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The risks of radioactive wastewater release

The wastewater release from the Fukushima Daiichi nuclear plant is expected to have negligible effects on people and the ocean

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In 2011, the east coast of Japan suffered an earthquake and tsunami that resulted in the meltdown of three of the reactors at the Fukushima Daiichi nuclear plant. This led to an uncontrolled release of large amounts of radioactive material to the surrounding land and to the Pacific Ocean. More than 10 years later, new releases of radioactive wastewater to the Pacific Ocean from the Fukushima plant have started. The historical ocean contamination from Fukushima included large quantities of long-lived radioactive cesium-137 (^{137}Cs), so there is widespread concern over these new wastewater discharges. However, these releases will result in much lower total radiation doses to people and aquatic ecosystems than the contamination caused by the accident (*1*–*3*). Furthermore, aquatic ecosystems, including those around the Chernobyl disaster site, have been shown to be remarkably resilient to radiation (*4*–*7*). Thus, the new Fukushima releases are not expected to cause substantial effects on seafood consumers or the marine ecosystem.

The highest-activity radioactive contaminant in the Fukushima wastewater is tritium (^{3}H), in the form of tritiated water (HTO). This molecule cannot be separated from the wastewater because its chemical behavior is the same as that of nonradioactive water. Like other radionuclides [such as natural carbon-14 (^{14}C) and anthropogenic ^{137}Cs], which emit high-energy γ rays and β particles when they decay, tritium can have biological effects on organisms, particularly DNA damage (*8*). But tritium's radiotoxicity by ingestion is very low compared to that of these other radionuclides owing to its very weak β emission and relatively short retention time in the body. Therefore, it is common practice for nuclear facilities worldwide to discharge wastewater containing HTO into the sea (see the figure).

The La Hague nuclear facility in France annually discharges ~10,000 terabecquerels (1 TBq = 10^{12} Bq; the becquerel is an amount of a radioactive element that produces one decay per second) of HTO into the English Channel, with annual discharges during 1996–2016 ranging between 8000 and 12,000 TBq (*9*). Radiation doses to people (in sieverts, the amount of energy deposited in tissue, taking account of the response of human biology to different radiation types) from the release of HTO from La Hague are low (<0.01 microsieverts per year (μSv/year) (*9*), which compares with the 1000 μSv/year recommended limit for members of the public from nuclear site releases (*2*)], and no environmental impacts have been found or are expected. For example, studies of fish (fathead minnow, *Pimephales promelas*) exposed to levels of HTO between 7700 and 21,900 Bq/liter in a river near a Canadian nuclear site (compared with <50 Bq/liter in seawater near La Hague) have indicated that it can induce DNA damage (as measured by comet assay), but no effects were observed on the survival of fish or various indices of health (*10*).

At Fukushima, 22 TBq of HTO per year will be released (*1*, *2*), which is a factor of ~450 less than that from La Hague per year. The planned Fukushima discharge annual limit is the same as when the facility was an operational electricity-generating boiling water reactor (BWR). Less tritium is produced in a BWR than in

other types of nuclear reactor, so the limit was originally set to be low compared with that of some other reactor types. The very low release limit for the Fukushima wastewater was selected by the Japanese government owing to societal concerns such as the reputational impact on the local fishing industry. The planned releases will therefore take much longer, ~30 years, than strictly necessary according to current radiation safety recommendations.

There will be radionuclides other than tritium in the Fukushima discharge. The wastewater has been treated by passing it through a series of columns in which ion-exchange chemical reactions remove most of the radioactive elements that the wastewater contains. It will be treated again before release if radiation levels are higher than the discharge limits. But tiny amounts of 30 other radionuclides remain after treatment, including ^{14}C, ^{60}Co, ^{90}Sr, ^{137}Cs, and Pu isotopes (*1*, *2*). In this regard, the Fukushima release is no different from routine releases from other nuclear sites around the world. For example, in 2019, the Sellafield nuclear site in the UK discharged 19 times more HTO, 1600 times more ^{14}C, 320 times more ^{60}Co, 180 times more ^{129}I, and over 1000 times more ^{90}Sr, ^{137}Cs, and Pu isotopes (*1*, *11*) than is planned annually for the Fukushima release. In 2019, increased radiation doses to seafood consumers near Sellafield were low and mainly due to historical discharges of natural radioactivity from a nearby non-nuclear site that produced phosphoric acid using uranium-rich phosphate ores, with the nuclear site contributing about a third of the dose of the phosphoric acid manufacturer (*11*).

During discharge, the Fukushima wastewater is diluted 100 times so that tritium levels will be 2.5% of the Japanese Government regulatory limit and the sum of the 30 other relevant radionuclides will be less than 1% of the limits. The planned maximum 1500 Bq/liter of tritium in the discharge water is ~14% of the 10,000 Bq/liter that the World Health Organisation designates as the drinking water limit for tritium (*12*).

Monitoring will take place to ensure that the levels of radiation in the Fukushima releases are below the regulatory limits (*1*, *2*). This includes analyses of the wastewater for all 30 radionuclides present, including tritium, total α and β radiation, and the energy spectrum of γ-emitting radionuclides. The process will be independently verified by the International Atomic Energy Agency (IAEA) by measuring wastewater, seawater, and aquatic organisms near the 1-km-long offshore discharge pipeline during the entire ~30-year discharge period (*2*). Since the first release began on 24 August 2023, publicly available information from Tokyo Electric Power Company (TEPCO), the IAEA and the Japanese Ministry for Agriculture, Fisheries and Food, reveals that tritium levels are negligible within 3 km of the site. Of 251 seawater measurements taken by 13 September at 10 sites within 3 km of the Fukushima plant, only one (10 Bq/l) is above the detection limit of ~8 Bq/l. No detectable tritium has been found in 25 fish at two sites 4-5 km North and South of the discharge point (limit of detection ~8 Bq/kg). Tritium is likely to be detectable by more sensitive methods and when releases are higher than that of the first batch release (~200 Bq/l of tritium).

Concerns have been expressed about biomagnification—the increased concentration of pollutants in organisms—of tritium and its potential detrimental effects on marine life, but these concerns do not correctly reflect the risk. If, as planned, tritium is released in the form of HTO, it cannot biomagnify because its biological uptake and distribution follow that of the greater mass of water (13), which does not biomagnify. This lack of biomagnification is due to the chemical similarity of HTO and H_2O, which means that the ^{3}H:^{1}H ratio remains essentially unchanged in chemical and biological processes (*13*). Indeed, this is the very reason that HTO cannot be separated from ordinary water by Fukushima's water treatment facility. Tritium can be retained longer in organic molecules (and thus in organisms) as organically bound tritium (OBT) (*8*) when HTO is digested by aquatic organisms. But even assuming long exposure times, the radiation dose rates are

vanishingly small.

Radiation doses of tritium and the 30 other radionuclides in the treated Fukushima wastewater have been calculated by independent researchers (*3*) and the IAEA (*2*) using models that include dispersion in water, biomagnification, the different radiotoxicities, and longer retention times in organisms. These calculations result in very low dose rates (measured in energy deposited in tissue, Gy) to organisms from all radionuclides in the release: <0.005 μGy/hour (*3*) and <0.0001 μGy/hour (*2*). These levels are below the 40 μGy/hour dose rate that is considered to be the limit at which no ecosystem effects from damage to animal and plant tissues occur (*15*).

Aquatic ecosystems are surprisingly resilient to radioactive pollution because of the relatively high doses that are required to damage an organism's development and reproduction. Studies in lakes near Chernobyl and Fukushima found no effect of radiation on aquatic invertebrate abundance and diversity (*7*), or on developmental and genetic indicators (*4*, *5*). In perch (*Perca fluviatilis*), a slight delay in maturation of female gonads was associated with radiation levels in lakes at Chernobyl, but no effects were seen in roach (*Rutilus rutilus*), and fish condition indices were no different from those of uncontaminated lakes (*6*). Moreover, the fish population in the most contaminated lakes is diverse (*6*). Radiation dose rates in waterbodies at Chernobyl are more than 1000 times higher than those expected from the Fukushima discharges (*3*, *6*).

Radiation doses from the radioactive isotopes in the planned Fukushima releases to people, through all potential pathways including seafood consumption and bathing, are calculated to be less than 1 μSv/year (*2*, *3*). This is a factor of >2000 less than the 2400 μSv/year global average radiation dose from natural background radiation. Risks from natural radiation primarily result from DNA damage by internal exposure to α and β radiation and to γ radiation originating inside or outside the body. So, the mode of action of naturally occurring radiation can be compared to that of the radioactivity from Fukushima. Natural radiation doses vary widely—millions of people worldwide receive doses >10,000 μSv/year. Current radiation protection models assume that any extra dose could potentially cause cancer, because all ionizing radiation could damage DNA. But a radiation dose of less than 1 μSv/year from the Fukushima release is not expected to have any public health consequence compared with, for example, natural radiation.

The impact of the Fukushima releases on the Pacific Ocean can also be understood by considering radioactivity in the natural environment. There is ~860 TBq of tritium in the Fukushima storage tanks, with 22 TBq discharged to the Pacific Ocean every year. The Pacific Ocean currently contains 500,000 TBq of natural and 2,500,000 TBq of anthropogenic tritium, the latter almost wholly from past atmospheric nuclear weapons testing. Furthermore, all tritium contributes just 0.04% to the total radioactivity of 8 billion TBq in the Pacific Ocean, where most radioactivity is due to naturally occurring potassium-40 (91%) and rubidium-87 (8.6%). It is important to note that there has long been awareness of radioactivity in seawater, but this has not been considered a health hazard.

Fears of radiation are likely to damage the livelihoods of Fukushima's fishing community, who are still recovering from fishing bans and reputational damage caused by the 2011 accident. To protect marine environments in the best possible way, resources and attention should be focused on key stressors including climate change, overfishing, and plastic pollution. The radiation protection science is clear that the Fukushima wastewater release presents no real threat to the organisms of the Pacific Ocean or to Fukushima's seafood consumers if carried out as planned. Any substantial deviation from the release plans would quickly be noticed by monitoring. Governments and researchers from elsewhere are also expected to closely monitor radi-

oactivity in the Pacific Ocean during the release. The planned release at Fukushima is likely to be the most closely monitored wastewater discharge from a nuclear site.

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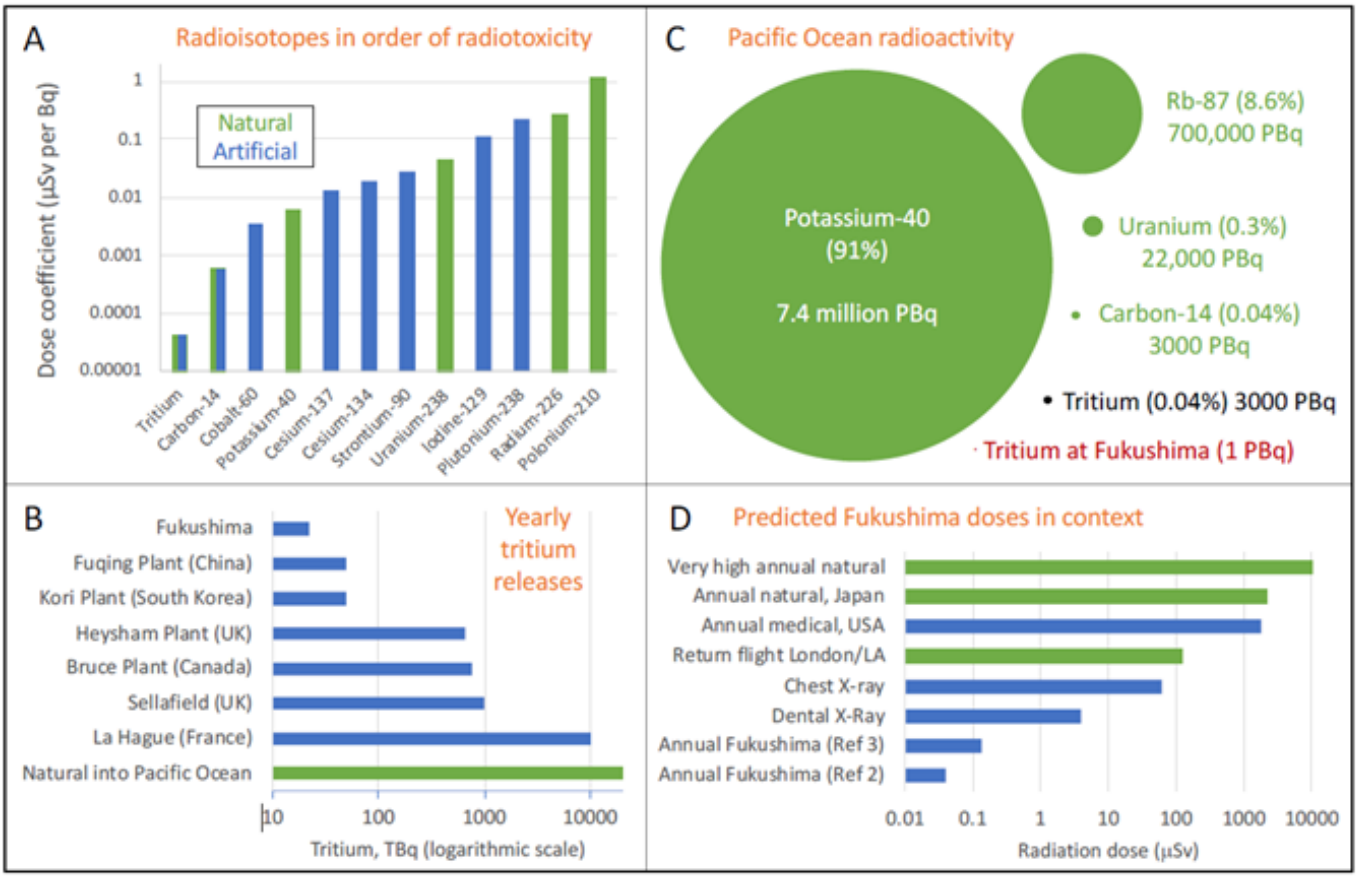

Figure. Tritium at Fukushima placed in context. (A) Some naturally occurring (green bars) and anthropogenic (blue bars) radioisotopes in order of increasing radiotoxicity per Bequerel ingested. Based on dose coefficients from (14). Tritium has an exceedingly small dose coefficient, because its radiation is very weak. (B) Planned annual release of tritium from Fukushima compared with yearly release of tritium at representative nuclear facilities elsewhere in the world. (C) Natural radioactivity in the Pacific Ocean with areas of circles proportional to the total activity in becquerels. Tritium contributes around 0.04% of total radioactivity in ocean water. Planned annual releases at Fukushima of tritium and other radionuclides are too small to be visible at the resolution of the image. Panel (D) shows predicted doses to local seafood consumers following the Fukushima discharge compared to other natural and artificial radiation doses. Note the logarithmic scales in A, B and D. Data in figure assembled from the indicated references and publicly available information from the IAEA, Woods Hole Oceanographic Institute, US Environmental Protection Agency (EPA), Japanese Ministry of Economy, Trade and Industry (METI), the UN Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the International Commission on Radiological Protection (ICRP).