollution was not contained to a singular event, ongoing annual rates of radio-

caesium release are estimated to be at 15-20 TBq/year of Cs<sup>137</sup> through groundwater release and 10-12 TBq/year resulting from river runoff [10].

From April 2011 through to September 2015, following the incident, there were an additional 70 instances of radioactive material being released from the FDNPP, material from these instances all reached the ocean through a number of routes.

One significant factor determining the oceanic movement of radioisotopes was the mixing of dominant oceanic currents. Interaction between the northward-bound Kuroshio and southward-bound Oyashio produces a net transport of water offshore to the East [10] (Fig. 1). Upon their release, seaborne radioisotopes were carried by these current systems and dispersed Eastward by the North Pacific current. Initially, the caesium was transported at 7 km/day until March 2012 when it slowed to 3 km/day and retained this speed up until August 2014 [10]. In June of 2013, caesium originating from the FDNPP accident was first detected in the West Coast waters off North America [10]. By 2015 detectable levels were measured at sites 55° North and 25° North, which are considerable deviations North and South of the FDNPP (37.4213° N, 141.0281° E) [10].

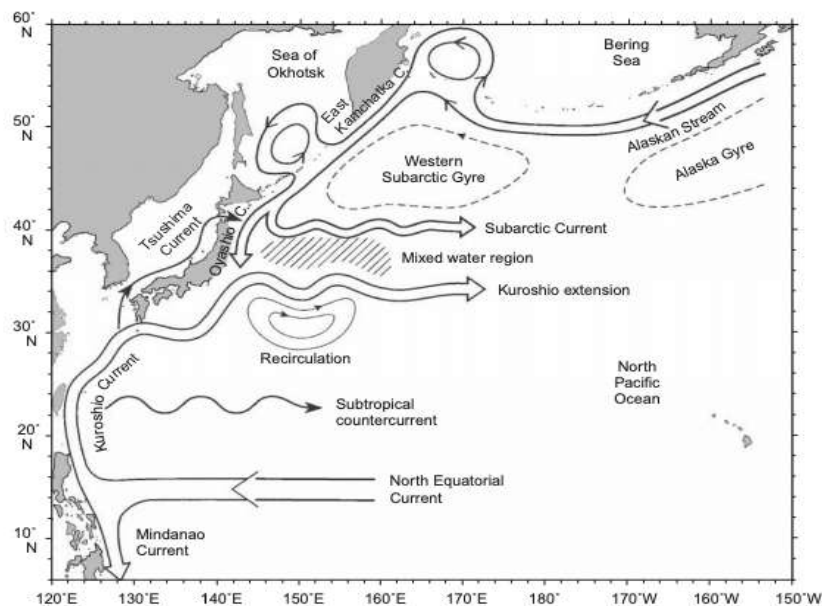


Figure 1 Schematic current patterns associated with the subtropical and subarctic gyres in the western North Pacific Ocean.

Fig. 1. Map of oceanic current interactions (from Qiu et al., 2001)

Caesium associated with sinking particles contributed to a considerable downward export flux over a short temporal span following the release of the source term. Once associated with the benthos, resuspension may occur through bioturbation, which reintroduces sequestered pollutants to the water column over decadal time scales or by physical oceanic properties on un-sequestered caesium particles, followed by lateral displacement under the influence of current systems. Alternatively, benthic fauna may influence sequestration through bioturbation, facilitating downward vertical movement. Increased bioturbate activity is directly correlated with increased rate of surface caesium decline.

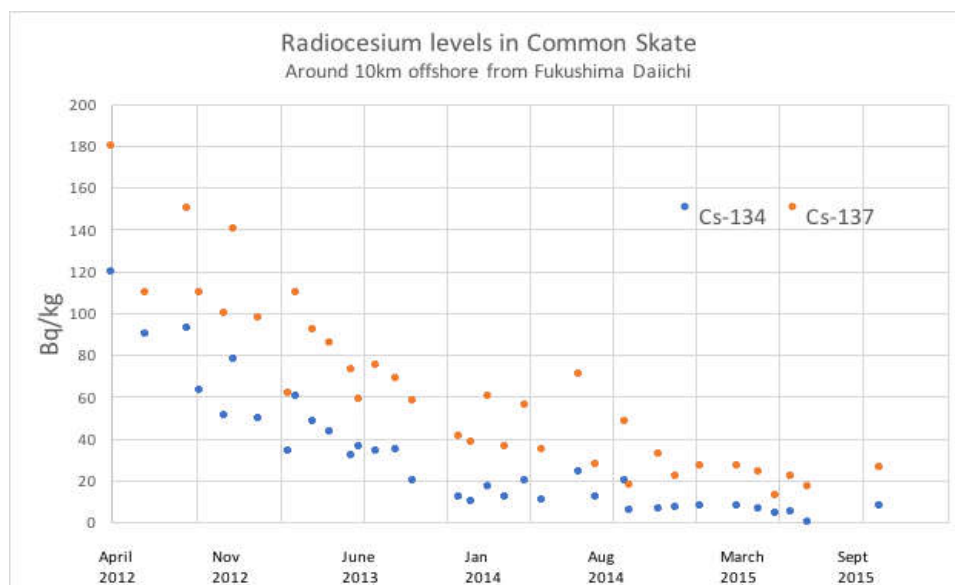
### 3. RESULTS

Immediately after the FDNPP disaster, commercial fishing operations within the Fukushima prefecture were suspended until caesium levels within seafood products available for sale fell to an acceptable level. The Fukushima Fisheries Association (FFA) decided that the acceptable level to resume fishery operations would be 50 Bq/kg, which is considerably lower than the United Nations (1000 Bq/kg) and Japanese Government (100 Bq/kg, as of 1 April 2012) upper threshold [11, 12].

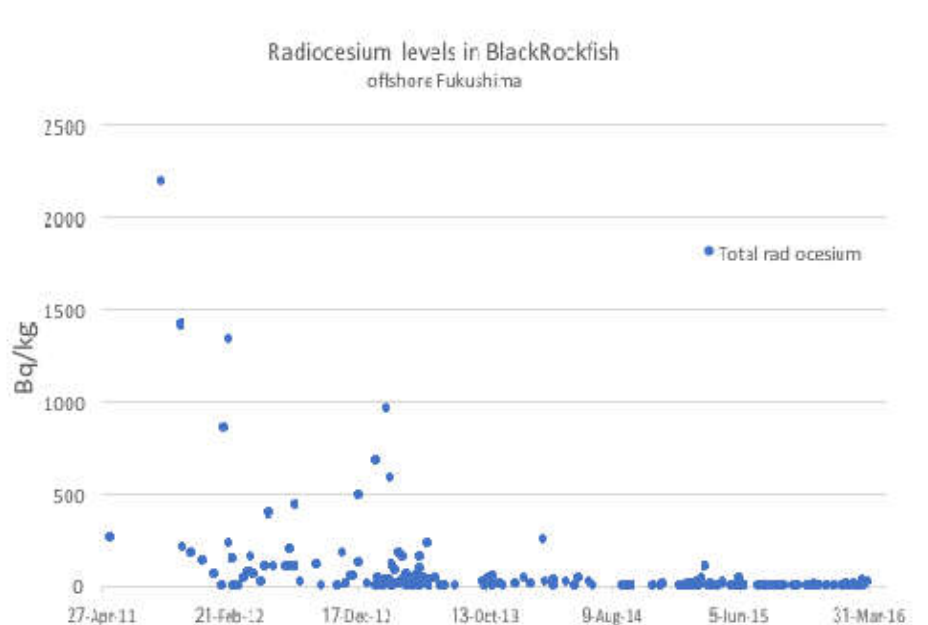
A large concern for ecosystems' function was the interaction between caesium and ocean life.

Demersal species, which have life history strategies associated with benthos and sediment, are likely to exhibit much greater concentrations of radio-caesium than pelagic species. Following the disaster, screening of a number of fish species in coastal waters of the Fukushima prefecture showed 90% of individuals contained detectable levels of radio-caesium (> 7 Bq/kg). By 2015, this situation had greatly improved with only 20% of individuals presenting detectable levels and less than 1% having over 100 Bq/kg [10]. This decrease in radio-caesium was seen in two example species: the common skate (*Dipturus batis*) and black rockfish (*Sebastes schlegeli*).

The common skate, a pelagic species, showed levels of 300 Bq/kg total radioactive caesium, measured in April 2012 around 10 km offshore from Fukushima Daiichi, higher than the recommended 50 Bq/kg initially, dropping to below 20 Bq/kg by late 2015 (see Fig. 2). The black rockfish, however, had dramatically higher initial radio caesium levels, more than 2000 Bq/kg, measured in September 2011 (see Fig. 3). We suggest that this is reflective of a greater interaction with benthic substrates with high radioisotope sedimentation, however further analysis of this species long term is recommended. By March 2016, this species was also deemed safe for consumption by Japanese and UN guidelines.



**Fig. 2. Decrease in radio-caesium Cs<sup>134</sup> and Cs<sup>137</sup> tissue of the Common Skate (*Dipturus batis*) between April 2012 and September 2015**



**Fig. 3. Decrease in radio-caesium Cs<sup>134</sup> and Cs<sup>137</sup> tissue of the Blackfish (*Sebastes schlegelii*) between April 2011 and March 2016**

Life history, habitat, size, diet selection, mobility and physical oceanic mechanisms all play a role in the variation of the ecological half-life of radio-caesium. It is encouraging to see that of individuals tested, less than 1% showed activity above the 100 Bq/kg limit. However, by 2017 marine species still exhibited levels higher than background levels pre-dating the meltdown. As a result, the FFA commenced trial fishery operations on target species that tested at acceptable levels. As of May 2016, this comprised of 73 species making it to consumer market.

#### 4. DISCUSSION

While the radioactive impact of Fukushima has caused significant environmental damage, the disaster has also had a dramatic social and economic effect. Due to public health concerns, in September of 2013, Korea implemented a “blanket import ban” on all fishery products originating from the following prefectures; Aomori, Chiba, Fukushima, Gunma, Ibaraki, Iwate, Miyagi and Tochigi. This was coupled then with a lowering of acceptable Cs<sup>134</sup> and Cs<sup>137</sup> concentrations within all food products in Korea from 370 to 100 Bq/kg, reflecting the acceptable levels also adopted by Japan, making the sale of fisheries products more difficult [13-16]. Despite these guidelines, Korea continued to refuse to purchase fisheries

products for many years, despite passing strict radiation criteria.

In 2015, Japan presented a number of criticisms to the framework that Korea had implemented in relation to food safety and importation of fishery products. The contesting of these regulations however did not result in compromise and the World Trade Organization (WTO) formulated a panel in 2016. That panel comprised of representatives from Uruguay, France and Singapore and had a remit to investigate and attempt to settle the conflict. The WTO panel concluded that Korea were not acting in accordance with the scope of a number of WTO agreements. The culmination of loss of product, fear, national and international restrictions resulted in significant economic stress to the Japanese seafood market, stress that is evident to this day [17-19].

Even though radioactivity is considered to be now (early 2021) at acceptable levels and fishery systems are well on-track to being re-established, attitudes surrounding seafood products are far from optimal. This is evident from Korea's trade policies. We observed first hand evidence of this when interviewing fishermen from the Miyagi coastline, some 200 km North of Fukushima in November 2018. From talking to fishermen from Minamisanriku, we found that while there was initial fear over

the radiation risk, the lasting memory had been of the economic impact of damaged fisheries and there was little thought of radiation (by 2018).

## 5. CONCLUSION

The meltdown of the Fukushima Daiichi facility caused by the 2011 Tohoku earthquake and tsunami has had a widespread impact on the North-East Coastline of Japan, by critically impacting primary fisheries and aquaculture industries. While the tendency of radioisotopes in the water column to sequester in sedimentation, combined with the interaction of oceanic currents, has mediated the impact of radiation on the fisheries industry, the economic impact of the disaster continues to be felt and will likely be felt for an extended period. Long-term testing must continue, given the potential for resuspension of sequestered isotopes and the continued release of products (water) from the damaged Fukushima facility.

Even though fishes are now deemed to generally have acceptable radioisotope levels, the products are being exported for reduced revenue to a reduced market given the stigma of 'Fukushima' derived products. The UN concluded Korea's trade sanctions to be in violation of WTO agreements, an outcome which ought to be positive for Japan's market when projecting into the future. Though this is still being negotiated, resolution in Japan's favor will likely strengthen a recovering fisheries economy.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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