Journal of
Plant Ecology

Perspective

Uncharted effects of Fukushima Nuclear Plant Wastewater Discharge on marine life

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Handling Editor: Wen-Hao Zhang

Received: 16 December 2023, **First Decision:** 29 December 2023, **Accepted:** 19 January 2024, **Online Publication:** 24 January 2024

INTRODUCTION

On 24 August 2023, the Japanese government insisted on initiating the discharge of Fukushima nuclear-contaminated water into the sea, causing widespread global concerns regarding marine biological safety, seafood and marine resources (TEPCO 2023). Although the Japanese government has consistently emphasized that the nuclear wastewater has been treated using an Advanced Liquid Processing System (ALPS), resulting in very low concentrations of various nuclear elements, and that the International Atomic Energy Agency (IAEA) has conducted real-time monitoring of the treatment process and discharge flow (IAEA 2023), people around the world still harbor significant concerns. Here are a few reasons for this ongoing apprehension.

SOURCE OF FUKUSHIMA NUCLEAR WASTEWATER

The nuclear wastewater originated from the nuclear accident at the Fukushima Daiichi Nuclear Power Plant (FDNPP) in Japan, which occurred on 11 March 2011, following a 9.0 magnitude earthquake and subsequent tsunami (Normile 2021). At the time of the earthquake, Units 1–3 of the FDNPP were in operation. The seismic activity automatically shut down the fission reactions in the reactors, but it also caused a failure in the power supply, rendering the water pumps unable to function. This led to the inability to inject cooling water into the reactor core and spent fuel pools, resulting in the melting of fuel rod cladding. The fuel particles fell to the bottom of the reactor pressure vessel, causing core meltdown and damage to control rods. Ultimately, explosions occurred, severely damaging the reactor buildings and surrounding facilities (Normile 2021). The wastewater discharged from the Fukushima nuclear power plant contains radioactive isotopes from the melted fuel, which sets it apart from the wastewater typically released by conventional nuclear power plants. Initially, the plant's owner, Tokyo Electric Power Company (TEPCO), denied and concealed this fact multiple times. However, they eventually admitted to it. Since then, the amount of nuclear wastewater has steadily increased (TEPCO 2023).

RADIOACTIVE SUBSTANCES IN THE FUKUSHIMA NUCLEAR WASTEWATER

The IAEA conducted a detection of the concentration of radionuclide ^{3}H in the Fukushima wastewater being discharged into the ocean. Even after dilution with seawater, the radioactivity of tritium still reached 207 Bq per L, exceeding Japan's set standard of 100 Bq per L (IAEA 2023). Tritium, as a highly difficult-to-remove isotope, primarily exists in the form of tritiated water. Once it enters the ocean, tritium directly integrates into the marine ecosystem and rapidly affects the entire ecological environment (Buesseler 2020). However, the low-energy beta particles released by tritium have virtually no harmful effects on living cells. Therefore, tritium has the lowest dose coefficient and higher allowable release limit among the radioactive isotopes in contaminated water. However, the enormous total amount of ^{3}H (approximately 1 PBq, amount to 10^{15} Bq) in these contaminated waters may still pose potential harmful impacts, regardless of its properties (Buesseler 2020). In fact, existing research reports that more than 60 radioactive substances have been detected in the Fukushima nuclear wastewater, such as ^{106}Ru, ^{60}Co, ^{90}Sr, ^{137}Cs and ^{131}I (Buesseler 2020). Some of these radioactive isotopes, such as ^{137}Cs and ^{131}I, are relatively volatile fission products that can be released into the atmosphere (Yoshida and Kanda 2012). These particles have the ability to adhere to both the leaves and stems of plants, as well as bind firmly to clay minerals in the soil, resulting in their prolonged retention in the terrestrial ecosystems. Eventually, they can enter groundwater through rainfall and flow into the ocean (Fig. 1). The half-life of ^{131}I is approximately 8 days, indicating rapid decay, while the half-life of ^{137}Cs is much longer,

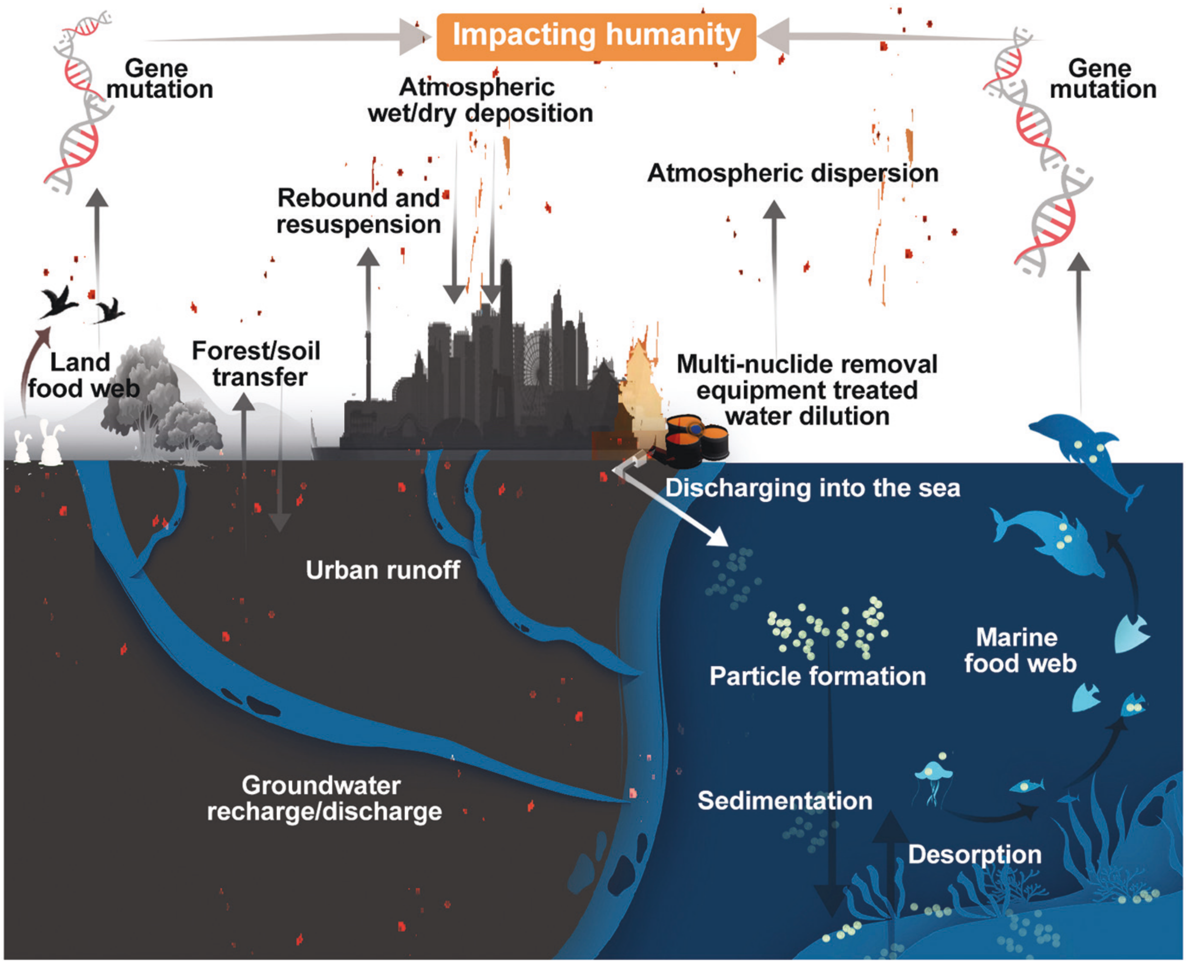

Figure 1: The long-term effects of low-dose radionuclides after the discharge of Fukushima nuclear wastewater on the evolution of marine organisms have not been reported or evaluated. It has been reported that Fukushima's nuclear wastewater contains over 60 types of radioactive substances, including ^{106}Ru, ^{60}Co, ^{90}Sr, ^{137}Cs and ^{131}I. Among them, certain radionuclides, such as ^{137}Cs and ^{131}I, emit volatile fission products into the atmosphere, which can subsequently settle on vegetation and bind tightly with clay minerals in the soil. As a result, these substances are retained in the soil for extended periods and can enter groundwater through rainwater, ultimately finding their way into the ocean (left figure). Conversely, the radioactive elements present in the Fukushima nuclear wastewater can spread more rapidly with ocean currents compared with terrestrial radionuclides. This poses a threat to the evolution and health of marine organisms worldwide, consequently impacting the well-being of humanity as a whole (right figure).

about 30 years. The impact of ^{137}Cs on marine life and human health has not been effectively assessed to date (Tanaka *et al.* 2012).

LONG-TERM EFFECTS OF RADIOACTIVE SUBSTANCES ON MARINE FOOD WEB

The expected discharge of radioactive wastewater from Fukushima is projected to continue for 30 years or even longer. Although the concentration of these radioactive nuclides is low after treatment, the long-term effects of low-dose nuclides on marine organisms and human health are still largely unknown. After the release of radioactive nuclides into the ocean, a portion of them settle on the seabed near Fukushima and enter the seaweeds, subsequently being transferred through the food chain to marine plankton and animals. Another portion disperses to other marine areas through ocean currents and the migratory behavior of marine fish (Fig. 1). During the process of dispersion, dilution can occur, reducing the radioactivity levels in fish as a result of both their growth and the decay of radioactive nuclides, ultimately leading to a decrease in radioactivity levels in the outer marine areas. However, the long-term migration has little impact on the accumulation of certain nuclides with longer half-lives, such as ^{137}Cs and ^{90}Sr. Due to their long half-lives, the ionizing radiation produced by trace amounts of these nuclides may be introduced into other marine areas through migratory organisms like fish and persist for a long time (Fisher *et al.* 2013). Highly migratory marine species, such as tuna, can carry radioactive nuclides across the Pacific Ocean at speeds that exceed those of wind or ocean currents (Madigan *et al.* 2012). Additionally, marine fish primarily accumulate radioactive nuclides through ingestion (Fig. 1), which is particularly evident in benthic fish species (Horiguchi *et al.* 2018). For example, among various large benthic animals, the activity concentration of ^{137}Cs in fish is significantly higher than in invertebrates (Horiguchi *et al.* 2018), and benthic fish have higher ^{137}Cs levels compared with other (pelagic, deep-sea and floating) marine fish (Buesseler 2012). Cesium accumulates in the muscle tissue of fish and exhibits 'delayed accumulation' in higher trophic level fish, indicating the enrichment of radioactive nuclides as they move up the food chain (Fig. 1) (Horiguchi *et al.* 2018), although the concentration factor only slightly increases (Buesseler 2012). The absorption of ^{137}Cs by fish is balanced by excretion back into the ocean, and ^{137}Cs is rapidly lost from fish muscle after exposure ceases, with the loss increasing with fish size and metabolic rate (Buesseler 2012). Therefore, among individuals of the same or similar trophic levels, fish with higher feeding and metabolic rates typically exhibit stronger enrichment of radioactive nuclides. The concentration of radioactive nuclides absorbed per unit body weight is much higher in smaller fish compared with larger fish. Given the high ^{137}Cs content and high loss rate within benthic fish species, the seafloor may be a source of continuous ^{137}Cs contamination in the ocean.

LONG-TERM EFFECTS OF RADIOACTIVE SUBSTANCES ON THE EVOLUTION OF MARINE ORGANISMS

The long-term effects of low-dose radioisotopes on the evolution of marine organisms have not yet been reported or evaluated. These radioactive elements, while accumulating in marine organisms, also increase the risk of radiation exposure, thereby affecting biological evolution (Mousseau and Moller 2014). Biological evolution is the change in allele frequencies of a population from one generation to the next, and genetic mutation and genetic drift are the main mechanisms that affect the occurrence of allele frequency changes in populations (Johnson and Munshi-South 2017). Radioactive isotopes have mutagenic properties and can directly affect the genetic material DNA of cells through ionizing radiation, causing genetic damage such as DNA strand breaks and base mismatches (Møller and Mousseau 2013). For example, after the Chernobyl nuclear accident, people living in contaminated areas experienced cellular abnormalities, increased incidence of thyroid cancer and infant leukemia (Petridou *et al.* 1996); offspring of barn swallows exhibited loss of feather pigment genes and feather whitening, increasing the risk of predation (Ellegren *et al.* 1997). On the other hand, nuclear contamination also strongly affects genetic drift, leading to a decrease in population size and changes in allele frequencies, thus affecting species evolution (Johnson and Munshi-South 2017). Studies have found that bird, butterfly and cicada populations in the Chernobyl and Fukushima areas have experienced increased mortality and reduced population sizes after nuclear accidents (Mousseau and Moller 2014), which greatly alters genetic diversity and has negative effects on biodiversity. Compared with terrestrial radioactive elements, the release of radioactive elements from the Fukushima nuclear wastewater into the ocean spreads more rapidly with ocean currents, posing a threat to the evolution and health of marine organisms worldwide, and thus affecting our human well-being (Fig. 1).

OUTLOOK

Marine organisms and resources are a common wealth for all humanity. The ocean plays a crucial role in the biogeochemical cycles of the Earth. The discharge of radioactive elements from the Fukushima nuclear wastewater into the ocean can lead to the spread of radioactive nuclides, causing long-term unknown effects on the evolution and health of marine organisms, ultimately impacting human well-being. Based on this, I propose the following initiatives: (i) Continuous monitoring of radioactive elements in the nuclear wastewater discharged from the Fukushima nuclear power plant is essential, as it allows for close tracking of changes in ocean currents and dynamic sources and sinks of radioactive nuclides within atmospheric circulation over the long term. (ii) As the direct victims of the nuclear wastewater discharge, neighboring countries, Pacific island nations, fishing communities, environmental organizations and other stakeholders should allow scientific supervision of radiation monitoring by scientists and institutions from neighboring countries to ensure the authenticity and accuracy of monitoring data. (iii) Relevant institutions and research departments should conduct long-term monitoring and assessment of the ecological changes following the discharge of nuclear wastewater, ensuring the relative stability of marine ecosystems, forests, farmland and other ecosystem functions and services. (iv) Improvements should be made to ocean current models and atmospheric circulation models by incorporating radioactive nuclides, enabling the simulation and prediction of dynamic changes in radioactive elements in the future, providing reliable data support for policy-making.

Funding

The research was supported by the National Natural Science Foundation of China (32171635).

Conflict of interest statement. The authors declare that they have no conflict of interest.

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