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The consequences of disposal and leakage of radioactive materials on various species of marine and freshwater fish

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Abstract
This review paper highlights some of the existing findings in regard to radionuclide exposure and the impact that it has on marine and freshwater fish.
We performed a literature review on the disposal and leakage of radioactive materials on various species of marine and freshwater fish using the following database sources: Science Direct, Ovid, Google Scholar, Access Science, Web of Science, and JSTOR Search.
Our literature review shows that accumulation of radionuclides can lead not only to increased mortality and morbidity rates, but also to changes in reproductive and developmental patterns as well as alterations in the genetic makeup. We have also found three papers that provide strong evidence that radionuclides can be passed across the trophic levels and in turn impact the entire food chain. Furthermore, there are indications that migratory aquatic organisms can introduce trace radiation into food webs in an unaffected area.
Nowadays, this topic is of great significance due to the Fukushima Daiichi nuclear accident that occurred during 2011 in Japan. Our literature review shows that radiocesium (^{134}Cs and ^{137}Cs) levels in the tissue samples of Pacific bluefin tuna (*Thunnus orientalis*) after the Fukushima accident were 10 times greater when compared with measurements taken before the accident.
Greater emphasis in future research should be placed on this issue as the release of radionuclides can have a long-lasting impact on global fish populations.

Keywords Radionuclides, bioaccumulation, migration, food chain, trophic transfer

1. Introduction
1.1 Background
The rise in oil prices and mounting concerns about greenhouse gas emissions have prompted many countries to rely more on nuclear power. Nuclear power is an emission-free source of energy, but at the same time it creates as many environmental problems as it solves [1]. Radioactive waste is a by-product of nuclear power generation in addition to other usages of nuclear fission. Some of these low-level radioactive materials have been deliberately disposed into water bodies either by discharging low-level liquid wastes or by packaging radioactive wastes into barrels which are then usually released into oceans [2, 3]. The disposal of radioactive materials into aquatic environments in turn leads to accumulation of radionuclides (also called as radioisotopes) in water, sediments, and food chains [4]. Bioaccumulation of radionuclides can result in detrimental consequences on fish populations including increased mortality rates, changes in physiology, reproduction, development, as well as changes in the genetic makeup [5]. Disposal of radioactive wastes into marine environments enables the accumulation of radionuclides in phytoplankton which can then be passed down through the trophic levels [6, 7, 8]. It is therefore crucial to examine how radioactivity will be passed down the food chains and examine the impact that radiation may have on different life history stages of fish. Increased prevalence of developmental defects in embryos as well as radiation induced embryo death have been recorded in fish [9].Research on migratory patterns is important as some migratory fish species could potentially introduce trace radiation into food webs in an unaffected area. All the fish species are vulnerable to radiation and the fact that radioisotopes can easily spread as a result of water currents and fish migrations is of concern. The Fukushima Daiichi nuclear disaster that took place in 2011 in Japan has sparked a lot of interest in examining the consequences that large scale release of highly radioactive materials can have on fish populations.

2. Methods

We performed a literature review on the disposal and leakage of radioactive materials on various species of marine and freshwater fish using a number of database sources including: Science Direct, Ovid, Google Scholar, Acess Science, Web of Science, and JSTOR Search.

3. Literature review and Discussion

3.1 Bioaccumulation of radionuclides and trophic transfer between fish species

Radioactive decay half life depends on the element which is released, but the main issue is that the biological hazard of radiation is a long term one because of the accumulation of isotopes that can last for vast periods of time. In other words, radioactive contamination can be passed from one fish species to another and from one trophic level to another. Zotina and colleagues [10] examined the accumulation of radionuclides in the food webs of the Yenisei River at a location close to a nuclear power plant. The research group measured radionuclides in aquatic moss (*Fontinalis antipyretica*), gammarids (*Gammaridae*), dace (*Leuciscus leuciscus*), grayling (*Thymallus thymallus*), and pike (*Esox Lucius*) one year before and three years after the shutdown of the nuclear power plant [10]. The concentrations of most of the radionuclides (^{51}Cr, ^{54}Mn, ^{58}Co, ^{60}Co, ^{65}Zn, ^{141}Ce, ^{144}Ce, ^{152}Eu, ^{154}Eu, ^{239}Np) in dace, grayling, and pike samples decreased three years after the shutdown of the power plant, however the radioactive cesium (^{137}Cs) levels stayed the same as was the case when measurements were taken four years ago[10]. These findings indicate that some radioisotopes have a long half-life and that the effects of radioactive waste release can be documented long after the cessation of the disposal activity. This will be important when discussing physiological changes in fish as some forms of radioisotopes can persist for many generations. Another important piece of information from this study was that pike (a piscivorous fish) had accumulated a higher concentration of radioactive cesium when compared to other two non-predatory fish [10]. This in turn would indicate that biomagnification of radiocesium had occurred in the pike population. From a broader perspective, this data would also seem to indicate that fish at higher trophic levels (such as some piscivorous fish) are more vulnerable to the effects of radiation. A similar study in the same location was conducted in 2016 by Zotina and colleagues [11] in order to determine whether the radiocesium (^{137}Cs) accumulation in pike *(E. Lucius)* was age dependant. The results of the study indicate that the greatest ^{137}Cs content has been found among the juveniles (7 Bq/kg), which is significantly higher when compared with five year old pike (0.5 Bq/kg) [11]. In other words, the concentration of radiocesium in pike muscles and other body tissues significantly decreased with age. The researchers suggest that the high concentration of radiocesium among juveniles is most likely the result of greater intensity of feeding when compared to older individuals [11]. A study by Kryshev [12] from 1995 came with similar results after investigating the dynamics of radioactive contamination of aquatic ecosystems as a result of Chernobyl nuclear disaster. The samples were taken from the Chernobyl Nuclear Power Plant cooling pond which absorbed high doses of radionuclides after the accident. The researchers compared the difference in the radiocesium (^{137}Cs) accumulation for predatory and non-predatory fish species. In the non-predatory species (carp (*Cyprinus carpio*), silver carp (*Hypophthalmichthys molitrix*), and silver bream (*Blicca bjoerkna*)) it was determined that highest concentrations of radiocesium (140 kBq/kg of fresh weight) were found in 1986, the year of the accident [12]. On the other hand, for the predatory species (pike (*E. Lucius*), pike-perch (*Sander lucioperca*), and perch (*Perca fluviatilis*)) the highest concentrations of radiocesium (200 kBq/kg of fresh weight) was recorded in 1987-1988 [12]. This data provide strong evidence that the effect of trophic levels could have played a role as the predatory species accumulated highest concentrations of radiocesium 1-2 years after the accident. This is exactly how the researchers interpreted the data and to further back up their findings they determined that the highest radiocesium concentrations for predatory fish exceeded that of non-predatory fish by around 3-10 times [12]. A more recent paper by Doi and colleagues [6] published in 2012 examined the radioactive cesium (^{137}Cs) decay in fish in order to determine whether there was correlation between trophic position and metabolic rate in regards to decay process. While their work focuses more on the radioactive decay portion, the paper does yield valuable information as to how fish can accumulate radioactive isotopes. Based on these information we can then determine which species are more vulnerable and this can lead to implementation of conservation measures if possible. Doi and colleagues [6] examined the radiocesium content in fish species in order to evaluate biological (metabolic rate) and ecological (trophic position, diet type) influences on the decay process. They determined that the maximum radiocesium concentration in various species of fish found in freshwater systems was correlated with the trophic position and that fish accumulate radioceisum mostly from their diets and insignificantly from the surrounding water [6]. Once radiocesium is added into an ecosystem, the concentration of radiocesium increases first in primary producers and then transfers up the food chain. Fish species at the top of the trophic level are usually targeted by the fisheries and therefore this can pose a risk for humans as well [13]. The study by Doi and colleagues [6] also determined that environmental temperature of water in addition to metabolic rate can be used to estimate the half-life and decay rates for fish species. These studies highlight the importance of trophic relationships and provide biologists with vital information.

3.2 Spread of radioisotopes by the migratory patterns of fish

Focusing on the migratory patterns is important as some migratory fish species could potentially introduce trace radiation into food webs in an unaffected area. This is particularly problematic if the fish that are exposed to radiation are part of the diet of some larger fish species that were not initially exposed. Fish migrations of course are not the only mechanism of radioisotope transfer, however as mentioned in the study by Doi and colleagues [6], fish accumulate radiocesium (radioisotope) mostly from their diets and not from the surrounding water. Therefore, fish migrations should be considered whenever radioactive waste disposal or leaks take place in water bodies. The nuclear disaster that took place at the Fukushima Daiichi Power Plant resulted in the release of large quantities of various radionuclides into the ocean waters. A study on Pacific bluefin tuna (*Thunnus orientalis*) was conducted by Madigan and colleagues [14] shortly after the accident in order to determine whether Pacific bluefin tuna (PBFT) act as vectors for the transport of radionuclides between Japanese waters and the waters around California. It is important to note that the PBFT is a migratory fish that spends most of its life in either the western or eastern side of the Pacific Ocean. Additionally, PBFT tend to spawn in the Japanese waters with the majority of the juveniles then usually migrating towards the Californian waters of the Pacific Ocean [14]. The research group caught the migratory juvenile PBFT in the San Diego region and examined whether there is an existence of Fukushima derived radionuclides. All of the samples that were collected in California contained radiocesium (^{134}Cs and ^{137}Cs) levels that were approximately 10 times greater in 2011 when compared with measurements taken before the accident [14]. It is worth mentioning that growth and radioactive decay occurring during the migration period facilitated the lowering of radiocesium levels and that is why radiocesium levels were significantly lower in Californian waters when compared to Japanese ones [14]. This would indicate that while dilution of radionuclides across long distance migrations is possible, nevertheless migration seems to be a potent vector for the transport of radionuclides. The problem with radioactive substances is that they have a long half-life and therefore long migration times have minimal impacts on the overall concertation of the radioisotope. As already mentioned, the other main issue is that spread of radionuclides can occur particularly if the radiation exposed fish is part of the diet of an unexposed fish. Similar results were obtained in a study by Sazykina [15] from 1998 that looked at radionuclide transfer by migrating fish in the Barents Sea. While this study is relatively old, it is also unique since the Barents Sea was the site of radioactive waste disposal of highly radioactive objects such as reactors of decommissioned Soviet submarines. The Barents Sea is known for its productive fishing areas and it harbours a wide range of fish such as cod (*Gadus morhua*), herring (*Clupea harengus*), capelin (*Mallotus villosus*), etc. [15]. In the wake of the Fukushima accident another study was conducted by Neville and colleagues [16] on the Pacific albacore (*Thunnus alalunga*) that are famous for being able to complete long distance migrations across the Pacific that may bring them to the seas around Japan. The researchers wanted to determine whether there would be trace amounts of radionuclides detected on these migratory fish [16]. Some of the Pacific albacore samples were collected in the years prior to the accident and some only a few months to a year after the accident which was just enough for some species from Japan to migrate back to west coast of United States [16]. The albacore samples taken in the west coast of U.S. after the accident show increased levels of radiocesium when compared to the years before the accident [16]. Most of the samples taken in the months following the accident had greater concentrations of ^{137}Cs (234–824 mBq/kg of wet weight) and ^{134}Cs (18.2–356 mBq/kg of wet weight) when compared with all pre-accident samples that had lower ^{137}Cs concentrations (103–272 mBq/kg of wet weight) in addition to no detectable ^{134}Cs activity[16]. Another study by Arai [17] from 2014 looked at freshwater and anadromous salmon (*Oncorhynchus keta*) in order to determine whether the radiocesium concentrations were similar or dissimilar between the two. In other words, freshwater species of salmon in Japanese rives that did not make extensive migrations were compared with anadromous salmon (migratory) for radiocesium levels that were released from Fukushima Daiichi power plant. Salmon was probably chosen to be the study organism as many of them migrate from freshwater into oceans where they feed/grow and eventually return back to freshwater to spawn. Radiocesium concentrations were substantially lower in anadromous salmon when compared to freshwater salmon [17]. Freshwater salmon had a considerably greater accumulation of ^{134}Cs (25.3–40.2 Bq kg−1 in mean) and ^{137}Cs (41.4–51.7 Bq kg−1 in mean) when compared with anadromous salmon that had ^{134}Cs (0.64–8.03 Bq kg−1 in mean) and ^{137}Cs (0.42–10.2 Bq kg−1 in mean) [17]. Arai expected such results since the freshwater and terrestrial habitats were exposed to higher radiocesium levels at the onset of the accident [17]. We should also take into account that oceans are massive water bodies that have the capacity to dilute some of the radioactive inputs as opposed to freshwater bodies that do not have such dilution capacity. Overall, four different studies were examined above with each study yielding unique results. These studies also confirmed the predictions that fish migrations are a major determinant when it comes to radionuclide transfer. Radionuclide transfer by fish migrations should therefore not be neglected as it is a possible source of transport of various radionuclides across long distances.

3.3 Physiological changes in fish as a result of exposure to radionuclides

Disposal or leakage of radioactive materials usually consists of various forms of materials that emit ionizing radiation. In general ionizing radiation can induce changes in the DNA by producing lesions and if these lesions are not repaired then mutations may arise [18]. Radiation induced mutations have been documented in several species of fish, but most of these have been recorded in laboratory settings [19]. Nevertheless, these laboratory data are a good starting point to look at in order to have a broader understanding of effects of radiation on fish. Fish populations exposed to radiation in laboratory settings have developed a number of physiological and developmental changes including: reduction in larval survival, depletion of spermatogenesis and sterility, decreased immune response, increased incidence of anomalies, etc. [19]. Additionally it was found that radioisotope accumulation in fish directly influences their life cycle, metabolic characteristics, feeding, and spawning habitats [20]. Here we will present the literature on the reproductive and developmental consequences associated with exposure to radionuclides. Belova and colleagues [21] examined several species of fish in order to determine the state of their reproductive systems as a result of exposure to radionuclides that were released from the Chernobyl accident. Fish samples were collected from different water bodies (water cooler (lake) of the power plant, Lake Glubokoe, Kiev Reservoir, and Teterev River) with each having different concentration of radionuclide pollution [21].The goal of this study was to determine the percentage of fish that developed abnormalities of sexual cells and gonads in the listed water bodies during a time period from 1992-2004 [21]. The results from this study indicate that the least polluted water bodies with the smallest amounts of radionuclides housed fish with lower degree of anomalies in their sexual cells and gonads [21]. This study confirms that greater doses of radiation are more likely to induce harmful stimuli on the genetic makeup of fish reproductive systems. A study from 2011 by Simon and colleagues [22] has found that fish in water bodies that have been contaminated with heavy metals may develop reproductive abnormalities in any life history stage. The study objective was to analyse dietary uranium isotope consumption in zebrafish (*Danio rerio)* and its potential consequences on reproduction and embryonic development [22]. High levels of uranium isotopes were recorded in the gonads of zebrafish [22].High uranium isotope concentrations were found in the eggs as maternal transfer of radioisotopes is possible and this has major implications as this may impact their reproductive success [22]. The researchers were able to measure reproductive success and what they found was that uranium isotope exposure reduced the overall number of eggs by around 50%, while the viable eggs were classified as low quality [22]. This study points out that radioisotopes at high enough concentrations can directly impact the reproductive success of a fish species. Exposure to radioisotopes can be particularly problematic for species that produce only a few eggs in the case that the total number of eggs is reduced by 50%. Dramatic decline in recruitment is also predicted as the spawning fish will produce low numbers of low quality recruits. In terms of recruitment, it can also be expected that the number of recruits will fall well below the carrying capacity of the population. A study by Sazykina and Kryshev [23] from 2003 examined the long-lasting effects of low doses of radiation in fish by observing three main parameters that include morbidity, reproduction, and mortality. This study examined each of the three parameters separately and provided comprehensive information related to the physiological changes associated with exposure to radiation. It is important to note that exposure to a radioactive source results in a deterioration of health due to changes in physiological and metabolic parameters. Radiation exposure can lead to deleterious alterations in the blood composition of fish which in turn leads to a weakening of the immune response to microorganisms [23]. White blood cells are particularly sensitive to radiation and exposure usually leads to a decline in the number of immune cells that are crucial for providing immune protection [23]. For example, parasite infections are very common in fish that have weakened immune systems as a result of constant low radiation exposure [23]. We have already talked about the effects radiation can have on reproduction/development and the immune system, however exposure to radiation can also lead to decreased life expectancy and fish mortality. At low doses there is no observable increase in fish mortality, but life shortening may occur predominantly in long lived fish species [23].At higher doses there was a detectable increase in mortality usually associated with the weakened immune system that resulted in increased susceptibility to parasite infections [23]. Study by Sazykina and Kryshev [23] indicates the importance of the immune system in fish that can be compromised by exposure to radioactive materials. Recent research indicates that disease is the main cause of mortality in fish especially in the early life history stages [24]. The immune system is there to protect the fish from invading microorganisms, but problems arise when immunity is compromised due to radiation exposure. Another important question to ask is whether the effects of radioisotopes are more pronounced in smaller or bigger fish. Size matters in all species and is a major determinant of almost all physiological processes. A study conducted by Schulte [25] in 1997 examined whether radiocesium uptake had any relation to the weight of plaice (*Pleuronectes platessa*). The results of this study have shown that small plaice absorb significantly higher concentrations of radiocesium per gram of body weight as opposed to bigger plaice [25]. A study by Smith and colleagues [26] from 2002 found similar results as it documented that there is a correlation between body size and radiocesium content in fish. This information is essential for the management and conservation of fisheries that may have been impacted by radioactive pollution. Smaller animals are known to have higher metabolic rates and hence further research is needed in order to determine whether accumulation of radionuclides is tied to metabolic rate. Studies from Japan after the Fukushima accident indicate that excretion rates of radionuclides are actually greater in younger fish as opposed to older age categories [27]. Metabolic rate and diet in different age categories could be the factors that play a role in deciding the excretion rates of radionuclides.

4. Conclusion and Future Directions

Release of radioactive materials into water bodies affects the entire aquatic ecosystem including different fish species. A number of studies have shown that accumulation of radionuclides in fish can disrupt their physiological, reproductive, and developmental parameters as well as lead to changes in their genetic makeup. Furthermore, trophic interactions can play a major role in accelerating the spread of radioactive contaminants and the entire food webs may be affected. Large predatory fish species on the top of the food chain have been found to contain high concentrations of radioisotopes. Commercial fisheries tend to focus on the largest available fish species and this in turn may impose a risk on the human populations as well. Furthermore, migratory fish species could potentially introduce trace radiation into food webs in an unaffected area. Some of the radionuclides that may be released have a long half-life and can persist in the water for many years. This means that the release of radioactive materials into water bodies can cause long lasting impacts. Radiation has both mutagenic and teratogenic effects and hence particular attention should be given to see whether there will be an increased incidence of reproductive, developmental and any other physiological abnormalities. We hope that a greater emphasis will be placed on this topic in the future as it is evident that there is a lack of literature on this topic.

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