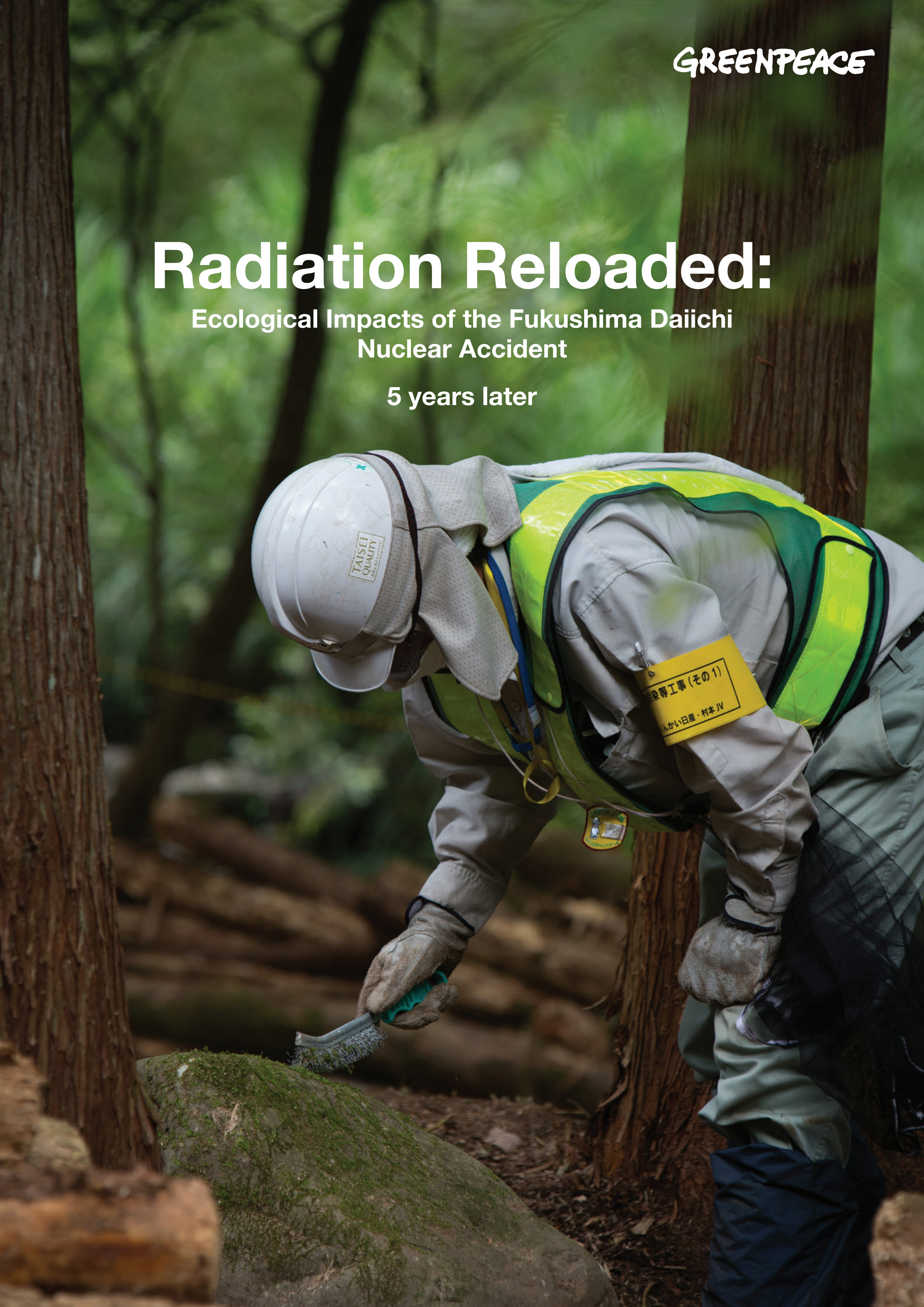
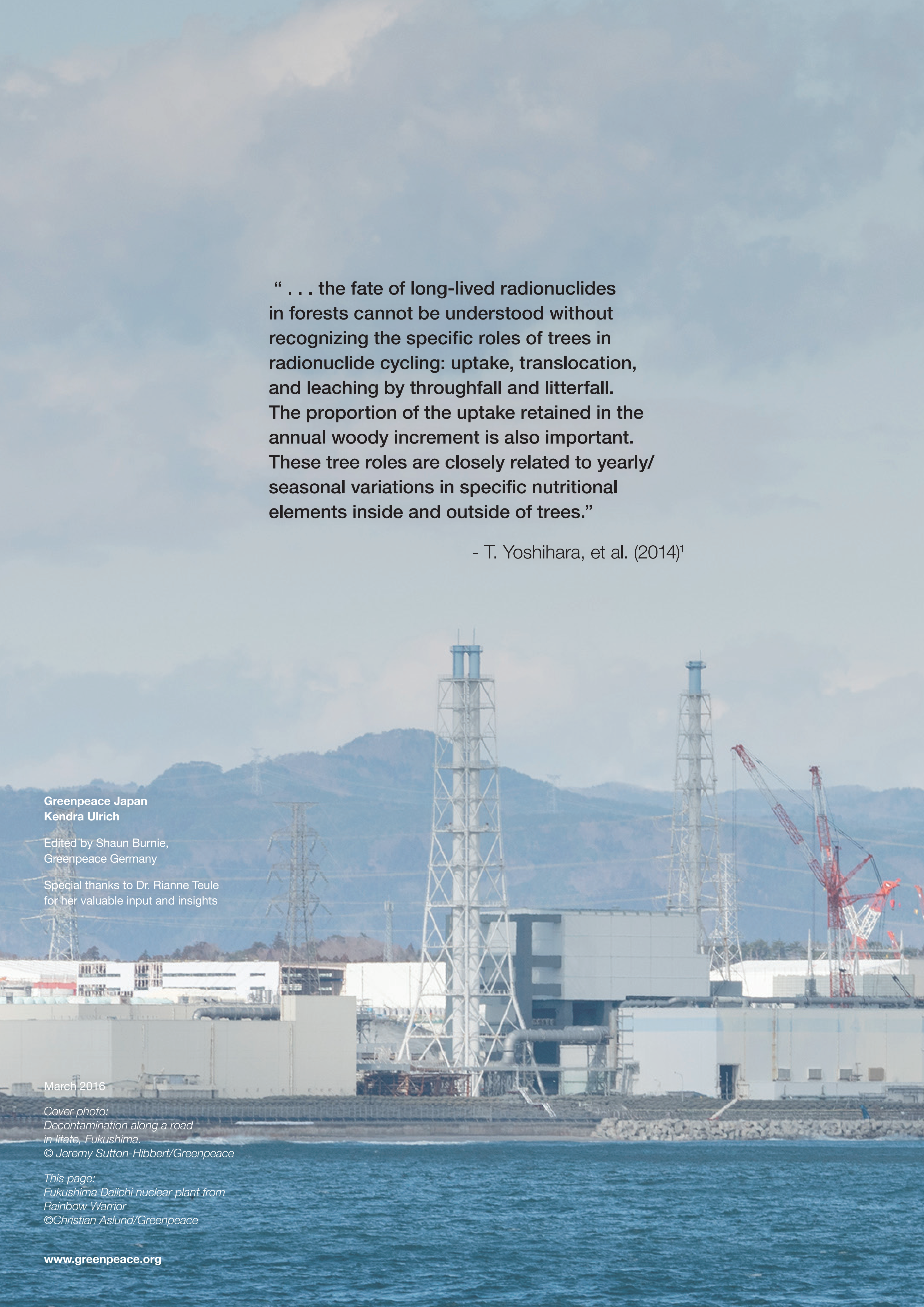
GREENPEACE



Radiation Reloaded:

Ecological Impacts of the Fukushima Daiichi Nuclear Accident

5 years later



> “ . . . the fate of long-lived radionuclides in forests cannot be understood without recognizing the specific roles of trees in radionuclide cycling: uptake, translocation, and leaching by throughfall and litterfall. The proportion of the uptake retained in the annual woody increment is also important. These tree roles are closely related to yearly/seasonal variations in specific nutritional elements inside and outside of trees.”

- T. Yoshihara, et al. (2014)[1]

Greenpeace Japan
Kendra Ulrich

Edited by Shaun Burnie,
Greenpeace Germany

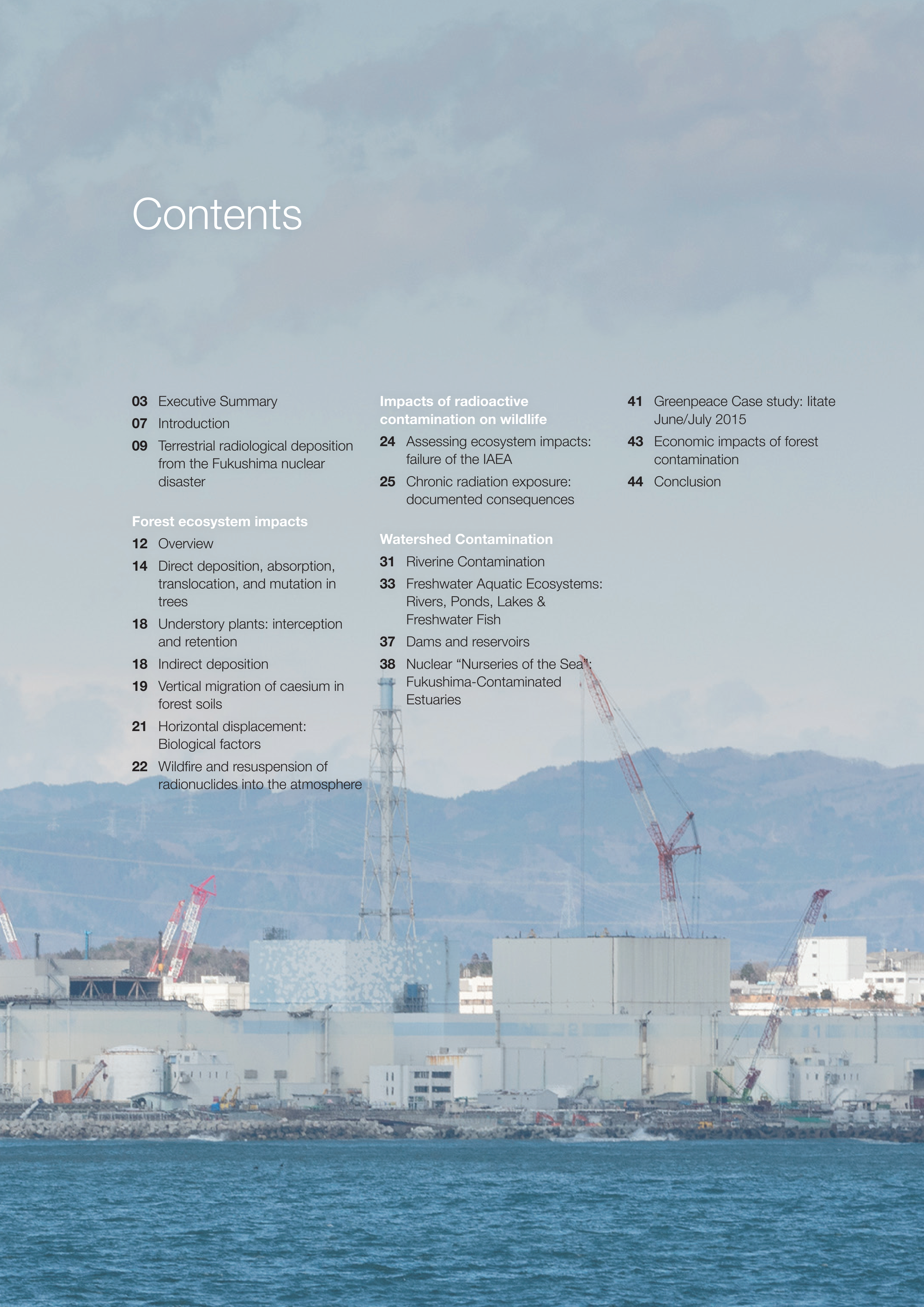
Special thanks to Dr. Rianne Teule
for her valuable input and insights

March 2016

Cover photo:
Decontamination along a road
in Iitate, Fukushima.
© Jeremy Sutton-Hibbert/Greenpeace

This page:
Fukushima Daiichi nuclear plant from
Rainbow Warrior
©Christian Aslund/Greenpeace

www.greenpeace.org



Contents

Forest ecosystem impacts

Impacts of radioactive contamination on wildlife

Watershed Contamination

Mountain streams and rivers transport radioactive particulates and contaminated forest litter downstream, potentially contaminating areas that did not receive fallout, recontaminating ‘decontaminated’ areas, or discharging radioactivity to estuaries and marine ecosystems.
©Robert Knoth/Greenpeace

Executive Summary

“No observations of direct radiation induced effects in plants and animals have been reported, although limited observational studies were conducted in the period immediately after the accident. There are limitations in the available methodologies for assessing radiological consequences, but, based on previous experience and the levels of radionuclides present in the environment, it is unlikely that there would be any major radiological consequences for biota populations or ecosystems as a consequence of the accident.” - IAEA, 2015[2]

This report draws on a large body of scientific research in Fukushima-impacted areas over the past five years to bring to light the current ecological situation as a result of the March 2011 Fukushima Daiichi nuclear accident. It is an attempt to document what is currently known about the radioactive contamination of the forests, rivers, floodplains and estuaries of Fukushima prefecture. Given the long half-lives of some of the radionuclides released into the environment of Fukushima prefecture and wider Japan, understanding their ecological impacts is essential.

This report also draws upon studies of the forest and aquatic ecosystems that were heavily contaminated in the Kyshtym and Chernobyl radiological disasters to provide some insight of what may be expected in the coming years and decades in Japan.

Forest ecosystem contamination

While there have been reductions in radiation levels since the disaster, these are largely expected to bottom out around five years. After that time, both forest and aquatic ecosystems reach a fairly “stable” state of persistent contamination. Further gradual reductions in radiation are largely due to the decay of long-lived radionuclides.

However, it is important to note that according to Chernobyl and Kyshtym studies, in contaminated forest systems there is evidence that there may be a gradual increase in the concentrations of radiocaesium in aboveground plant structures after 5 years, wherein uptake via root systems exceeds returns to the forest floor via leaching and litterfall, until a sort of equilibrium is reached.

The current approach of Japanese authorities to forest decontamination is the removal of leaf litter, soil, and understory plants in 20 meter strips along the roads and around homes that are surrounded by forests. In terms of decontaminating the large areas of Fukushima this approach is futile. Over seventy percent of Fukushima prefecture is forested, which is not possible to decontaminate.

Three of the most concerning radionuclides that are present in the environment as a result of the Fukushima disaster, ^{134}Cs, ^{137}Cs, and ^{90}Sr, behave much like the essential elements of potassium and calcium in the environment. Both caesium-bearing particulates as well as vaporized, water-soluble radiocaesium were released. Water-soluble caesium, which came down as wet deposition with precipitation and fog, is readily absorbed via bark and leaves into the internal tissues of trees. Hot particles appear to weather and leach caesium under natural conditions. In addition, radiocaesium and ^{90}Sr can be absorbed via root systems.

Once absorbed into the internal tissues of trees, ^{134}Cs and ^{137}Cs are translocated with nutrient flows, concentrating in rapidly growing tissues such as new foliar structures, flowers and pollen. Japanese cedar pollen in Fukushima forests appears to have high concentrations of radiocaesium, though calculated doses have shown potential exposures based upon current understandings would be quite low. However, little is known about the concentrations in the most contaminated forests or potential human exposure risks in these areas. High concentrations of radiocaesium in pollen were also found in Chernobyl contaminated forests in the exclusion zone, in Munich, and in flowering herbaceous species in Croatia – in which radiocaesium was found not only pollen, but also in the honey produced by bees foraging these radioactive flowers.

In Fukushima prefecture, timber production has been allowed to continue – except for in the exclusion zones – under the assumption that the removal of the outermost layers removes most of the radiocaesium. This currently appears to be true. However, caesium is not just transferred vertically (roots to canopy and vice versa) but also laterally, which contaminates tree rings formed long before any radiocaesium was present in the environment. Tests of Fukushima-contaminated red pine, oak and Japanese cedar trees showed contamination of bark, sapwood, and heartwood indicating rapid internal lateral translocation – though the highest concentrations were in bark and sapwood.

Executive Summary

While the mechanism for the translocation of caesium to heartwood is not well understood, researchers suggest that this may be due to moisture and potassium concentrations, i.e. higher moisture levels can result in higher potassium concentrations. Since caesium can displace potassium in the materials cycle of trees, the same could be true of caesium. One particularly concerning trait of Japanese Cedar, the most commercially important tree species in Japan, is that it concentrates moisture and potassium in its heartwood – unlike red pine and oak. And indeed, studies of caesium concentrations in Japanese cedar due to fallout from above ground nuclear bomb testing showed that this species had the highest concentrations of caesium in its heartwood. In the future, as more caesium is absorbed via root uptake, and internal translocation of radiocaesium continues, the continued harvesting of this tree species in contaminated forests could be severely impacted. Given that this is the most important timber species, this highlights the need for diligent monitoring of timber products from the prefecture in the coming years and decades.

Japanese fir trees appear to be already showing mutations – i.e. "morphological defects" – due to Fukushima-derived radiation. There is a significant correlation between radiation levels and incidence of a growth abnormality wherein the "leader" shoot is missing – i.e. the new growth each year that allows the straight, vertical growth of the tree and becomes the tree trunk. While it is important to note this abnormality can occur due to other factors, researchers confirmed that incidence of missing leader shoots increased after the Fukushima disaster by examining previous years' growth whorls. Further, incidence of this abnormality among the four test sites increased with higher levels of radiation.

The vertical penetration of caesium into soils is a critically important factor for both bioavailability and external exposure risks. Studies in Fukushima forests show that the vast majority is retained in the upper 0-5 cm of soil, where it is most available to plants and poses the greatest exposure risk. Symbiotic fungal relationships with plant roots can also increase the uptake of radiocaesium, which potentially could include the liberation and transfer of mineral-bound caesium. Due to interception and uptake into the phytomass, it will likely be retained in the surface layers for years and decades to come, as was the case in Chernobyl and Kyshtym contaminated forests.

In addition, according to Chernobyl studies radiological contamination appears to have a negative impact on natural decomposers. This leads to significant accumulations litter. In Chernobyl, this build up of litter due to the impact of radiation has been attributed with increasing the frequency and intensity of forest fires. These fire – particularly crown fires – can resuspend radioactive elements, which are currently sequestered in plant material, into the upper atmosphere in particulates small enough to be inhaled and carried long distances.

While Fukushima has higher levels of precipitation than Chernobyl, and thus fire risks are likely lower, fire hazards still pose the risk of radionuclide resuspension. According to a fire hazard analysis, the prefecture coniferous foothills are at highest risk – though spatial distribution can vary greatly with prevailing conditions. The Fukushima prefectural website states that fires are most likely to occur during the March – May dry season. It also states that 43 wildfires were recorded within the prefecture in 2014, one after another.

Wildlife impacts

Wildlife can also become contaminated from eating contaminated vegetation or eating contaminated herbivores – and thus caesium is passed up the food chain. They contribute to the displacement of radiocaesium via their excrements.

The IAEA has declared that there will likely be no impacts on wildlife from Fukushima-derived radiation – while also admitting that they did not consider ecosystems or populations, but rather focused narrowly on individuals. Further, it states that its methodology was based on that proposed by the International Commission on Radiological Protection (ICRP), whose models are largely based upon individuals in laboratory or controlled environment studies.

However, in recent years the French government-affiliated Institute for Radiological Protection and Nuclear Safety (IRSN), in its studies of wildlife in the Chernobyl Exclusion Zone, has found that animals in these natural conditions could be significantly more sensitive to chronic low-dose exposure to man-made radiation than they are in laboratory or controlled environment experiments. It was suggested that this could be due to a number of factors, including, but not limited to, increased stressors and length of exposure times. In fact, IRSN found that wildlife could be up to eight times in more sensitive in natural contaminated ecosystems.

Executive Summary

The implications could be extensive. It would appear that the traditional methods for assessing wildlife risks are outdated and based on deeply flawed assumptions.

In fact, impacts on wildlife have already been noted in several studies, including mutations in pale blue grass butterflies and gall-forming aphids, as well as DNA damage in earthworms collected in high dose areas.

In addition, a four-year study – 2011 to 2014 – of 57 bird species in the 50 km zone around the Fukushima Daiichi reactor site, found that species abundance decreased in correlation with rising radiation levels. Further, 90% of the birds studied were chronically exposed to levels that could impact their fertility.

Another study, which examined barn swallow nestlings found decreases in juveniles, suggesting reduced fertility. This would be consistent with the findings of the previously mentioned study. Further, studies in Chernobyl-impacted areas have shown decreases in birds' brain size, increased cataract formation, and increases in albinism and tumor incidence in correlation with increasing radiation levels.

Aquatic radiological impacts

It is well understood that foliated trees intercept the majority of atmospheric fallout, and that forest ecosystems act as vast reservoirs for radioactivity. In the initial stage after contamination a portion of the radioactive fallout is rapidly washed off by precipitation into the watershed. The remainder is stored in the catchment for gradual, long-term migration.

Even with low discharge rates from forests to water systems, the redistribution of caesium via watersheds can be significant due to the sheer magnitude of the contaminated forests and land. Fukushima and surrounding prefectures have a number of major and minor river systems that flow from their contaminated upland forests to the Pacific Ocean. These river systems have catchments of thousands of square kilometers.

According to radiocaesium discharge projections for the century between 2011 and 2111, the major rivers whose catchments are primarily in Fukushima prefecture (the Abukuma, Arakawa, Naka, Agano, and Tadami rivers) could discharge as much caesium into the Pacific Ocean as is hemorrhaging from the Fukushima Daiichi plant itself. The Abukuma River alone is projected to discharge 111 TBq of ^{137}Cs and 44 TBq of ^{134}Cs, even with current rates of "decontamination", in the century after the disaster.

The transfer of radiocaesium from land to both freshwater and marine aquatic ecosystems is of particular importance given the potential transfer from the abiotic (e.g. non-living plant material, minerals, etc.) to the biotic systems (i.e., aquatic & marine plant and animal life – including the potential contamination of species consumed by humans).

Riverine contamination

The topography of Fukushima prefecture is characterized by steep slopes, more gradual foothills, and flat coastal flood plains. As discussed above, the upper regions are covered in dense, mature forests and tree plantations – interspersed with rice paddies, homes and other agricultural fields. Its climate is highly erosive, with typhoons in the fall and snowmelt in the spring. During significant rainfall events, typhoons, and spring snowmelt, the stocks of radiocaesium in forests, hillslopes and floodplains can be remobilized and contaminate areas downstream – including those that did not receive fallout from the radioactive plumes, as well as areas that have already been decontaminated.

While the impacts on coastal and marine ecosystems from radioactive contamination are, and will continue to be, significant, freshwater aquatic ecosystems appear to be even more vulnerable. For example, the accumulation of radiocaesium in Fukushima-contaminated freshwater fish is approximately 100 times higher than the concentrations marine fish.

Like in forest ecosystems, the length of time that radiocaesium is present in water systems is greatly influenced by both abiotic and biotic processes. Lake turnover, continual slow leaching from the contaminated watersheds, typhoons and other processes can resuspend contaminated sediment and organic matter – i.e. rather than caesium simply being buried under newer sediments, it can be mechanically remixed by these processes creating secondary contamination. In addition, the contaminated suspended particulates and organic matter brought down from forests and fields with heavy rains and typhoons will create continuing inputs of radiocaesium into lakes and coastal ecosystems for years and decades to come.

Executive Summary

Also similar to forest ecosystems, aquatic ecosystems experience a phase of initial flux up to five years after radiological contamination. After that time, decreases tend to bottom out and thereafter remain fairly stable – with gradual decreases mostly due the slow decay of radionuclides and further fixation of caesium. Thus, nearly five years post-disaster, we may expect the initial declining trends to level out – and the impacts on the aquatic ecosystems, particularly in heavily contaminated regions, to persist for years or decades to come.

It is worth noting that studies of dams and reservoirs in Fukushima-impacted watersheds have been shown to be both sinks for radiocaesium and potential sources. In one study of the Niida and Mano coastal catchments, a large dam in the Mano River played a significant role in reducing the amount of downstream sediments attributable to upstream areas. For the Niida River, 47% of the coastal sediment sampled was attributed to upstream areas, vs. 19% for the Mano coastal sediments.

However, for safe operation in the monsoonal climate of the region, these dams must be opened occasionally. Thus, while dams and reservoirs may play some role in slowing radiocaesium transfer from the heavily contaminated forested mountain regions, or even act as an intermediary radioactivity sinks, these do not present a solution to the problem of significant contributions of radioactive sediments to coastal regions from contaminated river catchments and may, in fact, exacerbate the concentrations during heavy precipitation events.

River Estuaries

Estuaries have often been referred to as the “nurseries of the sea” because of the high productivity and biodiversity found in them. Due to the high nutrient inputs from rivers, and the fact that estuaries are often sheltered from strong coastal currents, many fish, shellfish, and marine animals use estuaries for food and as breeding grounds. In fact, most commercially important fish species spend some point of their life cycle in an estuary. Further, migratory birds frequently use estuaries for resting places during their migrations, and many species of birds rely on these uniquely important ecosystems for food and nesting sites.

The very systems that provide rich nutrients for the abundant life in these ecosystems also make them vulnerable to contamination transported in the river catchments that feed them. Radioactive contamination is no exception.

It’s critically important to understand that only a portion of the suspended caesium-bearing particulates is deposited into sediments once reaching an estuary. Although in most circumstances, caesium forms a nearly irreversible bond to clay particulates, the desorption of caesium from suspended particles with increasing salinity is a well-documented phenomenon. Radiocaesium that is bound to fine particulates is rendered biologically unavailable. These fine particulates that caesium preferentially binds to are also the most likely to be eroded in heavy precipitation and the most likely to travel from headwaters in contaminated basins to the Pacific Ocean. Due to desorption, a portion of the caesium becomes biologically available at the precise time it enters one of the most important ecosystems for coastal, migratory, and marine animals. It can then be taken into the marine food web.

Consequently, this not only has potential health impacts for the animals that rely on estuaries for food and breeding grounds, but also has implications human beings who may consume fish or other seafood that lived there at some point in their life histories.

Introduction

Nearly five years have passed since a triple disaster struck the people of Japan on 11 March 2011. A massive 9.0 earthquake off the northeastern coast of the Honshu island (Japan's main island) unleashed a tsunami that devastated the seaboard and claimed the lives of 15 893 people. Another 6 152 people were injured and approximately 2 500 people are still listed as missing.

These natural disasters also triggered the worst nuclear catastrophe in a generation: the triple reactor core meltdowns and exploded containment buildings at Tokyo Electric Power Company`s (TEPCO) Fukushima Daiichi nuclear power plant. While the initiating events were natural tragedies, the nuclear disaster was man-made. As the Japanese government review committee concluded in its final report on the accident[3], the Fukushima accident was largely the result of regulatory capture and a lack of industry safety culture.

The Fukushima Daiichi catastrophe is one of only two International Nuclear Event Scale (INES) Level 7 disasters in world history – the other being Chernobyl. It released enormous amounts of radiation into the atmosphere and ocean. Due to prevailing winds at that time of year, the majority of the atmospheric releases were carried out into the Pacific.

However, when the winds turned landward, significant levels of radiation were deposited on the heavily forested, mountainous region and its coastal plains, resulting in high levels of terrestrial contamination. Due to the nuclear crisis, over 160 000 people were evacuated. Today, five years on, nearly 100 000 remain displaced.

The heaviest land contamination occurred northwest of the crippled plant between 14th -16th of March, when precipitation and prevailing winds brought the massive releases from the explosions of the Unit 2 & 3 reactors down as wet deposition. The second largest land contamination event occurred from the 20th – 23rd of March.

Over the past four years, a massively expensive and labor-intensive decontamination effort has been underway in the much of the heavily contaminated areas. Workers scrub down buildings, sidewalks, and roads, and remove enormous amounts of contaminated surface soil and debris – which is then packed into bags roughly a m^3 in size and piled into up in mountains of temporary radioactive waste storage sites scattered throughout the prefecture. Forests are “decontaminated” in 20-meter strips along roads and around homes in an effort to lower radiation doses. Yet, due to the complexities of these ecosystems and the transfer of radiation within them, this effort is more symbolic than effectual.

As such, despite the admirable and dedicated work of the decontamination workers, their heroic efforts in the Fukushima-impacted areas have yielded limited success.

Greenpeace investigations have shown that radiation levels still remain too high for people to safely return in areas where evacuation orders have either been lifted or will soon be. This is largely a problem of politics being put before public health. Rather than focusing these efforts where people are currently living, which still have hot spots and where such work could be most successful in reducing human exposures, much of the effort has been focused on attempting to decontaminate the evacuated towns – and little 20 meter strips of forests along roads where no one lives.

The vast expanses of Fukushima's radioactive forests, which cannot be decontaminated, highlight a fundamental truth: human beings do not live divorced from our environment, but rather are embedded in it.

And therefore it's critically important to understand the ecological impacts of the Fukushima disaster to both fully grasp the magnitude of the nuclear catastrophe and the potential implications for the people that live in these contaminated environments.

These forests are a vast reservoir of man-made ionizing radiation that will continue to pose a threat to human and non-human health. They also represent an entire way of life that has been corrupted and lost due to the radiological contamination.

The majority of the citizens in this region were employed in natural resource dependent industries: forestry, fishing, and farming. All of these industries have been enormously impacted by TEPCO's nuclear disaster. In addition to livelihoods, the forests, fields, and rivers of Fukushima-impacted areas were a part of people's daily lives: many people used wood from the forests for heating and cooking; collecting wild edible mushrooms and plants was commonplace.

The victims of the nuclear disaster are not only the citizens of Fukushima and other impacted areas, but also the ecosystems – the plants and animals that comprise them – that have been irreversibly damaged by this man-made catastrophe.

A decontamination worker along a roadside in Iitate uses pruning scissors to trim blades of grass in July 2015. The district of Iitate Village is comprised of over 200 km2 of mountainous forest, with homes and agricultural fields interspersed. Only one quarter of Iitate's land is officially being "decontaminated", and these still largely fail to meet the Government's long-term decontamination targets. Iitate's forests are a vast reservoir of radioactivity, and will be a perennial source of contamination for the foreseeable future. ©Sutton-Hibbert/ Greenpeace 2015, all rights reserved.

Which begs the question: what are the impacts of the Fukushima disaster on the environment and its wildlife?

How long will the Fukushima Daiichi disaster continue to pose radiological threat to the people of Fukushima, surrounding prefectures, and the flora and fauna that call this region home?

This report seeks to answer these important questions by bringing together a large body of research from Japanese and international scientists who have been studying the environmental consequences of the Fukushima disaster over the past five years. It also draws on the vast body of research from studies of forest and freshwater aquatic ecosystems contaminated in the Chernobyl and the Kyshtym[4] radiological disasters.

It explores how some of the wildlife in the region have been impacted by chronic low-dose exposure to Fukushima-derived radiation, as well as the systems that cycle and remobilize some of the most concerning elements released by the disaster: caesium-134 (^{134}Cs) and caesium-137 (^{137}Cs). We examine the processes by which these radioactive elements are spread from heavily contaminated areas to those that have been decontaminated or did not receive direct fallout, as well as from the heavily contaminated forests to coastal and marine ecosystems.

And unfortunately, the crux of the nuclear contamination issue – from Kyshtym to Chernobyl to Fukushima – is this: when a major radiological disaster happens and impacts vast tracts of land, it cannot be "cleaned up" or "fixed."

While in the initial 0 to 4-5 year phase, there are reductions in radiation levels, due in large part to the decay of shorter-lived radionuclides like Iodine-131 (^{131}I) and ^{134}Cs, history teaches that such declines tend to bottom-out 5 years post accident.[5] After that time, radiation levels remain fairly "stable" with declines mostly due to the slow decay of long-lived radionuclides. For example, the half-life of one of the most concerning radionuclides, ^{137}Cs, is 30 years; its hazardous life is 300.

In natural systems, man-made radioactive elements are taken up by plants and animals in the place of important minerals and nutrients. That means that these radionuclides are cycled and recycled through living organisms in the food web. Thus, these Fukushima-derived radionuclides will remain a threat to living organisms – people included – for extended periods of time.

And as such, for the foreseeable future, Fukushima-contaminated ecosystems will continue to be radiation loaded. And reloaded.

Terrestrial radiological deposition from the Fukushima nuclear disaster

In order to have a better understanding of the potential impacts of the disaster, it is necessary to have some background on the scale and types of land contamination resulting from the disaster.

According to the IAEA's own definition, land that has surface radioactivity levels (for beta and gamma emitters) above 40 kBq/m^2 is considered contaminated (2005, 2009). And while the IAEA emphasizes repeatedly in its Fukushima Report, released in September 2015, that most of the atmospheric releases were carried out over the Pacific Ocean – and they were – that does not mean that there was an insignificant amount of land contamination.

During the acute phase of the Fukushima nuclear disaster in March 2011, on the afternoon of the 12th, the prevailing winds carried radioactivity from the venting and hydrogen explosion of the Unit 1 reactor to the northeast and coastal areas of Miyagi prefecture. These releases resulted in the dry deposition of radionuclides.[6]

The hydrogen explosion in Unit 3 on March 14th followed by the failure of the containment of Unit 2 on the 15th resulted is enormous releases of radioactivity from the night of the 14th through the morning of the 16th.[7] Initially, radioactivity from these releases was carried to the southeast coastal regions of Fukushima, to the northeastern portions of Ibaraki prefecture, and later over much longer distances to the southwest.[8] Precipitation began in the afternoon on the 15th, and while the initial massive releases from the Unit 2 failure were carried southwest, the change in wind direction caused the most significant levels of wet deposition to the northwest of the crippled reactor site.[9]

From the 20th – 23rd, terrestrial contamination peaked again due to the prevailing winds, initially to the northwest and then southward from late night on the 21st through the morning of the 22nd, where subsequent further releases on the 23rd contaminated parts of Iwate, Miyagi, Ibaraki, Chiba and other prefectures on the Kanto plain via wet deposition.[10]

As mentioned earlier, the highest terrestrial contamination occurred northwest of the reactor site: respectively, in this area, the IAEA states that deposition densities of long-lived Caesium-137 (^{137}Cs) between 1000 kBq/m^2 and 10 000 kBq/m^2 were recorded.[11] **The IAEA's average deposition density for ^{137}Cs throughout Fukushima Prefecture is 100 kBq/m^2.[12]**

This is an astounding figure, given that these numbers far exceed IAEA's own benchmark of 40 kBq/m^2 for contaminated land.

To put this into further context, **some of the most contaminated areas around Chernobyl range between 40 to more than 1480 kBq/m^2.[13]**

And while the radioisotopes primarily discussed – ^{134}Cs, ^{137}Cs, and ^{131}I – pose a significant threat to the health of human beings and non-human biota, these are not the only dangerous radioactive elements released in the disaster. In addition to caesium isotopes and radioactive iodine, the accident has released a large number of other dangerous radionuclides, such as Strontium-90 (^{90}Sr). ^{90}Sr is of particular concern because it is the chemical analogue of calcium and can be incorporated into bones. This is especially dangerous for children as their bones are growing.[14]

Further, sample testing of black dust collected from roadsides and soil samples throughout Fukushima prefecture, and as far away as 25-45 km from the reactor site, in the heavily contaminated village of Iitate, showed transuranic contaminants that were confirmed to share the same transuranic profile as the fuel core in the Fukushima reactors. These elements were detected in nearly all samples taken and included: Plutonium-238, 239 and 240; Americium-241; and Curium-242, 243, and 244.[15] Thus, they could be confirmed as being present as a result of the Fukushima Daiichi NPP disaster.[16]

In another study, plutonium isotopes that were confirmed to be in the environment as a result of the Fukushima disaster were found at similar levels throughout the entire 80km survey area, though more often detected in the evacuated zones.[17] Perhaps this should not have been quite so surprising to them, as this was also the case in Chernobyl, albeit at much high concentrations.

Although the amounts of these dangerous transuranic elements from the Fukushima disaster were very low, their longevity and toxicity – even in extremely small amounts – makes them particularly harmful if inhaled, and potentially dangerous if ingested.

According to data collected at the Meteorological Research Institute in Tsukuba, Japan – located 170km southwest of the Fukushima Daiichi nuclear plant – two significant plumes reached that area.[18] The initial spike in radiation due to Plume 1 occurred on March 14th and 15th, and deposited caesium-bearing spherical particulates of

Terrestrial radiological deposition from the Fukushima nuclear disaster

2.0 µm diameter and greater.[19] Testing results suggest that these were highly radioactive and insoluble in water.[20]

The second plume, from March 20th-22nd, showed small Cs particles attached to dominant aerosol particles.[21] Sulfate aerosols dissolved to cloud droplets appear to have been the primary transport mechanism for vaporized caesium, which accounted for wet deposition via both precipitation and fog.[22] The fog deposition process is largely responsible for observed altitude dependent dose rates in some mountainous regions, with higher recorded dose rates corresponding to cloud layer altitude.[23]

The impact of this enormous amount of artificial radiation on non-human biota and in functioning ecosystems in the Fukushima-contaminated areas of Japan has not been fully explored. However, previous studies of radiological contamination in diverse forests throughout Europe due to the Chernobyl catastrophe, as well as studies of above ground nuclear bomb testing contamination in various ecosystems globally, provide useful insights to the potential mechanisms of radionuclide cycling and impacts on ecosystems in Japan. Further, many of the important findings of biologists studying the impacts of the Fukushima disaster for the past nearly five years have been ignored – intentionally or otherwise – by the IAEA and the Abe government.

The radioactivity of water-soluble caesium that heavily contaminated vast areas of Japan is low-density, but its wide distribution makes it a significant source of external radiation.[24] Additionally, in a water-soluble form, caesium can bind to minerals and soils. It is also bioavailable, and as a result is incorporated into the materials cycle of ecosystems.[25] To put it simply, caesium behaves similarly to potassium, is incorporated into the tissues of plants, and consumed by animals via herbivory and passed up the food chain.

In multi-storied forest ecosystems, the migration of radionuclides to the forest floor happens gradually as plants intercept much of it.[26] As such, the binding of ionic caesium to soil minerals in complex forest ecosystems happens slowly, as caesium must migrate vertically through the organic soil horizons before reaching the mineral layers.[27] The rate of this varies, but can be increased in areas with high levels of precipitation.[28] Even so, much of the caesium is retained in the upper 0-10 cm of soil where it is available to biota for significant periods of time.[29] This will be discussed in more depth below.

During the Fukushima accident, micro-particles containing radiocaesium were released. The radiation density of these hot particles – determined to be spherical silicate glass particulates bearing caesium[30] -- released in the disaster is very high, making them particularly dangerous if inhaled or ingested.[31] These particulates can adhere to rough surfaces, and can be transferred amongst soils and living organisms via contact[32] and consumption.[33] According to the findings of N. Yamaguchi, et al. (2016), caesium appears to slowly leach from these hot particles in the natural environment.[34]

Caesium-contaminated soil particles can also be resuspended into the atmosphere via raindrop splash, and be shaken off vegetation due to wind as well as animal disturbance.[35] Additionally, submicron particles of caesium[36] can be generated on plant surfaces especially during periods of intense growth and transpiration.[37] These submicron particles can then be redistributed by wind, though this is likely to be most significant following the initial deposition event. The longer-term quantitative importance of this particular resuspension mechanism may vary in different ecosystems and would need further evaluation.[38]

Through the wash-down of both mineral-bound caesium as well as insoluble particulates, radiocaesium from the contaminated forests can be transported within the watershed to less-contaminated, populated areas.[39] In addition, the wash down of contaminated decomposed plant material is also of concern.[40] Forest discharges of caesium due to average rainfall are low.[41] Heavy rains – such as typhoons – can further increase caesium discharge rates from Fukushima forests by one or two orders of magnitude.[42]

Thus, the radioactive forests of Fukushima are vast areas of persistent, long-term contamination due to the incorporation of radionuclides into the ecosystem, and will continue to present a threat of contamination and recontamination within the watershed for years to come.

Forest ecosystem impacts

One of 113,000 (as of September 2015) temporary radioactive waste disposal sites in Fukushima Prefecture. ©Sutton-Hibbert/Greenpeace 2015, all rights reserved.

Forest ecosystem impacts

"It is difficult to decontaminate all of the forests and there could be adverse effects from such work." - Japanese Ministry of Environment Official, December 2015[43]

Fukushima prefecture is heavily forested, with 71% or 984,000ha of the prefecture's 1 378 000 ha covered in forested lands.[44] According to Yoshihara, et al (2014),[45] 44% or 430 000 ha – the size of approximately 524 000 large FIFA standard football (soccer) pitches – of these forests are contaminated with caesium at more than the International Commission on Radiological Protection (ICRP) recommended level for constraining the optimization of long-term post-accident scenarios.[46] There are another 360,000 ha – approximately 440 000 football pitches – of similarly contaminated forests outside of Fukushima prefecture, which gives a total of 790 000 ha (roughly 960 000 football pitches) of heavily contaminated forests.[47] Radiocaesium is retained strongly in the forest floor and surface soils, and due to its limited removal in forest ecosystems, presents a long-term contamination hazard.[48]

Fukushima forests are primarily boreal and cool temperate forests[49] with coniferous evergreen, broadleaf evergreen, and broadleaf deciduous dominant species. In this regard, the vegetation is somewhat similar to that near the Chernobyl disaster site, which is predominately boreal forest.[50] Although there are significant differences in topography, substrates, and precipitation, Chernobyl provides a useful example for comparison.[51]

Like Fukushima, the Chernobyl catastrophe heavily contaminated large areas of forested land, and these radioactive forests also continue to present particularly difficult challenges for managing the radiological contamination caused by the disaster.

The IAEA has put forth that environmental contamination due to the Fukushima Disaster has rapidly decreased, and that weathering effects contribute in part or largely to this – in addition to radioactive decay. This is to some extent true – especially as it is related to shorter-lived contaminants like ^{131}I, which has a half-life of only 8 days, and ^{134}Cs, with a half-life of two years.

However, these acute phase reductions are expected to bottom out within five years after the disaster.[52] After that time, radiation levels remain fairly stable and subsequent slow reductions are mainly due to the decay of longer-lived radionuclides, like ^{137}Cs, ^{90}Sr, and transuranics.[53] These radionuclides will persist in the environment for decades – and in some cases, centuries and even millennia – to come.

Overview

Forest ecosystems are very complex, with multiple mechanisms and systems for absorbing and transferring nutrients – or contaminants, as it were. Radioactive contamination varies among tree species, between individuals, within various organs of the same tree, and change with season.[54]

Trees are extremely efficient interceptors for radioactive particles.[55] In Chernobyl and Kyshtym disaster forest studies, it was found that 60-90% of radionuclides falling on forests are intercepted by the canopy.[56] This would be consistent with finding in Fukushima Daiichi-contaminated evergreen cedar and cypress forests located in Tochigi prefecture 150km southwest of the reactor site. The study concluded that these canopies intercepted 93% and 92% of total ^{137}Cs fallout, respectively.[57] Further, the cypress forests intercepted 62.3% of ^{137}Cs deposited via atmospheric washout (rainfall), and likewise the cedar forest incepted 65%. Five months after the accident, 60% of the initial canopy radiocaesium deposition remained in the canopy.[58]

This finding was further supported by T. Ohno, et al. (2012), who also concluded that over half of the deposited caesium in a contaminated cedar forest was retained in the canopy.[59]

The season in which radioactive fallout occurs can significantly impact canopy interception.[60] At the time of the acute phase of the Fukushima disaster, deciduous trees were not yet foliated. As such, interception by deciduous species was significantly lower than that of evergreen species.[61] In contrast, evergreen contamination in 2011 was most present in foliage that had expanded before the disaster and could be washed out relatively easily, indicating high amounts of external deposition that had not yet been absorbed.[62] However, contaminated foliar parts in deciduous trees had expanded after the initial deposition, were contaminated likely via secondary surface contamination – e.g., raindrop splash – and absorption.[63] A large amount of the deciduous foliar contamination was impossible to remove, even after in vitro washing, and thus researchers concluded that the majority of this contamination was tightly bound to internal tissues.[64]

Radioactive waste bags sit by a roadside in the district of Iitate in Fukushima Prefecture in July 2015.
©Sutton-Hibbert/ Greenpeace 2015, all rights reserved

However, according to long-term studies of forests following the Chernobyl and Kyshtym radiological disasters, there are essentially two stages of radioactive contamination of forests.[65] The first stage lasts 2-4 years after the initial deposition, the primary mechanism of contamination being deposits on the tree canopy.[66]

In this initial period, the primary fallout event is the most significant source of contamination. It is characterized by "deactivation" wherein decreases in contamination of structural parts of the tree are recorded.[67] This would be consistent with observations of trees contaminated by the Fukushima disaster in the initial 0-4 year period.[68]

The second stage lasts between 10-15 years, where there are possible increases in radionuclide concentrations in aboveground plant structures, due to the uptake of via root systems.[69] During this stage, transfer of caesium from soil exceeds the rates of return to the forest floor with the shedding of fall foliage, until a sort of equilibrium is reached.[70]

There are numerous factors that may influence the uptake of radionuclides from forest soils including: concentrations, competition with other ions (e.g., potassium and calcium), soil pH, precipitation and vertical penetration of radioisotopes, binding of radionuclides in mineral structures, organic and mineral contents in various soil layers, root depths, and symbiotic relationships with mycorrhizal fungi.[71]

And while the IAEA has inexplicably attempted to downplay the impacts of radiation in the environment, it is important to be clear on its impacts on living organisms of all kingdoms. As researchers studying mutations in Chernobyl-contaminated coniferous trees stated:

> *Ionizing radiation was the first identified mutagen and it causes a wide range of intragenic and intergenic mutative changes. The range of mutation events caused by ionizing radiation vary from simple base substitutions to single- and double-strand breaks of DNA. An increase of mutation rates and changes in the structure and functioning of the genome is part of the complex reactions of an organism to exposure to ionizing radiation.*[72]

Forest ecosystem impacts

Thus, it is critically important to understand how accidentally-released radionuclides behave in the environment, both from an ecosystems perspective and for human health.

Direct deposition, absorption, translocation, and mutation in trees

As previously stated, the foliar[73] and bark[74] absorption of atmospheric deposition of radionuclides – in particular ionic water-soluble caesium – has been well documented in radioactively contaminated forests over decades of study.[75]

Further, according to a study of Fukushima-released, caesium-bearing hot particles collected from cedar leaves 8 months after the disaster:

> *"Coniferous forest canopy induces acidic condition due to ammonia uptake, nitrification and leaching of plant-derived acid . . . The finding of the alkali-depleting crust on the surface of the Cs-bearing radioactive microparticle indicates that radiocesium in the particles can be released by "weathering" of the glass in natural environments, and considering its small size, duration for the total release of the radioactive cesium from the particles is probably not long, from several years to a few decades, though it will strongly depends on the environment."*[76]

Thus, while researchers had previously assumed that caesium could leach from these hot particles, which appears to be confirmed. This slow release of caesium due to weathering may increase the amount of bioavailable caesium in the coming years and decades.

Once absorbed into internal tissues of plants, radiocaesium can translocate from older to new foliar structures. This phenomenon was noted by T. Nishikiori, et al. (2014)[77] in a study of contaminated Japanese cedar from March 2011 – May 2012. The study looked at caesium concentrations in precipitation, soil samples, and leaves sprouted in 2010, 2011, and 2012. In 2012, radiocaesium in throughfall was below detection limits, and thus the leaves sprouted in that year were not externally exposed. Despite this, the 2012 leaves contained significant amounts of ^{137}Cs (570 Bq/kg^{-1}) and the ratios of ^{137}Cs/^{133}Cs were almost equal to those measured in the 2010 and 2011 leaves, which had been externally exposed.

The authors further confirmed their results via measuring the newly sprouted 2012 leaves of 18 other woody species. Radiocaesium was found in these as well, and the ^{137}Cs/^{133}Cs ratio was equal to or higher than the soil samples taken in the cedar forest. Thus, the researchers concluded that the caesium present in 2012 leaves must have been a result of internal translocation, as no external source of these radionuclides was present.[78]

These findings were further corroborated by a study by the National Institute of Radiological Sciences (NIRS) in Chiba prefecture, 220 km southwest of the Fukushima Daiichi plant.[79] The institute collected samples near the research center of 14 different plant species, comprised of herbaceous plants, woody plants that were not foliated at the time of the most significant releases, and woody plants that were foliated. All samples were collected between March 2011 – June 2011. As expected, ^{137}Cs and ^{134}Cs were lowest in herbaceous species (on average: 92 ± 19 Bq/kg^{-1} for ^{137}Cs, and 87 ± 17 Bq/kg^{-1} for ^{134}Cs) as these plants were not present at the time of the initial releases.[80] Thus, the authors assume that the caesium in these herbaceous species must have been taken up via root systems.

However, among the woody species, those that were foliated before 11 March 2011 showed higher concentrations of ^{137}Cs and ^{134}Cs in newly emerged leaves than woody species that were not foliated at that time – leading the researchers to conclude that the foliated woody species had directly absorbed radiocaesium via their leaves and translocated it to newly forming leaves.[81]

In another study, conducted over the 3-year period between 2011 and 2013, of 10 different Fukushima-contaminated woody species consistently showed higher concentrations of caesium in the foliar structures of evergreen species, attributed in part to the higher interception fraction for the foliated coniferous trees at the time of initial deposition, as well as leaf longevity.[82]

The authors confirmed the transfer of caesium within internal tree tissues, particularly higher concentrations in new tissues, such as leaves and sapwood. The study also noted seasonal variations in concentrations – especially for deciduous species. Further, current-year foliar structures showed higher caesium concentrations than year-old leaves. Thus, as the impact of the direct depositions diminished, the translocation of caesium with nutrient flows – especially to developing tissues – became more apparent.[83]

Forest ecosystem impacts

While there were decreases over time for most tree species examined, levels varied among species, age of leaves, and location. In 2012, radiocaesium concentrations ranged from 29% up to 220% of 2011 levels.[84] In 2013, these fell to 14% to 42% of 2011 levels. The net decreases were highest for evergreen species, though these still consistently showed higher caesium concentrations than deciduous species.

Also, the observed decreases may be explained – at least in part – through seasonal variations[85] in concretions of various elements, including caesium. Samples in 2011 were gathered in early August. In 2012 and 2013, the leaves were collected in late May to early June – thus, providing significantly less time in the latter two years of the study for caesium accumulation in new leaves with growth and maturation over the late spring and summer months. As such, the total amount of the decreases in the study must be viewed with some caution, as values may have been different had the leaves been collected in early August in all three years.

However, some decreases would be expected, as it would correspond to the initial 2-4 year phase after contamination, as noted by Tikhomirov & Shcheglov regarding the Chernobyl and Kyshtym accidents (1994). Again, this stage is characterized by decreases in contamination of aboveground plant structures. As the fourth year post-Fukushima draws to a close, there may be a gradual reversal of this trend as caesium is increasingly transferred from root systems to the aboveground phytomass in the next years to decades, as has been documented in other contaminated forests.[86]

In the year after the Fukushima Disaster, a team of scientists from the National Institute of Radiological Sciences, the Japan Wildlife Research Center, and Japan NUS Co., Ltd. conducted an initial analysis of contaminated forests.[87] It is understood from the aftermath of Chernobyl that coniferous tree species are particularly radiosensitive. Thus, researchers focused on an endemic coniferous species, the Japanese Cedar (Cryptomeria japonica).

Although in the immediate aftermath of the Fukushima accident, the scientists did not find observable symptoms of radiation exposure, such as yellowing, malformation, and early withering of leaves, it was confirmed that there was significant contamination of coniferous forests.[88]

More significantly, the researchers noted that the trees had likely suffered internal (organ) radiation exposure, in addition to external exposures. In particular, the study confirmed reproductive organs such as cones were heavily contaminated during seed maturation, which could negatively impact seed development.

The authors concluded that:

> *Considering that the highest concentration of radiocesium observed in the cone samples was distributed uniformly in the ideal cone, the internal exposure dose rate received by the cone was estimated to be 15 µGy/h. Although this estimated internal exposure should only be a part of the complete exposure of the cone, it is still sufficiently high to be within the range of the criteria dose rate of 4-40 µGy/h selected for pine trees as the "derived consideration reference level" by the ICRP.* ***This indicates that there was a probability for certain deleterious effects that could result in reduced reproductive success or morbidity, and highlights the necessity for further analysis of cytogenetic and reproductive changes in plants in the most contaminated forest area, as was also suggested by Garnier- Laplace et al. (2011)*** *[emphasis added].*[89]

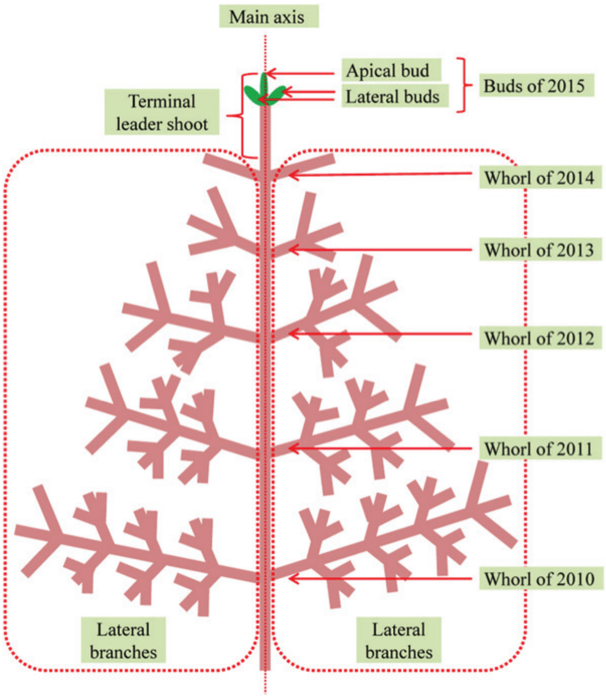
The effects of chronic radiation exposure appear to be already manifesting in some tree species. In August 2015, researchers – mostly from the National Institute of Radiological Sciences – acknowledged that fir trees in Fukushima Daiichi contaminated forests are showing "morphological defects," and the frequency of these defects corresponded with radiation levels.[90] The study examined 4 sites, at varying distances from the crippled Fukushima Daiichi plant. Dose rates at three of the four sites were 33.9 uSv/h, 19.6 uSv/h, and 6.85 uSv/h, respectively. The fourth site was in the distant town of Kita-Ibaraki in Ibaraki Prefecture, where radiation levels are only 0.13 uSv/h, which served as the control site.[91]

In the site closest to the destroyed nuclear plant, the town of Okuma, 90% of the fir trees examined showed abnormalities. At the two sites in Namie town, 40% and 30% respectively showed such defects. In contrast, at Kita-Ibaraki, less than 10% of trees showed such growth abnormalities.[92]

Forest ecosystem impacts

The primary observed defect, the deletion of the leader shoot – the central new growth that eventually becomes the trunk of the tree as it grows – can be caused by other factors. However, scientists were able to determine that there was a significant increase in this abnormality after the disaster by examining previous years' whorls.[93] Again, this abnormality also increased with increasing radiation levels amongst the test sites.

Thus, while it is difficult to say definitively this abnormality is due to radiation, there is a statistically significant correlation between radiation levels and this observed abnormality in Japanese fir trees, and a significant increase in incidence after the Fukushima disaster.[94]



Source: Watanabe, Y. et al. Morphological defects in native Japanese fir trees around the Fukushima Daiichi Nuclear Power Plant. Sci. Rep. 5, 13232; doi: 10.1038/srep13232 (2015).

This mutation – the deletion of the leader shoot – was also observed in coniferous trees in Chernobyl contaminated forests. The Fukushima researchers stated that:

> *In relation to radiation effects, deletion of the leader shoots has been reported in Scots pine trees chronically exposed to radiation in a contaminated area close to the Chernobyl nuclear power plant. The trees that showed forking defects with deletion of annual leader shoots eventually formed bushy canopies without a main axis. Another study showed that Scots pine trees in Chernobyl were characterized by the disappearance of a single trunk and replacement with two or more trunks or branches, corresponding to the estimated dose rate during the development of apical buds. Although the defects in pine trees close to the Chernobyl nuclear power plant were not all identical to the defects observed in Japanese fir trees in the area close to the F1NPP, the information seems to support the relationship between the morphological changes in Japanese fir and the chronic exposure to radiation from released radionuclides.*[95]

According to another study[96] of Japanese cedar (Cryptomeria japonica – also commonly called "sugi"), caesium concentrations in newly sprouted 2012 needles decreased when compared with older needles sprouted in 2010 and 2011. However, the authors found that the base part of the 2012 male flowers tended to accumulate high concentrations of ^{137}Cs, at levels higher than the new-growth, 2012 needles.

Further, no significant difference was found between caesium concentrations in the male flowers and the pollen they contained.[97]

This high concentration of caesium in tree and other pollens was also documented in Chernobyl-contaminated areas. Studies of Chernobyl-impacted areas found caesium in the pollen of a number of plant species including spruce[98] and pine[99], and herbaceous flowering species.[100]

The flowering species study was conducted in Croatia, four years after the Chernobyl accident. Concentrations of ^{137}Cs in pollen were found to be 8 to 10 times higher generally than levels in the flowers themselves. In addition, analysis of the honey produced by bees foraging in the contaminated areas studied found that a little over half of the caesium in pollen was transferred to the honey, and the concentrations in the honey corresponded to the contamination levels in Croatia.[101]

Further, a study conducted 6 years after the Chernobyl accident in Munich, Germany found that spruce pollen was responsible for significant spikes in airborne ^{137}Cs

Forest ecosystem impacts

during periods of peak pollen production due to the high concentrations the pollen contained.[102]

Another study in a highly contaminated forest in Chernobyl found increases in airborne radiation levels during peak pollen production for pine species, also due to contaminated pollen.[103]

The potential implications of these findings for Fukushima contaminated areas could be extensive – due to the resuspension and redistribution of caesium to more populated areas, or those that had been decontaminated, and the Japanese government's policy of "decontamination" in 20 meter zones around homes and along roads. Calculated projected doses have been quite low based on cedar pollen concentrations and average adult inhalation.[104] However, there is little knowledge about the radioactivity in pollen in the most highly contaminated forests, and further research is needed to determine the potential additional radiological risk for people living in the partially decontaminated areas. While this will be discussed in more detail below, it is important to note here that many homes are embedded in the forest, such as in the highly contaminated area of Iitate.

Different flowering and pollination times for different species could create an exposure hazard. At the very minimum, in the interest of human rights, this issue requires a robust understanding of potential health implications of exposures to radioactive pollen before people are returned to these contaminated areas.

It is worth noting that the timber industry is still harvesting trees in Fukushima, albeit not in the mandatory evacuation zones. This permitted under the assumption the removal of the outermost layers (bark and sapwood) removes most of the contamination and that the remaining timber is below currently actionable levels.[105] At present, this is likely true.

However, studies from other radioactively contaminated forests show both vertical and lateral translocation of caesium in contaminated trees. In simpler terms, this means that while caesium is transferred vertically from roots to canopy and vice versa, it is also translocated within tree tissues – i.e. inward – and thus tree rings formed long before any radiocaesium was present in the environment become contaminated.[106]

A study of three major tree species for forest product production – Japanese Cedar, Red Pine, and Oak – six months after the Fukushima accident found caesium in the bark, sapwood, and heartwood for all three species.[107] This contamination was attributed primarily to direct foliar and bark absorption, and demonstrates a rapid translocation of caesium within the internal tissues of all three species.[108]

The mechanisms for the translocation of caesium to heartwood is not well understood. It may be due to moisture content and potassium concentrations in heartwood – which vary across species – among other potential factors.[109] In this study, concentrations in bark were higher than sapwood, and concentrations in sapwood higher than heartwood, for all three species.[110]

However, in Japanese cedar – a very common species in natural forests and also the most important plantation tree in Japan – potassium concentrations are known to be higher in heartwood than in sapwood.[111] The opposite is true for red pine and oak.[112] Additionally, the heartwood of this species tends to have a high moisture content, which may be responsible for the high potassium concentrations.[113] As caesium behaves much like potassium within plant tissues, and concentrations may be higher with higher moisture content, there is a potential for high concentrations of caesium in the heartwood of this important and common species.[114]

In fact, a 1988 study of radiological contamination of Japanese cedar from nuclear bomb testing atmospheric fallout showed that caesium concentrations were highest in the heartwood of Japanese cedar.[115]

While the highest concentrations do appear to remain in the outermost layers in studies of Chernobyl contaminated forests,[116] evidence of lateral translocation of caesium and potential for high heartwood concentrations in a key timber species, Japanese Cedar, highlights the need for continued monitoring of timber products from Fukushima prefecture in the coming years.

It is also worth noting that evidence from forests contaminated by the Hiroshima bomb, as well as atmospheric nuclear bomb testing, show less lateral translocation of ^{90}Sr, though there is some inward migration.[117] However, uptake by root absorption of ^{90}Sr was considered to be at least two times greater than the absorption of ^{137}Cs.[118]

Forest ecosystem impacts

Understory plants: Interception and retention

Although trees account for the largest proportion of biomass in a forest ecosystem, understory plants also play an important role in the interception, retention, and cycling of radionuclides. The above discussions related to tree inception, absorption, and translocation following an initial deposition event can also be applied to both tall and short understory shrubs.[119]

Of particular note is the role that mosses and lichens play in absorption and retention of contamination. As they have a high capacity for liquid absorption, they serve as an intermediate sink for radioactivity.[120] Thus, in wet and humid ecosystems with bryophyte mats (mosses and liverworts) have the greatest biomass, soil samples that exclude the overlaying moss mats are not indicative of overall contamination levels because much of the radioactivity is contained in the mosses.[121]

In Fukushima forests, the understory vegetation appears to have absorbed a significant portion of the caesium deposition below the canopy. In fact, in a study of vertical soil distributions of caesium in a 30-year-old Japanese Cypress forest located 180km from the reactor site found the caesium concentrations in dried weight understory plants exceeded those in soil samples three-fold, indicating uptake by plants – either through root uptake or direct deposition.[122]

Indirect deposition

As only a small portion deposited caesium reaches the forest floor due to interception by plants, indirect deposition mechanisms play an important role in the redistribution of caesium and other radionuclides.[123]

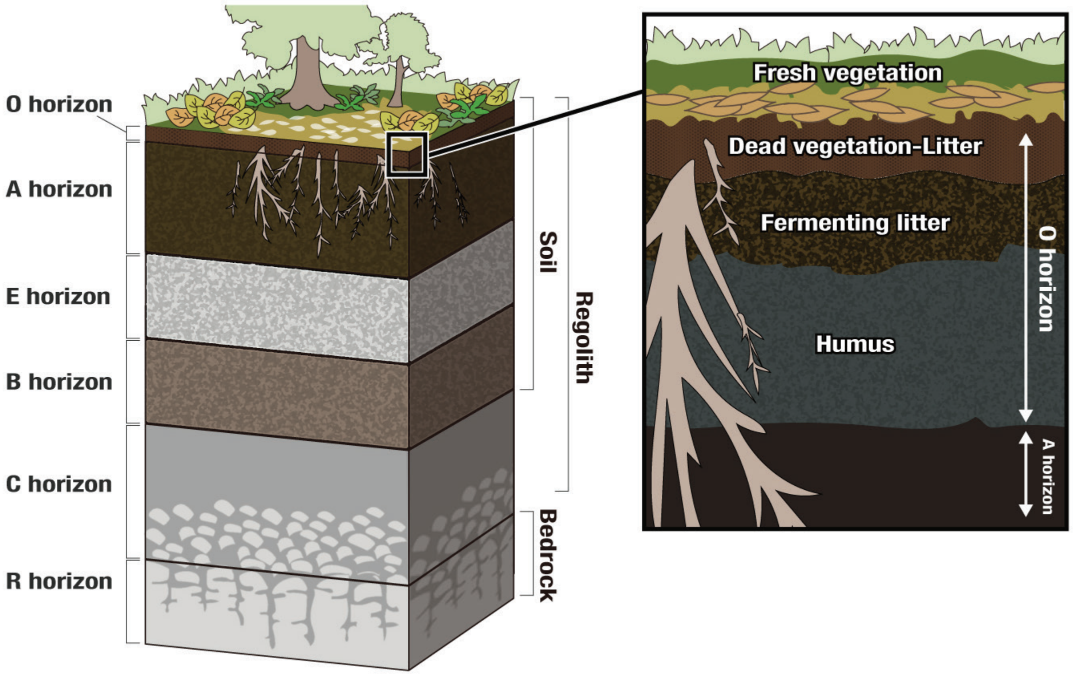
Initially, deposited particles can be washed off, and absorbed caesium leached, by precipitation heavy enough to saturate the canopy and allow water to fall to the forest floor. This occurs through two mechanisms: throughfall and stemflow. Throughfall is precipitation that is either not intercepted by the canopy or occurs when water drips from saturated leaves the forest floor. Stemflow is water that is funneled down trunks by leaves and branches.[124] Immediately following the contamination event, particulate wash off appears to be the primary mechanism for the redistribution of caesium to the forest floor.[125] However, precipitation leaching from the bioactive portions of plants appears to be a long-term phenomenon.[126]

A study conducted in both broadleaf deciduous forests and red pine forests at 1.5 and 3 years post-Fukushima disaster, clearly showed seasonal increases in caesium migration to the forest floor. Through-fall, stem-flow and leaf litter concentrations were measured.

Broadleaved forests contributed more caesium to the forest floor than did the red pine forests. Further, through-fall redistributed higher levels than did stem-flow, though stem-flow concentrations were higher.[127] Concentrations of ^{137}Cs tended to be higher in periods of low precipitation. However, generally in both red pine and broadleaved forests, there were higher concentrations in throughfall and stemflow from summer to autumn.[128]

In addition, the authors noted increases in ^{137}Cs concentrations in forest litter from summer to fall, though there was not a clear correlation with increases in litter fall amount.[129] In the red pine forest, the ^{137}Cs concentration in litter was almost always 10 kBq/kg or below, although in the first half of August 2013, the ^{137}Cs concentration exceeded 20 kBq/kg.[130] Likewise, in the broad-leaved forest the ^{137}Cs concentration was almost always 10 kBq/kg or below, although the ^{137}Cs concentration exceeded 20 kBq/kg from May until September of 2013, reaching a maximum of 62 kBq/kg. Migration of 137Cs through litter fall was correlated with the leaf fall period for the dominant species – with red pine forests showing peaks in spring and fall, and broadleaved forests showing the highest 137Cs contributions via litter in fall.[131]

Another study in cedar forests in the period of March 2011 – June 2012, found that 85% of the radiocaesium in through-fall and bulk precipitation was dissolved – and, as the authors suggest, probably ionic – and thus, in its most bioavailable form to be absorbed by direct absorption and via root uptake.[132]



There are three soil sub-horizons in the top O layer in mature forest soils, which are mineral-poor and organic matter rich: Litter, Fermentation and a thin layer of mineral poor humus. Studies show that in contaminated forest ecosystems radiocaesium largely stays in the top 0-5cm of soil for the long term, where plants are most likely to absorb it.

Vertical migration of caesium in forest soils

In order to understand the potential mobility of ^{137}Cs both within the ecosystem and transport from forests to other areas, it is essential to understand its vertical migration in forest soils. This is also a key factor in long-term external dose rates to human beings and other animals.[133]

Also, as M.T. Teramage, et al. (2014) note: “the remobilization of radiocesium accumulated in surface organic layers of forest soil may result in contamination of the soil and rivers for a long time. Therefore, understanding the early distribution and subsequent migration of radiocesium in the soil profile is essential.”[134]

It has been well documented that caesium sorption within clay minerals happens rapidly and is frequently nearly irreversible.[135] Thus, the caesium bound in clays is largely not bioavailable for uptake by plants – though potentially mycorrhizal fungi symbiosis may allow plants to access some of this mineral bound caesium, as discussed in more depth below.

Soil horizons are generally divided into 6 layers: **O** – the organic horizon comprised of loose and partially decayed plant matter; **A** – the topsoil comprised of a mix of minerals and rich humus (decomposed plant matter); **E** – leached horizon, which loses much of its minerals and clays through the process of eluviation (precipitation moving downward through the soil); **B** – Illuvial zone/ Subsoil, comprised of clay and mineral deposits; **C** – weathered parent rock material, with very little organic material; **R** – unweathered parent rock material/bedrock.

Agricultural fields, which have been extensively studied after radiological disasters, have poorly defined soil horizons and lack the soil microflora and fauna that are present in forest soils, due to tilling and cultivation. Thus, much of the research from Chernobyl and other disasters of agricultural fields attributed to clays – not organic layers – an important role in retaining caesium and preventing its downward migration.[136] Caesium fixed in clay minerals is largely unavailable for sorption by plant, which accounts for the low migration rates and low activity in agricultural products as reported in Chernobyl studies.[137]

However, the O horizon in “[f]orest soils are generally characterized by well-defined layers in which three superficial horizons very rich in organic matter can be distinguished. The L (litter) horizon consists of intact litter with little visible signs of decomposition; the F (fermentation) horizon, below the L horizon, consists of fragmented litter, and the H (humus) layer between the F layer and the mineral soil containing little or no mineral matter. When radiocesium reaches the ground, it generally accumulates in the litter fraction of the soil organic material.”[138]

Given that these organic layers are generally poor in caesium-binding clay soils, the majority of caesium inventory in this layer is bioavailable and root systems are likely to absorb it.[139] However, it may be that not all caesium measured in vertical soil samples is readily available for uptake, due its retention in the included soil biomass (roots, fungi, and micro-flora and fauna).[140]

Forest ecosystem impacts

Fukushima soils are heavily influenced by volcanic ash, which is generally poor in ^{137}Cs sorption capacities. However, studies shown have shown relatively high fine (clay +silt) fractions and ^{137}Cs retention capacities in the upper mineral layers in Fukushima forest soils.[141]

According to studies of Chernobyl and other radiological disasters, vertical penetration and sorption into clay and other minerals in forests happens slowly.[142] This a phenomenon that has been reported by so many authors that, "the slow downward migration of radiocaesium in organic horizons of forest soils can be considered as a well established fact, which still awaits a clear causal explanation."[143] In fact, studies from Chernobyl contaminated forests have shown that 90% of ^{90}Sr remained in the top 10 cm of soil, and ^{137}Cs remained in the top 5cm.[144]

Precipitation can influence vertical caesium migration via capillary water flow through organic soil layers. Due to the higher levels of precipitation in Fukushima than in forests in and near the Chernobyl exclusion zone, vertical penetration rates may be somewhat faster in Fukushima.[145]

This more rapid downward migration in Fukushima soils appears to be confirmed by studies conducted in the immediate aftermath of the 2011 deposition. These studies showed relatively higher velocities of downward translocation of a small percentage of deposited radiocaesium in forest soils, as compared to Chernobyl.[146] In addition to the possible effects of higher levels of precipitation, researchers suggested that this higher velocity may be due to the deposited ^{137}Cs being in more mobile forms – for example, attached to more exchangeable sites in clay minerals or dissolved in organic matter – and therefore able to be transported downward through the soil horizons.[147]

However, while a small percentage of the deposited radiocaesium in forest soils migrates rapidly downward after initial deposition, the majority of it is retained in the topmost layers. It has been suggested that there are two stages in vertical migration of radiocaesium in the soil profile. The first stage following deposition is characterized by high mobility, followed by fixation by plants and minerals. This was also observed in Chernobyl[148], albeit to a lesser extent.

Researchers studying the migration of radiocaesium in Fukushima forests concluded:

> *Most downward migration models consider a single phase of migration rate that assume a gradual and slow adsorption-desorption processes of radiocesium movement in the soil profile. Nevertheless, we observed some fraction of Fukushima-derived ^{137}Cs at a depth of 16cm most likely due to the infiltration of radiocesium-circumscribed rainwater during the fallout before selective adsorption started.* ***This implies that in forest soil there is additional and quick phase of radiocesium migration. In fact this phase cannot represent the long-term migration of Fukushima-derived ^{137}Cs*** *but still it is . . . important to understand the speed of contamination at the initial fallout period.*[149]

Multiple studies confirmed that the largest amounts of caesium inventories in Fukushima forests remained in the litter and upper horizons. In one study this was found to be between 50 – 91% of the total inventory.[150]

Another study of coniferous Fukushima-contaminated forest concluded that while there was rapid downward migration from the Ol horizon (litter), concentrations peaked in the Of (fermentation) horizon. Thus, the authors state that:

> *On the forest floor,* ***the understory plants and the upper few centimeters of soil can be considered as an active radiocesium remobilization interphase,*** *primarily due to its acidic nature and low clay content that made radiocesium bioavailable particularly for short-lived understory plants.* ***Almost all of the radiocesium activity (99% of the total soil inventory) was found in the upper ~10 cm*** *in which the [organic matter] content was greater than 10%. The raw organic layer (Ol + Of) holds 52% of the Fukushima-derived ^{137}Cs at the time of soil sampling, and the remaining ^{137}Cs is distributed in the soil below the Of- layer.* ***Specifically, the Of- horizon seems to accumulate Fukushima-derived ^{137}Cs, which accounts for 47% of the total inventory at the time of sampling, and retards its subsequent migration,*** *indicating that the [organic matter] turnover characterizing the Of-layer dynamics and its periodical changes will likely determine the migration,*

Forest ecosystem impacts

> *the residence time and the bioavailability of radiocesium [emphasis added].*[151]

This trend was also noted by another study of deciduous forests contaminated by the Fukushima disaster. As previously stated, the season of initial deposition and tree foliation has a dramatic effect on interception of initial atmospheric radioactive plumes.

Unlike coniferous evergreen forests, deciduous trees were not foliated at time of the Fukushima accident, and thus much of the initial contamination was deposited directly on the forest litter.[152] A year after the accident, the majority of the ^{137}Cs inventory had moved from litter into the topsoil, where it was largely prevented from migrating further downward.[153] Only 2% of the leachate from the litter and humus layers penetrated below 10 cm depth, while the annual migration rate below 10cm was 0.1% of the total ^{137}Cs inventory.[154] The authors also noted that the rate of vertical migration slowed in the second year after the accident.[155]

Thus, while it appears there was an initial period of rapid vertical migration in soil profiles after the accident, the majority of the ^{137}Cs remains in the organic soil horizons – primarily in the top 0 to 5cm[156] – where it is most bioavailable to plants, potentially mobile, and poses greatest risk for external exposures for people and other animals.

Horizontal displacement: Biological factors

In addition to migrating vertically downward within the soil profile, radiocaesium is also spread horizontally within the forest. There are three primary biological mechanisms by which caesium is spread horizontally: fungi, higher plants, and animals.[157]

Unlike agricultural soils, forest soil hosts intense fungal life which act as primary decomposers (along with bacteria), parasites on living plants, and perhaps most importantly, as symbionts with plant roots (mycorrhiza).[158] Many fungi have a well-documented affinity for radiocaesium, which is absorbed and then concentrated in the fruit bodies.[159] In addition, the mycelium of a single individual can extend significant distances in soil – and due to the fact that many fungi are perennial, as caesium is transferred with nutrient flows, fungi can form significant pools of radioactivity.[160]

Higher plants – as previously discussed – accumulate caesium from the soil in proportion to their biomass (trees obviously accounting for the greatest proportion of the biomass in a forest ecosystem).[161] Mychorrhizal symbiosis can further complicate this, as these fungi-root associations are a major source of nutrients for many trees and other higher plants – and also have been documented to both act as a barrier to the transfer of heavy metals and in other instances.[162]

P.L. Nimis (1996) describes the relationship thus:

> *Most species of vascular plants have evolved to a dependence on mycorrhizae as the most metabolically active parts of their root systems. Mycorrhizal fungi are vital for uptake and accumulation of ions from soil and translocation to hosts because of their high metabolic rates, and strategically diffuse distribution in the upper soil layers; they produce enzymes, auxins, vitamins, cytokines and other compounds that increase rootlets size and longevity. The fungal mycelium and sporocarps are sources of accumulated nutrients and energy for decomposers and consumers; nutrients and carbon can be translocated from one vascular plant to another by a shared mycorrhizal mycelium . . . Mycorrhiza is one of the least studied, and nevertheless one of the most important factors for understanding the cycling of radionuclides in natural and semi-natural ecosystems.*[163]

Further, in laboratory settings, mycorrhizae in pure cultures have been shown to utilize both organic and inorganic forms of phosphorous, unlike the un-colonized root systems of higher plants.[164] In addition, a lab study of mycorrhizal associations in eucalyptus seedlings demonstrated that the fungi were able to liberate potassium – the chemical analogue of radiocaesium – from clay minerals and transfer it to the seedlings.[165] Thus the possibility that mychorrhizae could increase the uptake by higher plants of caesium via root systems, including the liberation of otherwise unavailable mineral-bound caesium, cannot be excluded.

Forest ecosystem impacts

Finally, animals can be a significant contributor to horizontal displacements of caesium – in fact, studies in Chernobyl-contaminated Swedish forests showed that the displacement of caesium by herbivory (animals consuming contaminated plant matter and redistributing the caesium through their excrement) is within an order of magnitude of litterfall, and in some cases, transfer via herbivory can be higher than that of litterfall.[166]

Perhaps in a more cynically "amusing" example of the spread of radiation via animals and drifting plant structures, government contractors for the United States Department of Energy chase radioactive tumbleweeds and "nuclear bunnies" in an effort to stymie the spread of radionuclides from a highly contaminated former nuclear weapons manufacturing site at Hanford, in Washington State.[167]

Wildfire and resuspension of radionuclides into the atmosphere

When litter fall deposition occurs, the leaves must biodegrade for caesium to penetrate into deeper soil horizons. Studies in the Ukraine and Belarus of forests contaminated by Chernobyl suggest that the decomposition process may be significantly slowed[168] due to the impact of radiation on the soil invertebrates that would normally break down dead plant matter.[169]

As noted by T.A. Mousseau, et al. (2014):

> *. . . free-living microbes strongly regulate plant productivity through mineralization of organic matter. Soil invertebrates play a significant role in litter decomposition. Therefore, when the community of soil microbes and invertebrates is seriously perturbed, as in the case of a major nuclear accident, such perturbation can have dramatic indirect effects on performance of plants and hence herbivores, but also on the mineralization of organic matter.*[170]

In Chernobyl, this accumulation of litter over years and decades – referred to "fuel ladders" – have been documented to increase the risk of forest fires reaching the canopy and become large crown fires.[171] In addition, it provides an enormous amount of kindling that not only can significantly increase the intensity of a fire, but also allows it to quickly spread.[172]

When contaminated forests burn, they release strontium, caesium and plutonium in fine particulates that can be inhaled.[173] Crown fires are particularly problematic because the intensity of the fire can release up to 40% of the radionuclides contained in the forest – this release can enter the upper atmosphere, and be carried over long distances.[174] In addition, due to the low boiling point of caesium, it is partially volatilized in wildfires and transported in smoke, even when bound in soil.[175]

Thus, radionuclides previously sequestered in contaminated forests can be remobilized and redistributed – sometimes far from the initial site – via fire, and the very presence of radiation in the forest is disruptive to the ecosystem in such a way that it increases the likelihood, potential scope, and intensity of wildfires.

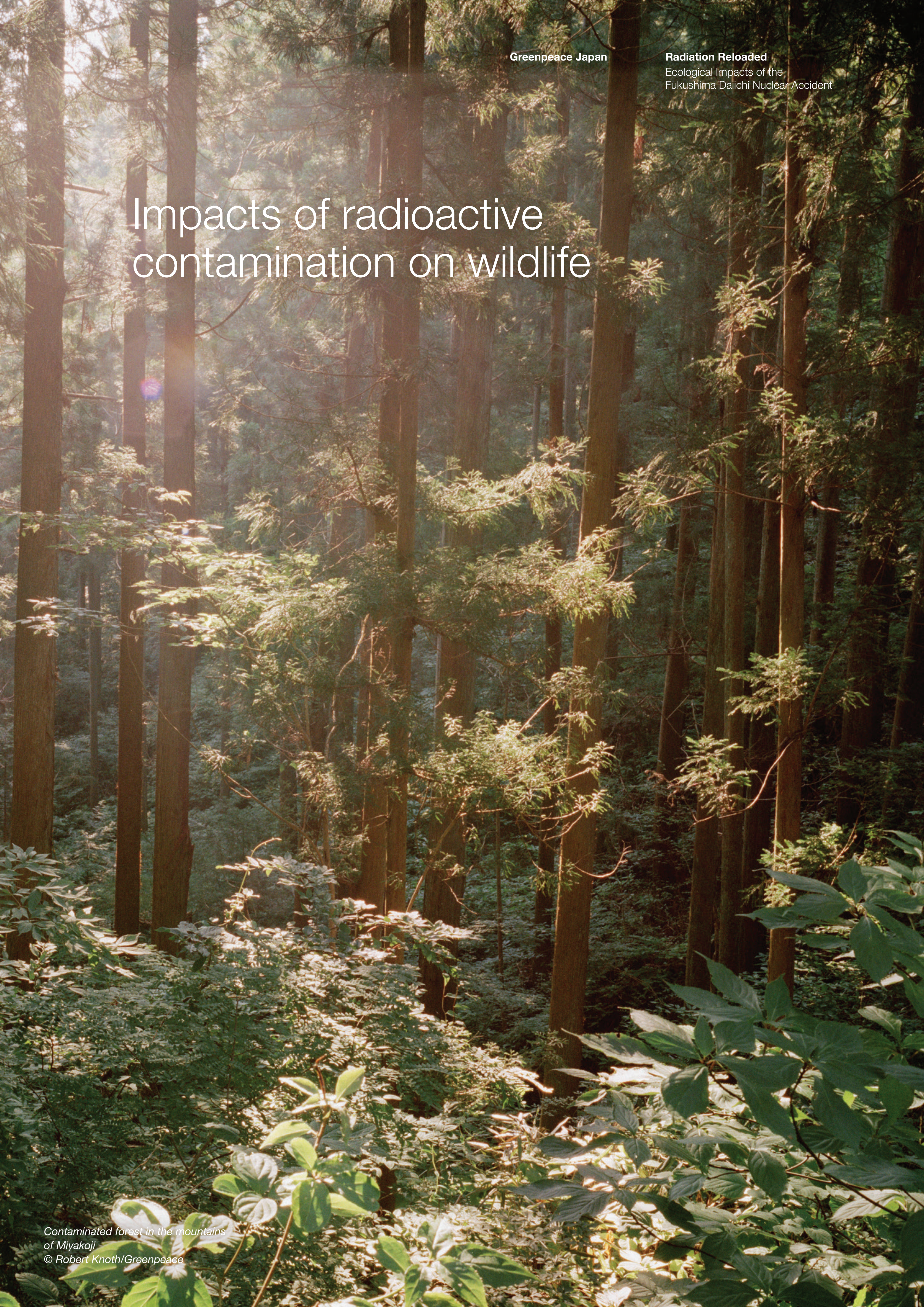
Due to the wetter climate, fire hazards and the threat of fire resuspension of radionuclides are likely lower in Fukushima-contaminated landscapes, even assuming similar slowed litter decomposition rates.

However, that does not mean the risks are nonexistent, by any means. According to the Fukushima prefectural website, forest fires are most likely to occur from March through May, when conditions are drier.[176] The site also states that 43 forest fires were recorded in the prefecture in 2014, which occurred one after another.[177]

A fire hazard analysis of Fukushima concluded that secondary radionuclide emission risks due to wildfire are greatest in the contaminated coniferous forests in the prefecture's foothills, though this spatial distribution can vary significantly with the weather conditions and season.[178]

While there is this current risk of resuspension of radiation due to wildfire, it remains to be seen in the coming years and decades whether significant levels of litter accumulation – and resulting increases in frequency and intensity of forest fires, including crown fires – will also occur in Fukushima forests as it has in Chernobyl.

Impacts of radioactive contamination on wildlife



Contaminated forest in the mountains of Miyakoji
© Robert Knoth/Greenpeace

Impacts of radioactive contamination on wildlife

Assessing ecosystem impacts: failure of the IAEA

As stated above, ionizing radiation is a well-established mutagen – meaning that it changes genetic material in such a way that it increases the frequency of mutations in living organisms, both animal and plant.[179] While plants appear to be more susceptible to the impacts of radiation than animals, the effects across taxa have been shown to be unusually large.[180] However, radiation sensitivity among species, even closely related species, can vary significantly.[181]

In a meta-analysis of Chernobyl studies on the mutagenic effects of the disaster-derived radiation in plants, animals, and bacteria, two world-renowned ecologists[182] A.P. Møller & T.A. Mousseau (2015) concluded:

A meta-analytical approach to examine the relationship between radiation and mutation rates revealed a surprisingly large overall effect size, across all studies and taxa, with the mean effect size exceeding almost all other mean effect sizes reported in the biological sciences. This means that mutation rates increased strongly in contaminated areas compared to control sites with normal background radiation. Furthermore, there were significant differences in mean effect size among taxa, including interspecific differences . . . Our study reaffirms that mutation rates differ widely even among closely related taxa, although based on our study it remains largely unclear why species differ in their resistance to radiation. **The surprisingly high mean effect size suggests a strong impact of radioactive contamination on individual fitness, as well as potentially significant population-level consequences, even beyond the area contaminated with radioactive material.**[183] [emphasis added]

The study also found that these effects did not diminish with time, suggesting that there was no notable improvement in environmental conditions in the Chernobyl-contaminated environment over the nearly three decades since the disaster.[184]

A study led by Dr. Garnier-Laplace – the Head of the Department on Research and Expertise on Environmental Risks for the French government-affiliated agency, Institute for Radiological Protection and Nuclear Safety (IRSN) – found a significant discrepancy between laboratory tests for ecotoxicity of ionizing radiation and field data of chronically-exposed wildlife in the Chernobyl Exclusion Zone.[185] Specifically, the authors found that animals in their natural environment were more vulnerable to the effects of chronic exposure Specifically, the authors found that animals in their natural environment were more vulnerable to the effects of chronic exposure to low-dose radiation than in laboratory and controlled-environment experiments.[186] It was suggested that the reason for greater radiosensitivity in chronically exposed wildlife may be due to the compounding factors of natural stressors (competition, food availability, and predation), though further study was needed.[187]

The authors state:

> *". . . we compared the range of variation of radiosensitivity of species from the Chernobyl-Exclusion Zone with the statistical distribution established for terrestrial species chronically exposed to purely gamma external irradiation (or chronic Species radioSensitivity Distribution e SSD). We found that* ***the best estimate of the median value [Hazardous Dose Rate]*** *(HDR$_{50}$) of the distribution* ***established for field conditions at Chernobyl*** *(about 100 mGy/h)* ***was eight times lower than the one from controlled experiments*** *(about 850 mGy/h),* ***suggesting that organisms in their natural environmental were more sensitive to radiation."***[188] *[emphasis added]*

Further, in a following study:

> *Recently, Garnier-Laplace et al. proposed a re-assessment of inter-species radio sensitivity emphasizing that* ***organisms in their natural environment from the CEZ appeared to be ca. eight times more sensitive to radiation than they were under laboratory conditions.*** *This is not surprising given that organisms under field conditions may suffer from poor nutrition and/or unfavorable abiotic factors, and parasitism and predation with strong effects on abundance and species diversity, while lab populations are usually kept under optimal conditions, partly as a consequence of legislation related to research ethics.* ***Additionally the duration of exposure is clearly a major feature that distinguishes laboratory and field experiments, since for the same exposure dose***

Impacts of radioactive contamination on wildlife

> ***rate, the resulting absorbed doses are drastically different with ultimately much higher doses in the field than in the laboratory.*** *Finally, any shift in sensitivity between field and laboratory may be due to the presence of other stressors such as stable contaminants and/or to selection of strains through phenotypic acclimation, DNA methylation, genetic adaptation across generations, or multigenerational phenotypic effects (e.g., maternal effects).*[189]

The importance of the finding that animals – at least terrestrial animals – in the natural, contaminated ecosystem of the Chernobyl exclusion zone appeared to be ***eight times*** more radiosensitive than in laboratory studies cannot be overstated.

This is particularly relevant with respect to the conclusions drawn by the IAEA regarding the expected ecological impacts of the Fukushima disaster. In its Fukushima Daiichi report summary, the IAEA cites the International Commission on Radiological Protection (ICRP) publication 91 as a primary basis for its methodology in coming to the conclusion that there are no expected ecological consequences.[190] However, ICRP (2003) admit in this publication, that:

> *Although* ***most of our information*** *on the effects of radiation is based on* ***studies of individuals, some field observations*** *on populations, ecosystems, and communities* ***have been made under controlled laboratory and experimental field conditions,*** *and some observations are available from studies made following the accidental releases of high levels of radionuclides into the environment.*[191]

The ICRP then recommends the development of reference organism data sets, to be supplemented with other data if needed (released in later ICRP publications).

In its assessment of the Fukushima nuclear disaster released in 2015, the IAEA admits:

> *The* ***overall uncertainties associated with the types of models applied in this assessment are large, particularly where assumptions about environmental transfers are involved. These assessment methodologies tend to be based on simple assumptions,*** *and uncertainties are usually taken into account by the use of conservative assumptions. The benchmarks used to relate calculated doses to radiation effects are* ***primarily related to chronic rather than acute exposures and to a limited range of individual organisms rather than populations or ecosystems. The current methodologies do not take account of interactions between components of ecosystems or the combined impact of radiation and other environmental stressors.***[192] *[emphasis added]*

Thus, the ICRP methodology that the IAEA relied upon for its assessment of ecological consequences from Fukushima was created as a framework based largely on data from laboratory and controlled-environment studies – which current research has demonstrated may result in significant underestimations[193] of risks.

The IAEA further admits its “conservative assumptions” are limited to individuals, and that it completely failed to consider the very factors that may be responsible for increased uptake of radionuclides[194] and significantly increased radiosensitivity in organisms in their natural environment.[195]

As such, the IAEA’s prediction of no ecological impacts from the Fukushima disaster is based on potentially erroneous assumptions.

Chronic radiation exposure: documented consequences

Even if the failures in the methods used by the IAEA to come to the baseless conclusion that there will be no expected ecological impacts from the Fukushima disaster were not so readily apparent, the evidence from Fukushima field studies would also prove the IAEA to be wrong in its ‘predictions’ – even before the IAEA “Fukushima Daiichi Accident” report was released in September 2015.

As previously discussed, in August 2015, a team of scientists led by the National Institute of Radiological Sciences in Japan confirmed that fir trees in Fukushima-contaminated forests were showing increases in morphological defects after the 2011 accident, that the incidence of the defects between test sites increased with increasing radiation levels, and that the observed “defect” was very similar to growth mutations observed in coniferous trees in Chernobyl contaminated forests.[196]

Swallow, Chernobyl Exclusion
Zone 2007
©Andrea Bonisoli Alquati

Further, with regard to animal impacts, a four-year study (2011-2014) in the 50 km zone northwest of the crippled Fukushima Daiichi plant, investigated the condition, reproduction rates, and abundance of birds and other animals.[197] The study states that:

> *Among the 57 species constituting the observed bird community, we found that 90% were likely chronically exposed at a dose rate that could potentially affect their reproductive success. We quantified a loss of 22.6% of the total number of individuals per increment of one unit log10- transformed total dose (in Gy), over the four-year post-accident period in the explored area. We estimated that a total dose of 0.55 Gy reduced by 50% the total number of birds in the study area over 2011–2014.*[198]

In simpler terms, the authors confirmed that in the 2011-2014 period, the abundance of birds in Fukushima decreased with increasing dose rates, and that 90% of the 57 observed species were chronically exposed at levels that could impact their reproduction.

It was also noted that increased dose rates appeared to be associated with increased species diversity (i.e. the number of different species of birds in a given area/community). The authors speculate that the increase in species diversity in a community may be the indirect result of the decrease in abundance.[199]

An investigation in Fukushima of barn swallow (Hirundo rustica) nestlings exposed to chronic low-dose radiation did not find any genetic damage attributable to radiation exposure.[200] This was somewhat in conflict with findings of genetic damage in adult Chernobyl barn swallows at comparable radiation levels, though it is difficult to say whether the impacts on nestlings and adults could be expected to be the same. The authors suggested that this current difference in Fukushima nestlings could be due to a number of factors, including: a difference in the radionuclide profiles released in the accidents, shorter exposure times for Fukushima nestlings as compared to Chernobyl adults, and the cumulative effects of chronic low-dose exposure over generations (the Chernobyl bird populations had been exposed to low dose radiation over 20 years at the time of the sampling).[201]

However, the study did find that:

> *. . . at higher levels of radioactive contamination the number of barn swallows declined and the fraction of juveniles decreased, indicating lower survival and lower reproduction and/or fledging rate. Thus, genetic damage to nestlings does not explain the decline of barn swallows in contaminated areas, and a proximate mechanism for the demographic effects documented here remains to be clarified.*[202]

Impacts of radioactive contamination on wildlife

The decline in juveniles appears to be consistent with findings of decreased fertility, as documented in barn swallows in Chernobyl.[203]

This impact on bird reproduction would also be consistent with the findings of the 2011-2014 Garnier-Laplace, et al. (2015) study, which showed that 90% of bird populations studied in the 50 km zone northwest of the Fukushima Daiichi plant were chronically exposed to levels of radiation that could impact their reproductive success.[204]

Other wildlife populations in Fukushima-contaminated ecosystems have been studied in the wake of the disaster. A 2012 combined laboratory and field study of the pale blue grass butterfly (Zizeria maha) found numerous abnormalities in Fukushima exposed individuals and their offspring, including: "morphological malformations in various parts including legs, antennae, palpi, eyes, abdomen, and wings. In addition to dented compound eyes, the entire eye structure was deformed in a pattern similar to that of Drosophila Bar mutants. Wing aberrations, including broken or wrinkled wings, were found in many individuals. Asymmetric hindwing size reduction was observed in a few individuals. Colour-pattern changes were relatively frequent."[205] Further, it appeared that these abnormalities were heritable across generations.[206]

Some criticisms were raised after this study was published, which the authors addressed in more depth in 2013, and further clarified the significance of their findings.[207] The observed impacts in the field may also be attributed, at least in part, to the likely higher radiosensitivity of species in their natural environment.[208]

Another invertebrate study showed that earthworms in the high-dose Fukushima contamination zone had significantly higher levels of DNA damage as compared to worms collected in a low-dose zone.[209]

In addition, a study of gall-forming aphids (plant lice) found significantly higher mortality rates and morphological defects – namely crooked and missing limbs – in Fukushima lice collected in 2012 and 2013, as compared to those collected in control sites.[210] The 2013 Fukushima samples appeared to be healthier than 2012 lice, which suggests either reduced levels of radiation (possibly due to the recorded decay of shorter-lived radionuclides such as ^{131}I and ^{134}Cs in the initial years after the accident) or to adaptation to artificial radiation.[211]

Another study of the pale blue grass butterfly also suggested that there was some evidence of adaptation to radiation in Fukushima over the course of two years, though the authors point out that this is a tentative conclusion.[212]

It is important to understand that some adaptation to radiation is to be expected amongst some species, particularly those that are adapted to other stressors such as living in higher natural radiation environments, e.g. areas exposed to significant amounts of sunlight.[213] Insects are also generally characterized as being more resistant to radiation than some other organisms.[214] Further, there appears to be a limit, or constraint, on the ability of organisms to adapt to the mutagenic effects of ionizing radiation.[215] Also, as discussed previously, radiosensitivity is highly species-dependent.[216]

In their discussion of the appearance of adaptation for the Blue Grass Butterfly, W. Taira, et al. (2014) state:

> *It is important to note that not all individuals died at the same age even under a given irradiation condition in the external and internal exposure experiments.* ***Among those that survived, some were sick or weak, and some were very robust or strong.*** *This variation provides the basis of the evolution of radiation resistance. In the field, this inherent variation at the population level may be enhanced by the introduction of random genetic mutations caused by irradiation,* ***although most of the induced mutations may be harmful or functionally neutral.***

In simpler terms, the evolution of radiation resistance assumes that if the individuals of a species that are "susceptible" or "weak" either die or fail to reproduce due to exposure to artificial ionizing radiation from man-made, highly radioactive substances introduced into the environment, then those that are more resistant to radiation will have a higher survival and reproduction rates and become more common in the population, because all other individuals were "eliminated" and could therefore not reproduce.

The researchers noted that the butterfly populations appeared to begin to recover, with the exception of one population that was severely impacted by ^{131}I. However, this should not be confused with a restoration to pre-disaster health or abundance.[217] Rather, survival rates seemed to improve when compared to the decimated populations in the most acute stages of radiation impacts for this species after initial radiological contamination.[218]

Impacts of radioactive contamination on wildlife

Again, this also raises the question as to whether the decreases from the significantly elevated mortality rates of 2011 is evidence of increased radiation resistance among surviving members of the Fukushima blue grass butterfly populations – especially after such a short time – or whether the increases in survival rates is the result of decreases in radiation levels as shorter-lived radionuclides, ^{131}I and ^{134}Cs, decay. As these initial phase radiation decreases are expected to bottom out within five years, and perhaps begin to reverse as discussed above, it will be interesting to see what impact this has on the ongoing trends in the survival rates and fitness of this species.

Studies from Chernobyl would also teach caution when approaching conclusions of supposed adaptation to artificial radiation in the environment. Reviews of such studies reveal that they largely fail to provide convincing evidence to support their conclusions – due to small sample sizes, inadequate spatial distributions of survey sites, and questionable methods.[219] Further, there is no evidence to support hormesis (the supposedly “beneficial” effect of low levels of radiation on organisms, which has been touted by some in the pro-nuclear village) in any of these studies.[220]

For example, one of these studies, released in 2015,[221] which received quite a bit of attention claimed that some animal populations, such as wolves and elk, are thriving in the Chernobyl exclusion zone. The authors suggest that, despite whatever negative impacts there maybe of chronic radiation exposure, the release of the land from human use allowed the animals to flourish. However, the study was met with criticism from other ecologists, who pointed out the significant flaws in its methods and sampling:

> *A recent study suggested that some large mammals, particularly those normally under significant hunting pressure, were thriving inside the Belarusian part of the Chernobyl Exclusion Zone. The data presented* ***only showed a partial rebound of some mammals following the initial highly deleterious effects of the disaster,*** *while the* ***data*** *for contemporary population densities* ***were primarily collected in regions of relatively low radioactivity while ignoring large regions of intermediate and high radiation levels in both Belarus and Ukraine*** *(e.g., the region in and around the so-called ‘Red Forest’), thus lowering the statistical power of any potential tests for radiation effects. In addition,* ***there was no attempt to estimate the internal dose of the species concerned.*** *Furthermore,* ***attempts made to correct for confounding factors,*** *such as habitat type or human habitation,* ***were inadequate and conducted at a geographic scale likely to obscure any relations with radiation effects,*** *which are highly heterogeneous.* ***Finally, no rigorous attempt was made to compare suggested population trends to those from other wildlife refuges in Europe. Overall, the reported findings do not address the issue of whether populations have adapted to the radiological conditions found inside the Chernobyl zone.***[222]

As such, while some adaptation in some species might be expected, conclusions purporting to show such effects should be approached with caution as most studies still largely fail to provide convincing evidence – even in Chernobyl, which has a much longer timeframe, compared to Fukushima, for such adaptations to take place.

While the particular studies related to radiation adaptation are largely questionable due to various critical shortcomings in the studies’ designs, an examination of Chernobyl wildlife impacts does provide useful insights into potential future consequences in Fukushima over generations in the coming decades.

Extensive long-term studies in Chernobyl have shown developmental abnormalities in animal populations. A.P. Møller, et al. (2011),[223] noted decreases in brain size with increases in ambient radiation levels in an extensive study of Chernobyl birds, which included 48 species and 550 individuals.[224] The authors state that radioactive environments increase oxidative stress in animals. Brain development is a costly process in oxidative terms. Exposure to ionizing radiation is costly in terms of increased oxidative damage to tissues. Thus, during development organisms exposed to radiation cannot ‘afford’ to build big brains, because the antioxidants required are being allocated to fight against the oxidative damage due to radiation.

Professor Tim Mousseau, University of South Carolina, studies the impact of radioactive contamination on moth and bird life in Iitate district, Katsurao, Japan, 14 July 2015. ©Sutton-Hibbert/ Greenpeace 2015, all rights reserved

In addition to smaller brains, an extensive study of birds in Chernobyl showed increased incidence and intensity of cataracts with increasing radiation levels.[225] Cataracts can be caused by exposures to ionizing radiation, as documented in acute doses in humans. However, the effects of chronic exposure to low-dose radiation in other animals are not well understood.

For wildlife cataracts can have significant fitness and survival costs.[226] Or, as the authors plainly put it, “Cataracts are a rare phenomenon in wild animals because any deterioration in vision will likely very soon be followed by death due to predation or lack of ability to find adequate and sufficient food for survival.”[227]

And indeed, increased cataract incidence was associated with depressed breeding population size in Chernobyl birds.[228] Though, it is difficult to say what percentage of the population decline was due to the directly to the higher mortality risks associated with the increased cataract formation as a result of higher radiation dose levels and what percentage of the population decreases is a result of other oxidative stress as a result of chronic exposure to low dose radiation.[229]

Another study of Chernobyl birds showed higher levels of tumor incidence and albinism in these populations than had been previously reported.[230] Further, like cataracts, rates of tumor formation and albinism increased in correlation with rising radiation levels, and population size was likewise depressed.[231]

Further, mammalian studies have also shown notable impacts from radiation exposure. Most recently, a study of Chernobyl bank voles showed higher rates of cataract incidence with increased accumulated doses. This relationship was only significant for female bank voles. The authors suggest that the most plausible explanation for this sex difference is due to the higher oxidative stress of reproduction for females, though there may be other factors as well.[233] Further, cataract incidence in females was associated with decreased fertility, suggesting negative impacts of cataracts on reproductive success.

Thus, from both studies in Chernobyl, as well as those in Fukushima, the negative impact of chronic low-dose exposures on wildlife due to radiological disasters is quite significant. And, if Chernobyl is a guide, then we can expect to see increases in negative consequences for Japanese wildlife in Fukushima-impacted ecosystems.

Watershed contamination

Mai Suzuki holding a sediment sample while conducting radiation survey work from Asakaze, a Japanese research vessel chartered by Greenpeace Japan. Greenpeace is doing a seabed survey, sampling marine sediment off the coast of Fukushima.
©Christian Aslund

Watershed contamination

It is well understood that forest ecosystems act as vast reservoirs for radioactivity. Similar to –and likely in concert with – the high mobility phase of caesium in forest soils which show rapid vertical penetration of a small percentage of the caesium inventory following initial radiological deposition, in watersheds, a portion of the radiocaesium migrates to water systems (i.e. through rapid washoff). The remainder is stored in the catchment for long-term migration.[234]

However, even with low discharge rates[235], the redistribution of caesium via watersheds can be significant due to the sheer magnitude of the vast contaminated forests and land.

Fukushima prefecture, and neighboring prefectures with contaminated upland forests, have a number of major and minor river systems that flow from contaminated forested uplands and coastal plains to the Pacific Ocean. These river systems, in particular the Abakuma, Naruse, Nanakita, Natori, Kuji and Naka, as well other smaller river systems including the Mano, Nitta, Ota, Udaka and Ukedo have catchments of thousands of square kilometers.

For example, a study of the Abukuma River catchment between June 2011 and May 2012 estimated that ~1% of the initial deposit inventory had been exported to the Pacific Ocean.[236] However, the total amount of the radiocaesium discharge during this time was within an order of magnitude of the Level 3 event on August 21 2013, wherein 24 TBq were leaked directly from the Fukushima Daiichi plant into the ocean.[237]

Further, Fukushima's rivers are used both for drinking water and directly for irrigation of rice paddies and other agricultural crops. Thus, contamination of the rivers not only presents a downstream threat to aquatic and marine ecosystems, but also presents a direct exposure risk for people using and accessing the rivers.[238]

According M.A. Pratama, et al. (2015), the discharges to the ocean from the major rivers in Fukushima (the Abukuma, Arakawa, Naka, Agano, and Tadami rivers) could be as high as the discharges from the Fukushima Daiichi plant itself.[239] The study estimates that in the century between 2011 – 2111, the Abukuma River alone will discharge 111 TBq of 137Cs and 44 TBq of 134Cs, even with current rates of "decontamination".[240]

It is crucially important to understand the dynamics of the transfer of radiocaesium from the terrestrial to aquatic to marine systems given the potentially enormous caesium discharges over the coming years and centuries from land to ocean. This is of particular importance given the potential transfer from the abiotic (e.g. non-living plant material, minerals, etc.) to the biotic marine systems (i.e., aquatic & marine plant and animal life – including the potential contamination of species consumed by humans).[241]

Riverine contamination

The topography of Fukushima prefecture is characterized by steep slopes, more gradual foothills, and flat coastal flood plains. As discussed above, the upper regions are covered in dense, mature forests and tree plantations – interspersed with rice paddies, homes and other agricultural fields. Its climate is highly erosive, with typhoons in the fall and snowmelt in the spring.[242] During significant rainfall events, typhoons, and spring snowmelt, the stocks of radiocaesium in forests, hillslopes and floodplains can be remobilized and can contaminate areas downstream – including those that did not receive fallout from the radioactive plumes, as well as areas that have already been decontaminated.[243]

Whether radiocaesium is transported via particulate matter (i.e. bound to minerals) or dissolved in water is a critical factor in understanding both its movement and its bioavailability – this is expressed as the Kd factor. Fukushima discharges have been documented to have a Kd factor 1-2 orders of magnitude higher than those found in Chernobyl watersheds in the initial years after the disaster.[244] This means that the ratio of particulate bound caesium transported in Fukushima river catchments in relation to dissolved (bioavailable) caesium was an order of magnitude or two higher than that in Chernobyl.

This has been attributed to several factors, including higher precipitation levels in Fukushima as compared to Chernobyl, the high clay content of Fukushima soils and that the fine clay particles to which caesium has a particular affinity are also the preferentially eroded soil particles – i.e. the fine particles[245] that most of the mineral-bound caesium are attached to are also the most likely to be carried into forest streams by rain and over long distances in rivers.[246] It's been further suggested that some of this particulate caesium in rivers is not mineral-bound, but rather wash-down of the hot glassy particles that were also released in the most acute phases of the radioactive releases.[247]

Near Iitate 2012
Emergency workers stand in an uncultivated rice paddy
©Andrea Bonisoli Alquati

According to one study, an estimated 84-92% of the radiocaesium transported in the Abukuma watershed was carried as suspended solids between August 10, 2011 and May 11, 2012.[248] The authors further state that:

> *The total flux of radiocesium into the Pacific Ocean estimated at the outlet station (basin area 5,172 km2) was 5.34 [Terabecquerels] TBq for 137Cs, and 4.74 TBq for 134Cs, corresponding to 1.13% of the total estimated radiocesium fallout over the basin catchment (890 TBq).* ***This was equivalent to the estimated amount of direct leakage from FDNPP to the ocean during June 2011 to September 2012 of 17 TBq and the Level 3 Scale Leakage on 21August 2013 (24 TBq).***[249] *[emphasis added]*

In particular, typhoons cause significant increases in caesium discharges. This study estimated that storm-mobilized caesium discharges were at 6.18 TBq, accounting for 61.4% of the total caesium discharges to the coastal areas during the observation period.[250]

Another study of the Natsui River and the Same River in 2011 reported that heavy rain and Typhoon Roke were responsible for 30-50% of the total annual radiocaesium flux to coastal regions for these rivers.[251] Further, during base-flow conditions, the particulate fraction of the total radiocaesium inventory was between 21 – 56%, but increased to nearly 100% after Typhoon Roke.

A 2013, study of low-flow, low turbidity conditions (base flow) in the Mano, Nitta, Ohta, Odaka, Ukedo and Takase Rivers in northern part of Fukushima prefecture found that contaminated organic matter, e.g. leaf litter, constituted a significant vector within the river catchments for the transport of radiocaesium from forests.[252] The authors further suggest that the presence of micrometer contaminated organic debris could be partly responsible for relatively high radiocaesium concentrations in sandy soil samples.

Further, according to another study of contaminated litter in forest streams impacted by the Fukushima disaster, water is able to leach radiocaesium from the litter under natural conditions and sorption with minerals in the water – in particular, vermiculite – could then take place.[253]

This role of contaminated forest organic matter not only has implications for the transport of radiocaesium to marine ecosystems, but also has potentially significant implications for rice paddy cultivation in the mountainous region. In a 2011 case study, surveys showed in

September that radiocaesium concentrations in brown rice were below detection limits in most of the test site, and the highest levels found were ¼ of the provisional limit.[254] However, a subsequent survey found that radiocaesium concentrations were nearly or greater than 500 Bq/kg in many samples taken from paddies in the hilly areas of Fukushima prefecture. These levels were "extraordinarily" high – 100 times or more – than the levels in the flatland rice paddies.[255]

The significant uptake of the brown rice in the lowlands of the foothills in the prefecture was attributed largely to the decomposition of contaminated organic matter.[256] These paddies are considered wetland ecosystems (albeit cultivated). In the summer months, when temperatures climbed above 30°C (86 ºF), decomposition of contaminated organic matter already present in the rice paddies (e.g. crop residues and weeds) would have increased releasing the caesium they contained into the paddies. The authors suggest that in the stagnant wetland ecosystem of the paddies, there were few suspended minerals in the water column. As the caesium was released in the water – and in a bioavailable ionic form – it was absorbed by root systems before it could be bound in minerals and rendered unavailable.[257]

The levels of caesium in the lowland paddies could have been further compounded by mountain runoff containing contaminated litter and debris. Many of the paddies in this study that exceeded the provisional limits at the time for radiocaesium concentrations used mountain runoff for irrigation.[258] This is otherwise very sustainable way to grow rice, being that mountain runoff is a natural source of concentrated nutrients, such as potassium and magnesium. But, this normally abundantly healthy and sustainable farming method had been corrupted by Fukushima disaster, and thus the same mechanism that naturally nourished these rice paddies was the reason for their very high levels of radioactive contamination.[259]

Further, another case study of impacted rice paddies compared the export of radiocaesium from a decontaminated paddy, which had 95% of fallout caesium removed, and one that had not been decontaminated. Surprisingly, the discharge of radiocaesium was greater from the decontaminated paddy than from the non-decontaminated paddy.[260] In this study, the authors attributed to high export rates of radiocaesium in the "decontaminated" paddy to high levels of mineral-bound caesium in the upstream water flowing into the paddy.

Freshwater Aquatic Ecosystems: Rivers, Ponds, Lakes & Freshwater Fish

Freshwater ecosystems are particularly vulnerable to radioactive contamination – more so even than their terrestrial counterparts – as has been studied extensively in Chernobyl impacted areas in Western Europe, Russia, and the Ukraine.[261]

In addition, there are differences in the recycling of radionuclides in freshwater and marine ecosystems. While the impacts on coastal and marine ecosystems from radioactive contamination are, and will continue to be, significant, freshwater aquatic ecosystems appear to be even more vulnerable.

The accumulation of radiocaesium in Fukushima-contaminated freshwater fish is approximately 100 times higher than the concentrations in marine fish.[262] This may be due to the fact that freshwater systems tend to be poorer in potassium, the chemical analogue of caesium, which accelerates caesium uptake of freshwater biota.[263] This is further compounded by differences in osmoregulation between freshwater and marine fish.[264] Freshwater fish maintain higher plasma osmolality, which results in higher concentrations of monovalent and divalent ions than the water in which they live. This explains, in part, longer biological half-times of caesium for freshwater fish as compared to marine teleosts (ray-finned fish), which actively excrete ionic caesium through their gills.[265] Simply put, freshwater fish tend to retain radiocaesium, whereas a major class of marine fish excretes it through their gills (though marine fish also retain caesium as well, just not as much per amount ingested).

This does not mean that there is an insignificant amount of contamination in marine fish, as high concentrations have been documented and persist, particularly in demersal marine fish (bottom-dwellers).[266]

In lakes, particulate-bound radiocaesium in sediments can result in extremely high concentrations compared to surrounding waters.[267] But, these bonds are not necessarily irreversible. In fact, it's been demonstrated that Cs+ is weakly bound and relatively mobile in organic-rich lake sediments – which means that it may become liberated from sediment particulates, and therefore become bioavailable.[268]

Natural lakes cycles can further extend contamination timeframes due to the resuspension of contaminated sediments and organic matter. For example, lake turnover – which is more pronounced in larger lakes – is the mixing

Watershed contamination

The upland forests and river catchments store radiocaesium for long-term discharge to fields, rice paddies, freshwater lakes and coastal ecosystems. Projections for discharges from Fukushima River catchments to coastal systems alone with current "decontamination" rates are 111TBq of ^{137}Cs and 44TBq of ^{134}Cs — or the approximate equivalent of the continued radioactivity hemorrhaging from the plant itself.

of water of different densities due to thermal radiation, which happens in spring and autumn in most lakes; i.e., water at different temperatures has different densities. In summer and winter, these water bodies have distinct layers in the water column – high-density cool water at the bottom, water of intermediate density and temperature in the middle, and the warmest layers at the top.[269] When the upper layers cool in the Fall, the density increases. As the water in the entire column reaches the same temperature and density, mechanical mixing (i.e. wind and wave action) of the entire body of water can take place. As the lake continues to cool, the density of the upper layers is greater than those below, and the water sinks. This displaces the bottom water, which is forced to the top of the lake, accelerating the mixing of the entire body of water. This mixing also happens in spring due to temperature changes (melted ice, being cooler than the water below, sinks) though spring turnover less dramatic than the mixing that happens in Fall.

As any freshwater fisherman can attest, when lakes turnover, they become quite murky – sometimes with flotsam and debris from the decaying matter floating on the surface.[270] This process is very important for re-oxygenating the lake water from the surface layers, and for redistributing nutrients from bottom of the lake – and this means that not only dead organic material, but sediments are resuspended into the water column.

It has been demonstrated from studies of Chernobyl that this and other natural processes can create periods of "intensive 137Cs recycling" in lakes, and may be part of the reason for slow contamination reduction rates.

The resuspension of caesium-bound sediments and the bioavailability of caesium in aquatic ecosystems not only has a significant impact on the aquatic ecosystem itself, but creates a long-term exposure hazard for terrestrial animals (people included) through external exposures – and more significantly, internal doses from the consumption of contaminated aquatic organisms.[272]

Thus, like in contaminated forests, it is important to understand the processes that cycle radiocaesium in the ecosystem, and extend the period of high contamination for years and even decades. In addition to the abiotic processes discussed above, aquatic biota play a significant role in recycling caesium. Microbial activity (e.g. zooplankton, phytoplankton, cyanobacteria) can significantly extend the time in which radiocaesium is present in the water column.[273]

Further, freshwater benthic invertebrates (small animals without a backbone that live in the sediments of streams, rivers, and lakes) play a critical role in aquatic food webs and thus also in the cycling of radiocaesium. Their role in the food web is described thus:

> *Benthic invertebrates are estimated to process 20–73% of riparian leaf-litter inputs to headwater streams. Second, benthic invertebrates release bound nutrients into solution by their feeding activities, excretion, and burrowing into sediments. Bacteria, fungi, algae, and aquatic angiosperms can quickly take up these dissolved nutrients, accelerating microbial and plant growth. This increased growth of benthic microbes, algae, and rooted macrophytes is in turn consumed by herbivorous and omnivorous benthic invertebrates. Third, many benthic invertebrates are predators that control the numbers, locations, and sizes of their prey.*

Watershed contamination

> *Fourth, benthic invertebrates supply food for both aquatic and terrestrial vertebrate consumers (e.g., fishes, turtles, and birds). Finally, benthic organisms accelerate nutrient transfer to overlying open waters of lakes as well as to adjacent riparian zones of streams.*[274]

This remobilization of particle-bound caesium by these organisms is particularly important, due to the rapid transfer of Cs+ across trophic levels.[275] As noted by the Nordic Nuclear Safety Research 1995 technical report, benthic species ingest contaminated sediment, resulting in the direct uptake of radiocaesium into the food web.[276] Although sediment-bound caesium is poorly assimilated in organisms as compared to caesium in tissues, this is still an important transfer mechanism due to the large inventories and very high ^{137}Cs concentrations found in sediments.[277]

It's important to note, however, that at least for aquatic insects, caesium concentrations do not appear to be correlated to air dose rate itself.[278] According to a study by Y. Mayumi & A.Akio (2014)[279], water insects were contaminated even when air dose rates were low (160km from the Fukushima Daiichi plant). Other factors, such as habitat and adapted behaviors, appear to influence contamination – for example, pool-dwelling aquatic insects had higher concentrations of caesium than their riffle-dwelling counterparts. Further, caesium concentrations were not higher in the substrate of the pool as compared to the riffle. Rather, the authors suggest that the higher concentrations in pool-dwellers is due, in part, to the behaviors of the insects in these respective habitats – riffle dwellers being adapted to collect floating organic matter, while pool dwellers use benthic organic matter. Due to the fact that in stagnant water, contaminated sediments drop out of the water column along with organic particulate matter, the pool-dwelling insects became contaminated with high levels of caesium due to their borrowing in contaminated sediments and ingesting organic material.[280]

Additionally, as discussed in relation to the leaching of caesium from contaminated organic matter into streams, rivers, and rice paddies, submerged litter and continual forest inputs of contaminated organic matter (streams and rivers feeding the lake) can increase the caesium inventory in lakes. It has also been noted that organic litter can leach radiocaesium for up to 300 days.[281] Further, certain species of aquatic animals at various trophic levels may consume contaminated organic detritus directly (e.g. microorganisms, benthic species, fish).

However, as should be expected, there have been reductions in caesium concentrations in freshwater fish species over the past nearly five years since the disaster. This declining trend may level out in the next year according to the Nordic Nuclear Safety Research (1995)[282] technical report on the fate of radiocaesium in contaminated freshwater ecosystems. The authors note:

> *In lake ecosystems, the initial dynamic phase of contamination and equilibration after fallout of Cs-137 lasts up to five years and appears to be largely ruled by biological processes. After that, Cs-137 activities in fish approach a "steady" state, with a slow decline that is probably controlled by continuous secondary inputs of Cs-137 into the lakes and their food webs.*[283]

Thus, similar to the forests ecosystems discussed above, reductions in caesium concentrations could potentially bottom out in the relatively near future, followed by a fairly stable phase of persistent contamination with gradual declines.

The contamination of freshwater fish is of particular concern with regard to human exposures due the fact that many of these species are commercially important both as food sources and for recreational fishing.[284] Given that caesium accumulates in muscle tissue, i.e. the edible parts of the fish, the consumption of contaminated fish is a major potential internal exposure pathway and can, therefore, pose significant human health risks.[285]

An important factor that influences radiocaesium concentrations in fish is its trophic level. In short, species at the top of the aquatic food chain – omnivorous and piscivorous fish – tend accumulate radiocaesium more slowly (due to gradual food chain transfer). However, these species bioaccumulate higher concentrations and show persistent contamination for longer periods of time.[286] A 1998 study of 137Cs in freshwater systems in Canada shows significant biomagnification across trophic levels, with a four-fold increase in caesium concentrations with each trophic level.[287]

This magnification was consistent with the findings in Fukushima-impacted freshwater systems as well.[288] Multiple studies have confirmed higher concentrations and very gradual reductions in top fish species, such as the masu salmon, white spotted char, rainbow trout, and the Japanese dace, though high concentrations were also found in species such as the ayu and smelt.[289]

Watershed contamination

One study conducted between March 2011 and December 2014, which included 16 different fish species from 3 different habitats – described as rivers, lakes, and culture ponds (though irrigation channels were included in this category) – found that the highest concentrations for several species at the highest trophic levels were found in 2012 or later, which is consistent with observed lag time for food chain transfers in Chernobyl studies.[290] In contrast, some smaller fish species and filter feeders reached maximum concentrations 59-140 days post-deposition. Carnivorous and omnivorous species – masu salmon, white spotted char, and Japanese dace – in the Ura-bandai Lakes (comprised of Lake Hibara, Lake Akimoto, and Lake Onogawa) did not reach maximum concentrations until 217-400 days post-accident.

Further, the studied fish had a longer calculated biological half-life for radiocaesium in freshwater fish than had been previously been reported for freshwater fish.[291]

It was found that radiocaesium concentrations varied significantly between different habitats. Concentrations in river and lake dwelling fish were higher and decreased much more gradually than the fish in cultured ponds – which, the authors state, is evidence that the majority of radiocaesium in wild species is accumulated through the food web.

During the years 2011-2014, the percentage of samples above detection limits for rivers, lakes, and culture ponds were 68.5%, 83.9%, and 8.5%, respectively. Maximum concentrations and the percentages above detection limits decreased across the span of the study for all 16 species in all three habitat types. However when the samples from the (less contaminated) western part of Fukushima Prefecture were excluded, the percentages of samples above detection limits rose to 87.9% for rivers and 100% for lakes.[292] For the observation period, of the 16 species tested, 14 were above the Japanese government limit of 100 Bq kg-1 wet: 9 in rivers, 8 in lakes, and 3 in culture ponds.[293]

High deposition densities and air dose rates were positively correlated with higher caesium concentrations – which the authors attributed to the likely higher concentrations of ^{137}Cs in food organisms, such as zooplankton and water insects.

The researchers noted that overall concentrations have decreased gradually – something they attribute to the decay of shorter-lived radionuclides like ^{134}Cs and a decrease in inputs from the surrounding environment (which would be consistent with the stages of caesium cycling in forest systems after deposition). However, even with these decreases, some freshwater fish samples still exceed the Japanese limit of 100 Bq kg^{-1} wet, even in 2014. According to the Japan Ministry of Agriculture, Forestry, and Fisheries, these were 3.6% for river samples and 15.4% for lakes[294] – though, these percentages would average the prefecture as a whole. As previously noted, there have been far greater reductions in the less-contaminated western portions of the prefecture, which would result in lower overall figures.

A case study of Lake Chuzenji[295], located 160km from Fukushima Daiichi, would further support the conclusion that both habitat and trophic level play an important role in the accumulation of radiocaesium – though other factors such as metabolism can play a role as well. The Lake Chuzenji watershed received between 8 – 36 kBq/m^2 of radiocaesium[296] – quite significant, but still far lower than the highest concentrations in the trace northwest of the reactor site.

The study included masu salmon, kokanee, brown trout, and lake trout, collected between September –December 2012. Mean muscle concentrations for all four species were 142.9–249.2 Bq/kg. Co-distributed species, rainbow trout, freshwater goby, smelt, and others also tested above the regulatory 100 Bq kg^{-1} wet limit.[297]

In addition, the study found that even among the same species, concentrations varied dependent upon dominant prey species. For example, brown trout were collected from two habitats in the Lake Chuznji system, including the lake and a tributary feeding the lake. Brown trout living in the lake primarily prey upon benthic gobies and smelt. However, those collected in a tributary stream primarily feed on aquatic and terrestrial insects. Those from the tributary had lower concentrations of radiocaesium, though they were collected nearby the lake, in the same water catchment. This suggests that dietary difference was likely responsible for the markedly lower caesium concentrations in stream-dwelling fish.[298]

As of June 2014, all salmonid fishing activities in the lake were prohibited – except for catch and release.[299]

Thus, like in forest ecosystems, the length of time that radiocaesium is present in the systems is greatly influenced by both abiotic and biotic processes. Lake turnover, continual slow leaching from the contaminated watershed, typhoons and other processes can resuspend contaminated sediment and organic matter – i.e. rather than caesium simply being buried under newer sediments, it can be mechanically remixed by these processes

Watershed contamination

creating secondary contamination. In addition, the contaminated suspended particulates and organic matter brought down from forests and fields with heavy rains and typhoons will create continuing inputs of radiocaesium into lakes for years and decades to come.

In addition, Cs+ is transferred through aquatic food webs with high efficiency, and biomagnification results in increasing concentrations – potentially up to a four-fold increase – at each trophic level.

This means that many of the species commonly consumed and recreationally fished in Japan may have some of the highest concentrations of radiocaesium. These high levels in omnivorous and piscivorous fish are likely to persist for extended periods of time – particularly in the heavily contaminated areas.

Also similar to forest ecosystems, aquatic ecosystems experience a phase of initial flux up to five years after radiological contamination. After that time, decreases tend to bottom out and thereafter remain fairly stable – with gradual decreases mostly due to decay times for radionuclides and further fixation of caesium. Thus, nearly five years post-disaster, we may expect the initial declining trends to level out – and the impacts on the aquatic ecosystems, particularly in heavily contaminated regions, to persist for years or decades to come.

Dams and reservoirs

It is worth noting that studies of dams and reservoirs in Fukushima-impacted watersheds have been shown to be both sinks for radiocaesium and potential sources of significant downstream caesium deposition.

In one study of the Niida and Mano coastal catchments, a large dam in the Mano River played a significant role in reducing the amount of downstream sediments attributable to upstream areas.[300] For the Niida River, 47% of the coastal sediment sampled was attributed to upstream areas, vs. 19% for the Mano coastal sediments.

The authors also state:

> *It has been demonstrated that decontamination may potentially increase the dose rates measured in river sediment. Therefore, the increased contribution of the upstream soils to the coastal plain sediments could be related to the occurrence of these decontamination works.* [301]

As will be discussed in the Iitate case study, though there may be some reductions in contamination levels, there is a serious question of prioritization – i.e. areas where there are hot spots or lower levels in which people are actually living are being neglected in favor of massive and largely ineffective measures in heavily contaminated areas, like the mountainous region of Iitate. Given the very limited success – despite the admirable and hard work of the thousands of decontamination workers – it was already apparent that the choice of where to focus such efforts was driven by politics and a desire to create the impression of a return to normalcy after the disaster, rather than science or human health concerns. This will be discussed further in the Iitate case study below. However, the potential downstream impacts due to increased inputs of radioactive caesium from the decontamination efforts increases the urgency for a re-evaluation and reprioritization of where to focus the decontamination efforts.

While many authors looking at the potential role of dams and reservoirs have pointed out, they could theoretically play an important role in mitigating downstream radiocaesium fluxes. Some have suggested raising the height of dams. However, as has been pointed out:

> *The challenge with the management of these reservoirs in the temperate/monsoonal climate in the Fukushima region is that occasional water releases are required for their safe operation. Evrard et al. (2014)[302] indicated these dam releases could enhance the natural migration of radiocesium downstream . . .*
>
> *Understanding the storage of radiocesium within dams and reservoirs is important. As the decontamination efforts remove significant inventories of radiocesium from low-to-medium impacted areas, dams and reservoirs may present significant long- term radiocesium storages. These reservoirs are not only major dams that provide water for the region, they also include hundreds of smaller irrigation and farm dams.* ***These dams could store significant quantities of radiocesium that could be redistributed during a major flood event throughout the landscape potentially contaminating, for example, previously decontaminated paddies.***[303]

Watershed contamination

Thus, while dams and reservoirs may play some role in slowing radiocaesium transfer from the heavily contaminated forested mountain regions, or even act as an intermediary radioactivity sinks, these do not present a solution to the problem of significant contributions of radioactive sediments to coastal regions from contaminated river catchments and may, in fact, exacerbate the concentrations during heavy precipitation events.

Or, as O. Evrard et al. (2013) put it: "the storage of contaminated sediment in reservoirs and in coastal sections of the river channels now represents the most crucial issue."[304]

Nuclear "Nurseries of the Sea": Fukushima-Contaminated Estuaries

Estuaries have often been referred to as the "nurseries of the sea" because of the high productivity and biodiversity found in them.[305] Due to the high nutrient inputs from rivers, and the fact that estuaries are often sheltered from strong coastal currents, many fish, shellfish, and marine animals use estuaries for food and as breeding grounds. In fact, most commercially important fish species spend some point of their life cycle in an estuary. Further, migratory birds frequently use estuaries for resting places during their migrations, and many species of birds rely these uniquely important ecosystems for food and nesting sites.

However, like the lowland rice paddies discussed above, the very systems that provide rich nutrients for the abundant life in these ecosystems also make them vulnerable to contamination transported in the river catchments that feed them. Radioactive contamination is no exception.

Although some of the suspended caesium-bearing particulates are deposited along riverbanks – particularly at river bends[306] – on sandbars, at barriers, and other areas where water velocities slow enough for the particulates to drop out of the water column, a large portion of the mineral-bound radiocaesium is discharged into marine estuaries.[307]

For example, in the Abukuma River estuary, sediment samples with dry concentrations of 300 Bq kg^{-1} were recorded.[308] Since most of the radiocaesium in marine sediments were recorded to the south of the reactor site, it is assumed that the spikes in caesium concentrations in the estuary sediments are the result of the transportation and accumulation of contaminated river sediments, which can then be a source of external exposure for significant periods of time.[309]

As was demonstrated by C. Chartin, et al. (2013), the river catchments will be a long-term, ongoing source of radiocaesium to coastal areas.[310] Additionally, it was noted that fine sediments quickly accumulated significant stocks of radiocaesium:

> *By November 2011, 1^{34+137}Cs activities measured in river sediment ranged between 500 and 1,245,000 Bq kg^{-1}, sometimes far exceeding (by a factor 2–20) the activity associated with the initial deposits on nearby soils. This result confirms the concentration of radionuclides in fine river sediments because of their strong particle-reactive behavior.*
>
> *Those contamination levels are between 1 and 5 orders of magnitude higher than before the accident. As we could expect it, the highest contamination levels (total $^{134+137}$Cs activities exceeding 100,000 Bq kg^{-1}) were measured in sediment collected along the coastal rivers (i.e., Mano and Nitta Rivers) draining the main radioactive plume. Contamination levels were logically much lower in sediment collected along the Abukuma River that drains less contaminated areas.*[311]

It has been noted[312] that there is a decrease in the levels of suspended solids in the rivers (though still significant, as discussed above) since the initial phase after the disaster, which suggests higher mobility of radiocaesium after the initial deposition event. This, too, would be consistent with the findings of a high mobility phase in the forests themselves in the early stages post-disaster.

An analysis of clay-rich platy sediments in the Kuma River estuary – deposited during multiple storm events – showed the highest levels of radiocaesium in the bottom layers of sediment.[313] The upper layers contained approximately 28 Bq g^{-1} and the lower approximately 38 Bq g^{-1}. As the area was impacted by the massive 2011 tsunami, it was assumed at all sediments in the estuary were formed after the 2011 disaster.

However, it's critically important to understand that only a portion of the suspended caesium-bearing particulate is deposited into sediments once it reaches the estuary waters. Although in most circumstances, caesium forms a nearly irreversible bond to clay particulates, the desorption

Watershed contamination

of caesium from suspended particles with increasing salinity is a well-documented phenomenon.[314]

S. Yamasaki, et. al (2016) further demonstrated this in laboratory experiments with artificial sea water. The estimated desorption rate was a small percentage of the total inventory, with 3.4% of the total particulate-bound ^{137}Cs desorbed in 8 hours.[315]

The fact that the percentage of the total ^{137}Cs inventory carried in the suspended solids that is desorbed in sea water is small ***does not*** mean that the contribution of desorption to the amount of bioavailable, dissolved ^{137}Cs in coastal environments is insignificant.

In another study, caesium-bearing particles were collected from riverbanks and bottom sediment samples in Fukushima-impacted areas, sieved, and added to filtered salt water.[316] Although, in this study as well, only a small percentage of the total ^{137}Cs inventory in suspended solids was desorbed in salt water (between 0.75% and 6.6%, with an average of 3.3%), desorption raised the dissolved ^{137}Cs faction by a factor of 3 to 100, depending on the activity of the sieved particles.

The researchers thus concluded that a major factor in the amount of remobilized (desorbed) ^{137}Cs contributed by river systems to coastal environments was the concentrations of ^{137}Cs in the suspended solids and the volume of contaminated suspended solids discharged.[317]

As such, the authors concluded that:

> *. . . although suspended particle concentrations were low, the ^{137}Cs concentrations in the particles were remarkably high (2307 – 21,000 Bq/kg dry) resulting in a high percentage contribution of desorbable ^{137}Cs to the export flux . . .*
>
> *These results indicate that in rivers whose catchments are highly contaminated with [Fukushima Nuclear Power Plant] derived ^{137}Cs, such as the Abukuma and Kuji rivers, a considerable amount of ^{137}Cs is remobilized by desorption from suspended particles.*[318]

In addition, the authors point out that dissolved radiocaesium in the marine environment can "easily accumulate in marine biota," and thus, the desorption fraction of ^{137}Cs from suspended particles must be considered when assessing the impact of riverine caesium exports on coastal environments.[319]

Other studies have also suggested that desorption[320] accounts for a significant portion of the dissolved radiocaesium in estuarine waters. For example, according to another study of the Abukuma estuary, desorption from river sediments accounted for 36% of the dissolved caesium in the water.[321]

In fact, in noting low levels of radiocaesium in the sediments of the Ohta estuary, F. Eyrolle-Boyer, et al. (2016) concluded:

> *Relatively low radiocaesium concentrations in bed sediments from the estuaries, in particular in their upper sections, would be partly explained by radiocaesium desorption from riverine particles within the salinity gradient. Additionally, it is not excluded that typhoon events may generate significant remobilisation of contaminated sediments that accumulate during periods of low and moderate flow rates, as it is generally the case.*[322]

This phenomenon is quite important because it means that while radiocaesium is bound to fine particulates that render it biologically unavailable, and are the most likely to travel from headwaters in contaminated basins to the Pacific Ocean, a portion of it becomes biologically available at the precise time it enters one of the most important ecosystems for coastal, migratory, and marine animals. As stated above, it can then be taken into the marine food web. Consequently, this not only has potential health impacts for the animals that rely on estuaries for food and breeding grounds, but also has implications human beings who may consume fish or other seafood that lived there at some point in their life histories.

Case study: Iitate June/July 2015

Iitate, Fukushima Prefecture
© Jeremy Sutton-Hibbert/Greenpeace

Case study

"Remediation of forests has been implemented in a limited manner by the removal of material under the trees in a 20-meter buffer strip adjacent to residences, farmland and public spaces, in response to public concern. The Mission Team acknowledges that the authorities in Japan have implemented a practical option for remediation of the forest areas." - IAEA, 2013[323]

Iitate Village is a district northwest of the Fukushima Daiichi nuclear plant, and was heavily contaminated by the March 2011 accident. It is comprised of over 200 km^2 – much of it mountainous forest – with homes and agricultural fields interspersed throughout the wooded landscape. Well outside the 20km area of the nuclear plant, Iitate is a constant reminder to the people of Japan that a severe nuclear accident cannot be limited to a small area around reactor sites. The over 6000 people from Iitate were the most exposed population in Japan before they were finally evacuated between April and July 2011. Today they remain displaced.

Greenpeace has conducted 25 radiation surveys throughout Fukushima prefecture since March 2011.[324] sIn mid-July and October 2015, the organization completed its latest investigations into the radioactive contamination in Fukushima. Specifically, we have undertaken a survey of areas of Iitate, including forests, which are acting as a repository for a large amount of radioactive material released during the early stages of the Fukushima Daiichi accident. Radioactive fallout, in particular ^{131}I and ^{133}I and ^{134}Cs and ^{137}Cs were deposited on the vast forests, farmlands, and homes of Iitate.

The results of Greenpeace radiation monitoring and sample analysis in a Tokyo laboratory have revealed levels of radiation in both decontaminated and non-decontaminated areas that make any return of the former inhabitants of Iitate not possible from a public health and safety perspective.

In addition, only a quarter of Iitate's 200km^2 of land is officially being "decontaminated" – creating little islands of lower radiation levels that still largely fail to meet the Government's long-term decontamination targets.

The levels of radiation in the forests, which pre-accident were an integral part of the residents' lives and livelihoods, are equivalent to radiation levels within the Chernobyl 30km exclusion zone. Over 118,000 people were permanently evacuated from the 30km zone around Chernobyl in April 1986, with no prospect or plans for them ever returning.

The Japanese government plans, if implemented, will create an open-air prison of confinement to "cleaned" houses and roads – where radiation levels are still largely unsafe – and the vast and untouched radioactive forests continue to impact quality of life, forestry industries and real estate, and pose a risk of recontamination of these "decontaminated" areas to even higher levels.

With radioactive decay, the principle radioactive material of concern as of today and into the future is radiocaesium, particularly ^{137}Cs, which has a half life of 30 years. This means that it will remain a hazard for around ten half lives – or 300 years.[325]

As noted earlier, 75% of Iitate is covered by dense forest. As a case study, Greenpeace measured radiation levels in the forest along a small river heading to the Ganbe lake in Iitate. Radiation levels were measured in the range of 1-3mSv/h. Soil samples of forest sediment were in the range of 6,200-33,500Bq/kg at one location (see illustration below) and between 24,800 and 83,000Bq/kg at another small river entering Ganbe lake at a different location.

These levels are about a factor of ten higher than the levels of silt measured in the riverbed, which indicates that some radiation, is slowly migrating from the forest floor to the river by erosion, and is washed down by the river towards Ganbe lake. Research financed by the Japanese government (F-Trace project) also shows such slow migration[326]. The precise mechanisms of migration of radioactive cesium are still largely unknown today.

The decontamination efforts also do not "get rid" of the contamination – they simply move it. The process is generating vast amounts of radioactive waste, which is being piled up at temporary sites throughout the district and the prefecture.

What is clear from our investigations is that in spite of the effort of thousands of workers, the decontamination of Iitate is likely to be a never ending process and with limited impact on reducing radiation dose levels. Due to the scale of contamination of the hills, mountains and forests of Iitate, radiological recontamination of areas declared decontaminated will likely continue to the foreseeable future.

Forest decontamination along a road in Iitate, Fukushima ©Jeremy Sutton-Hibbert/Greenpeace

Additionally, when considering the impact of the forest contamination on human life in the region, we must also consider the quality of life. Life in Iitate was largely lived outdoors. Many people were employed as farmers or in forestry. Residents gathered wood, mushrooms and wild fruits and vegetables from the mountain forests. Children played outside in the forests and streams.

The damage of radiological contamination of the Iitate forests extends far beyond the immediate threat to health, and includes the destruction of livelihoods and an entire way of life. Even if the 20 meters around people's houses were to be successfully decontaminated – which is largely not the case – the damage to former residents' lives is irreversible.

Key findings from the Greenpeace investigations in 2015:

- Radiation levels do not decline significantly more than 4 years after the accident, due to the fact that all short-living isotopes have already decayed and ^{134}Cs with a half-live of only 2 years has already been reduced by more than 75%. The remaining ^{137}Cs, with a half-life of 30 years, is now either incorporated into the materials cycles of ecosystems or strongly bound to soil sediments. It will not decrease significantly over the coming years, posing a long-term risk.
- Radiation levels in Iitate are much higher than in the two areas where the evacuation order was lifted in 2014 (Miyakoji and Kawauchi).
- The forests, which cannot be decontaminated, are a massive stock of radioactivity which will pose a risk to the population for the coming decades. The ecological half life of caesium is between 180 and 320 years due to recycling through the ecosystem, thus the ecological life of cesium is equivalent to its radiological half life.
- Areas that have been decontaminated, in narrow forest strips along roads and around people's houses, remain heavily contaminated.

Economic impacts of forest contamination

“There are places where workers cannot enter because radiation levels are high. Unless they are decontaminated, we won't be able to engage in forestry like the way we did before the nuclear accident." - Chohei Sato, 64, Iitate forestry cooperative chief [327]

While the ecological, human health, and quality of life issues are of upmost importance when considering the Fukushima disaster, the economic consequences of forest contamination have also been immense and are worthy of further discussion.

In the wake of the disaster, the Japanese Government imposed shipment restrictions on multiple non-wood forest products, which was a devastating blow to the shitake mushroom growing industry in the region. As of December 2013, 21 non-timber forest products were under shipment restriction, encompassing 175 municipalities in 12 prefectures (>100bq/kg were found).[329] As of December 2014, 22 non-timber products in 180 municipalities were under restriction.[329]

As of July 8, 2015, 22 non-wood forest products were still under shipment restriction.[330] It’s also important to note that these restrictions on mushrooms and other products are not isolated to Fukushima prefecture, but are enforced in many municipalities throughout the Kanto region.[331]

However, although the Japanese government has restricted such activities as mushroom collection, gathering wild vegetables, firewood, and hunting, it has not restricted timber in the contaminated areas, except for the mandatory evacuation zones.[332] Despite this, as of March 2015, forestry production in Fukushima prefecture was still down by 40% of what it had been before the disaster. By the end of March 2015, the forestry industry had requested 4.2 billion yen in compensation from TEPCO; 4.0 billion yen was paid.

Mushroom cultivation remains devastated, with only 30% of pre-disaster production as of March 2015. As of Nov. 2014, 24.6 billion yen was requested for mushroom industry losses and 22.7 billion was paid.[333]

In September 2014, applications for loss of real estate value related to forests in the evacuation zone had begun to be accepted.[334] Approximately three months after TEPCO began accepting these applications, there were 16.6 billion yen in claims.[335] It should be noted that this figure does not include relevant compensation won in the Alternative Dispute Resolution (ADR) process nor does it reflect court settlements. Greenpeace contacted TEPCO in January 2016 to request an updated figure for forest real estate compensation claims, but was told that no updated figure exists that can be disclosed to the public.

In December 2015, NHK reported that a government panel[336] on decontamination had confirmed what was already known – that there would be no decontamination efforts in the vast and heavily contaminated forests of Fukushima. Instead, decontamination would focus solely on the 20 meters around homes and infrastructure.[337]

Conclusion

Five years after the start of the Fukushima Daiichi nuclear accident, it is clear that the environmental consequences are complex and extensive. Due to the radionuclides released by the accident, and their incorporation into the materials cycle of ecosystems, the impacts of the disaster will last for decades and centuries. However, the understanding of the full scale of the Fukushima disaster for the natural environment is only its early phase, highlighting the need for continued and expanded independent research into the multiple ecological effects.

Clearly, some early impacts are already being seen: internal tissue contamination in forest plants and trees resulting in caesium translocation in bark, sapwood, and heartwood; high concentrations in new leaves, and at least in the case of cedar – pollen; apparent increases in growth mutations of fir trees with rising radiation levels; heritable mutations in pale blue grass butterfly populations; DNA-damaged worms in highly contaminated areas; high levels of caesium contamination in commercially important freshwater fish; apparent reduced fertility in barn swallows; and radiological contamination of one of the most important ecosystems – coastal estuaries.

With the history of the Chernobyl and Kyshtym radiological disasters as a guide, we can expect further serious consequences for flora and fauna of Fukushima-contaminated terrestrial and freshwater aquatic ecosystems.

Further, the vast stocks of radiation in the forests will be a perennial source of radiological downstream contamination, including high radiocaesium inputs into coastal and marine ecosystems, for the foreseeable future.

Greenpeace fully supports the dedicated efforts of independent scientists working to better understand the impacts of this man-made nuclear disaster on the ecosystems of Fukushima. It is their work and investigations, inexcusably under resourced, that will help the people of Japan grasp the scale of the environmental impacts.

And the people of Fukushima, who have lost so much to TEPCO's nuclear disaster, deserve to have accurate and complete information so that they may face the decisions ahead with clarity and knowledge. This report is dedicated to them, as they have and continue to face the enormous challenges wrought by this nuclear disaster with resiliency, hope, and courage.

Endnotes

1 Yoshihara, T., et al. (2014) “Changes in radiocesium contamination from Fukushima in foliar parts of 10 common tree species in Japan between 2011 and 2013.” *Journal of Environmental Radioactivity.* 138 (December 2014) 220–226. *http://www.sciencedirect.com/science/article/pii/S0265931X14002689*

2 “The Fukushima Daiichi Accident.” *Director General of the International Atomic Energy Agency.* 2015. pg. 136 *http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1710-ReportByTheDG-Web.pdf*

3 Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company Final Report. *http://www.cas.go.jp/jp/seisaku/icanps/eng/*

4 On September 29, 1957 a storage tank containing highly radioactive liquid wastes exploded at the Mayak plutonium-production and reprocessing facility in present-day Russia. It caused an INES level 6 disaster, and is the third worst radiological disaster in world history after Chernobyl and Fukushima Daiichi. For more information, see: “Mayak: A 50 year tragedy.” *Greenpeace International. http://www.greenpeace.org/international/en/publications/reports/mayak-a-50-year-tragedy/*

5 Yoshihara, T., et al., *op. cit.* (2014) See also, Bergan T.D. (1995) Long ecological half-lives of radionuclides in Nordic Limnic. Technical Report EKO-2.3. Nordic Nuclear Safety Research, Norway.

6 “The Fukushima Daiichi Accident.” *International Atomic Energy Agency.* Technical Volume 4/5: Radiological Consequences. 2015. pg. 8. *http://www-pub.iaea.org/MTCD/Publications/PDF/AdditionalVolumes/P1710/Pub1710-TV4-Web.pdf*

7 *Ibid.*

8 *Ibid.*

9 *Ibid.*

10 *Ibid.*

11 “The Fukushima Daiichi Accident.” *Director General of the International Atomic Energy Agency.* 2015. pg. 131 *http://www-pub.iaea.org/MTCD/Publications/PDF/Pub1710-ReportByTheDG-Web.pdf*

12 *Ibid.*

13 Evangeliou, N., et al. (2015). “Fire evolution in the radioactive forests of Ukraine and Belarus: future risks for the population and the environment.” *Ecological Monographs,* 85(1), 2015, pp.49–72.

14 “Public Health Statement on Strontium.” Agency for Toxic Substances and Disease Registry. United States Center for Disease Control. April 2004. *http://www.atsdr.cdc.gov/PHS/PHS.asp?id=654&tid=120*

15 Yamamoto, M., et al. (2014). “Isotopic Pu, Am and Cm signatures in environmental samples contaminated by the Fukushima Daiichi Nuclear Power Plant accident.” *Journal of Environmental Radioactivity.* 132 (2014) 31- 46.

16 *Ibid.*

17 International Atomic Energy Agency. *op. cit.*, Tech Vol 4/5. 2015. pg. 29

18 Adachi, K., et al. (2013). “Emission of spherical cesium-bearing particles from an early stage of the Fukushima nuclear accident.” *Scientific Reports 3,* Article number: 2554. *http://www.nature.com/articles/srep02554*

19 *Ibid.*

20 *Ibid.*

21 *Ibid.*

22 Kaneyasu, N., et al. (2012). “Sulfate aerosol and a potential transport medium of radiocesium from the Fukushima Nuclear Accident.” *Environmental Science and Technology.* 46 (11), pp 5720–5726. *http://pubs.acs.org/doi/abs/10.1021/es204667h?src=recsys&*

23 Hososhima, M. & Kaneyasu, N. “Altitude-Dependent Distribution of Ambient Gamma Dose Rates in a Mountainous Area of Japan Caused by the Fukushima Nuclear Accident.” *Environmental Science and Technology.* 49 (6), pp 3341–3348. *http://pubs.acs.org/doi/abs/10.1021/es504838w?journalCode=esthag*

24 Yamaguchi, N., et al. (2016). “Internal structure of cesium-bearing radioactive microparticles released from Fukushima nuclear power plant.” Scientific Reports 6, Article number: 20548. *http://www.nature.com/articles/srep20548*

25 Okada, N., et al. (2015) Radiocesium Migration from the Canopy to the Forest Floor in Pine and Deciduous Forests. Journal of the Japanese Forest Society. 97: 57—62. *https://www.jstage.jst.go.jp/article/jjfs/97/1/97_57/_article*

26 Nimis, P.L. (1996). “Radiocesium in Plants of Forest Ecosystems.” *Studia Geobotanica.* Vol. 15: 3-49. See, pg. 8. *http://dbiodbs.univ.trieste.it/ecoapp/cesio.pdf*

27 *Ibid.*

28 *Ibid.*

29 Evrard, O., et al. (2015). “Radiocesium transfer from hillslopes to the Pacific Ocean after the Fukushima Nuclear Power Plant accident: A review.” *Journal of Environmental Radioactivity. http://www.ncbi.nlm.nih.gov/pubmed/26142817 See also, Nimis, P.L., op. cit.* (1996).

30 Yamaguchi, N., et al. *op. cit.* (2016). “

31 *Ibid.*

32 Niimura, N., et al. (2013). “Physical properties, structure, and shape of radioactive CS from the Fukushima Daiichi Nuclear Power Plant accident derived from soil, bamboo and shiitake mushroom measurements.” *Journal of Environmental Radioactivity.* January 2015 139:234-9. *http://www.ncbi.nlm.nih.gov/pubmed/24445055*

33 Nimis, P.L., *op. cit*. (1996). pg. 11

34 Yamaguchi, N., et al., *op. cit.* (2016).

35 Nimis, P.L., *op. cit.* (1996) pgs. 7-8

36 *Ibid.* pg 8

37 Moisture transport in plants and its evaporation from small pores (stomata) on the underside of leaves. See: *http://water.usgs.gov/edu/watercycletranspiration.html*

38 Nimis, P.L., *op. cit.* pg. 8

39 Konoplev, A., et al. (2015). “Behavior of accidentally released radiocesium in soil—water environment: Looking at Fukushima from a Chernobyl perspective.” *Journal of Environmental Radioactivity. https://www.academia.edu/19545183/Behavior_of_accidentally_released_radiocesium_in_soil-water_environment_looking_at_Fukushima_from_a_Chernobyl_perspective*

40 Yoshihara, T., et al., *op. cit.* (2014)

41 *Ibid.*

42 *Ibid.*
See also, Konoplev, A., et al., *op. cit*. (2015).

43 “Gov't plans not to decontaminate Fukushima forests away from residential areas.” *The Mainichi.* December 22, 2015. *http://mainichi.jp/english/articles/20151222/p2a/00m/0na/012000c*

Endnotes

44 Yoshihara, T., et al., *op. cit.* (2014)

45 *Ibid.*

46 *Ibid.*

47 *Ibid.*

48 Nishikiori, T., *et al*. (2015). “Uptake and translocation of radiocesium in cedar leaves following the Fukushima nuclear accident.” *Science of the Total Environment.* 502: 611-616. ***https://www.researchgate.net/publication/266744005_Uptake_and_translocation_of_radiocesium_in_cedar_leaves_following_the_Fukushima_nuclear_accident?requestFulltext=1***

49 Kolbek, J., et al. (eds.) Forest Vegetation of Northeast Asia. *Kluwer Academic Publishers.* 2003. Pgs 231-261. ***http://www.springer.com/jp/book/9781402013706***

50 Evangeliou, N., et al., *op. cit.* (2015)

51 Konoplev, A., et al., *op. cit.* (2015)

52 Yoshihara, T., et al., *op. cit.* (2014)

53 *Ibid.*

54 *Ibid.*
See also, Nimis, P.L., *op. cit.* (1996).
See also, Okada, N. et al., *op. cit.* (2015)

55 Kato, H., et al (2012). “Interception of the Fukushima reactor accident derived 137 Cs, 134 Cs and 131 I by coniferous forest canopies.” *Geophysical Research Letters,* 39(20). ***http://onlinelibrary.wiley.com/doi/10.1029/2012GL052928/abstract*** See also, Nimis, P.L., *op. cit.* (1996). pg. 5.

56 Nimis, P.L., *op. cit.* (1996). pg. 5.

57 Kato, H., et al., *op. cit.* (2012).

58 *Ibid.*

59 Ohno, T., et al. (2012). “Depth profiles of radioactive cesium and iodine released from the Fukushima Daiichi nuclear power plant in different agricultural fields and forests.” *Geochemical Journal.* Vol. 46: 287 - 295. ***https://www.terrapub.co.jp/journals/GJ/pdf/4604/46040287.pdf***

60 Nimis, P.L., *op. cit.* (1996). pg. 6.

61 Yoshihara, T., et al., *op. cit.* (2014)

62 *Ibid.*

63 *Ibid.*

64 *Ibid.*

65 Tikhomirov, F.A. & Shcheglov, A.I. (1994). “Main investigation results in the forest radioecology in the Kyshtym and Chernobyl accident zones.” Sci. Tot. Envir., 157: 45-57. ***http://www.ncbi.nlm.nih.gov/pubmed/7839123***

66 Nimis, P.L., *op. cit.* (1996). pg. 26.

67 Tikhomirov, F.A. & Shcheglov, A.I., *op. cit.* (1994)
See also, Nimis, P.L., *op. cit.* (1996)

68 Yoshihara, T., et al., *op. cit.* (2014)
See also, Okada, N., et al., *op. cit*. (2015)

69 Tikhomirov, F.A. & Shcheglov, A.I., *op. cit.* (1994)
See also, Nimis, P.L. op. cit. (1996). pg. 26.

70 Nimis, P.L. *op. cit.* (1996). pg. 26

71 *Ibid.*

72 Kuchma, O., et al. (2011). “Mutation rates in Scots pine (Pinus sylvestris L.) from the Chernobyl exclusion zone evaluated with amplified fragment-length polymorphisms (AFLPs) and microsatellite markers.” *Mutagen Research*. 725(1-2):29-35. ***https://www.researchgate.net/publication/51515296_Mutation_rates_in_Scots_pine_Pinus_sylvestris_L_from_the_Chernobyl_exclusion_zone_evaluated_with_amplified_fragment-length_polymorphisms_AFLPs_and_microsatellite_markers***

73 Nimis, P.L. *op. cit.* (1996). See pgs. 24-25.

74 Mahara, Y. et al. (2014). “Atmospheric Direct Uptake and Long-term Fate of Radiocesium in Trees after the Fukushima Nuclear Accident.” *Scientific Reports 4.* Article 7121. ***http://repository.kulib.kyoto-u.ac.jp/dspace/bitstream/2433/196856/1/srep07121.pdf***

75 Tikhomirov , F.A. & Shcheglov, A.I., *op. cit.* (1994).

76 Yamaguchi, N., et al., *op. cit.* (2016).

77 Nishikiori, T., et al., *op. cit*. (2015).

78 *Ibid.*

79 Tagami, K., et al. (2012). “Translocation of radiocesium from stems and leaves of plants and the effect on radiocesium concentrations in newly emerged plant tissues.” *Journal of Environmental Radioactivity.* Vol. 111: 65–69. ***http://www.sciencedirect.com/science/article/pii/S0265931X11002396***

80 *Ibid.*

81 *Ibid.*

82 Yoshihara, T., et al., *op. cit*. (2014)

83 *Ibid.*

84 *Ibid.*

85 Okada, N., et al., *op. cit.* (2015)

86 Tikhomirov, F.A. & Shcheglov, A.I., *op. cit.* (1994)

87 Watanabe, Y., et al. (2013). “Effects of radionuclide contamination on forest trees in the exclusion zone around the Fukushima Daiichi Nuclear Power Plant.” In Nakatani, Maki (Ed.). *Proceedings of the international symposium on environmental monitoring and dose estimation of residents after accident of TEPCO's Fukushima Daiichi Nuclear Power Stations,* (p. 231). Japan. ***https://inis.iaea.org/search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=45097283***

88 *Ibid.*

89 *Ibid.*

90 Watanabe, Y., et al. (2015). “Morphological defects in native Japanese fir trees around the Fukushima Daiichi Nuclear Power Plant.” Scientific Reports 5. Article 13232. ***http://www.nature.com/articles/srep13232***

91 “Morphological defects found in Japanese fir trees around Fukushima nuclear plant.” August 29, 2015. *The Asahi Shimbun.* ***http://ajw.asahi.com/article/0311disaster/fukushima/AJ201508290045.***

92 *Ibid.*

93 Watanabe, Y., et al., *op. cit.* (2015)

94 *Ibid.*

95 *Ibid.*

96 Kanasashi, T., et al. (2015). “Radiocesium distribution in sugi (Cryptomeria japonica) in Eastern Japan: translocation from needles to pollen.” *Journal of Environmental Radioactivity,* 139: 398-406.

97 *Ibid.*

98 Bunzl, K., et al., (1993). "Spruce pollen as a source of increased radiocesium concentrations in air." Naturwissenschaften 80.4 : 173-174.***http://link.springer.com/article/10.1007/BF01226376***

Endnotes

99 Tschiersch, J. et al. (1999). "Enhanced airborne radioactivity during a pine pollen release episode." *Radiation and Environmental Biophysics.* Vol. 38(2): 139-145. *https://www.researchgate.net/publication/12837730_Enhanced_airborne_radioactivity_during_a_pine_pollen_release_episode*

100 Barisic, D., et al. (1992). "137Cs in flowers, pollen and honey from the Republic of Croatia four years after the Chernobyl accident." *Apidologie.* 23 (1): 71-78. *https://hal.archives-ouvertes.fr/hal-00890972*

101 *Ibid.*

102 Bunzl, K., et al., *op. cit.* (1993)

103 Tschiersch, J. et al. (1999). "Enhanced airborne radioactivity during a pine pollen release episode." *Radiation and Environmental Biophysics.* Vol. 38(2): 139-145. *https://www.researchgate.net/publication/12837730_Enhanced_airborne_radioactivity_during_a_pine_pollen_release_episode*

104 Tsuruoka, H., et al. (2015). "Variation of radiocesium concentrations in cedar pollen in the Okutama area since the Fukushima Daiichi Nuclear Power Plant accident." *Radiation Protection Dosimetry* 167: 1-3.

105 「森林・木材と放射性物質　福島の森林・林業再生に向けて　2014年」　発行：林野庁 *http://www.ringyou.or.jp/publish/detail_1270.html*

106 Kagawa, A., et al. (2002). "Tree-ring Strontium-90 and cesium-137 as potential indicators of radioactive pollution." *Journal of Environmental Quality.* 31(6):2001-7. *https://www.researchgate.net/publication/11001617_Tree-ring_Strontium-90_and_cesium-137_as_potential_indicators_of_radioactive_pollution*

107 Kuroda, K., et al. (2013). "Radiocesium concentrations in the bark, sapwood and heartwood of three tree species collected at Fukushima forests half a year after the Fukushima Dai-ichi nuclear accident." *Journal of Environmental Radioactivity.* Volume 122. 37-42. *http://www.sciencedirect.com/science/article/pii/S0265931X13000568*

108 *Ibid.*

109 *Ibid.*

110 *Ibid.*

111 *Ibid.*

112 *Ibid.*

113 *Ibid.*

114 *Ibid.*

115 Chigira, M., et al. (1988). "Distribution of 90Sr and 137Cs in annual tree rings of Japanese cedar, Cryptomeria japonica." *Journal of Radiation Research.* 29, 152 -160. *http://jrr.oxfordjournals.org/content/29/2/152.full.pdf*

116 Mousseau,T.A., et al. (2013). "Tree rings reveal extent of exposure to ionizing radiation in Scots pine Pinus sylvestris." *Trees.* Volume 27, Issue 5, pp 1443-1453. *http://link.springer.com/article/10.1007%2Fs00468-013-0891-z*
See also, Yamagata, N., et al. (1969). "Cesium-137 and Strontium-90 in a forest." *Journal of Radiation Research.* 10-3-4. 107-112. *http://jrr.oxfordjournals.org/content/10/3-4/107.full.pdf*

117 Yamagata, N., et al. (1969). "Cesium-137 and Strontium-90 in a forest." Journal of Radiation Research. 10-3-4. 107-112. *http://jrr.oxfordjournals.org/content/10/3-4/107.full.pdf*
See also, Kagawa, A., et al., *op. cit.* (2002)
See also, Chigira, M., et al., *op. cit.* (1988)

118 Yamagata, N., et al., *op. cit.* (1969)
See also, Kagawa, A., et al., *op. cit.* (2002)

119 Nimis, P.L. *op. cit.* (1996). See, pg. 7

120 *Ibid.*

121 *Ibid.*

122 Teramage, M.T., et al. (2014). "Vertical distribution of radiocesium in coniferous forest soil after the Fukushima nuclear power plant accident." *Journal of Environmental Radioactivity.* Vol. 137: 37-45. *http://www.sciencedirect.com/science/article/pii/S0265931X14001817*

123 Nimis, P.L. *op. cit.* (1996). pgs. 8-12

124 *Ibid.*pg. 8.

125 *Ibid.*

126 *Ibid.*

127 Okada, N., et al., *op. cit.* (2015)

128 *Ibid.*

129 *Ibid.*

130 *Ibid.*

131 *Ibid.*

132 Nishikiori, T., et al., *op. cit.* (2015). "Uptake and translocation of radiocesium in cedar leaves following the Fukushima nuclear accident." *Science of the Total Environment.* 502: 611-616. *https://www.researchgate.net/publication/266744005_Uptake_and_translocation_of_radiocesium_in_cedar_leaves_following_the_Fukushima_nuclear_accident?requestFulltext=1*

133 Nakanishi, T.et al. (2013). "137Cs vertical migration in a deciduous forest soil following the Fukushima Dai-ichi Nuclear Power Plant accident." *Journal of Environmental Radioactivity.* Vol. 128. Pgs 9-14. *http://www.sciencedirect.com/science/article/pii/S0265931X13002348*

134 Teramage, M.T., et al., *op. cit.* (2014)

135 Evrard, O., et al., *op. cit.* (2015)

136 Nimis, P.L. *op. cit.* (1996). pg. 17

137 *Ibid.* pg. 18

138 *Ibid.* pg. 14

139 *Ibid.*

140 *Ibid.*

141 Fuji, K., et al. (2014). "Vertical migration of radiocesium and clay mineral composition in five forest soils contaminated by the Fukushima nuclear accident." Soil Science and Plant Nutrition. 60: 751–764. *http://ci.nii.ac.jp/naid/110009910384*
See also, Nakanishi, T.et al., op. cit. (2013).

142 Nimis, P.L. *op. cit.* (1996). pg. 15

143 *Ibid.*

144 Evangeliou, N., et al., *op. cit.* (2015)

145 Fuji, K., et al., *op. cit.* (2014)

146 *Ibid.*
Teramage, M.T., et al., *op. cit.* (2014)
See also: Fujiwara, T., et al. (2012). "Isotopic ratio and vertical distribution of radionuclides in soil affected by the accident of Fukushima Dai-ichi nuclear power plants." *Journal of Environmental Radioactivity.* Vol. 113: 37-44. *http://www.sciencedirect.com/science/article/pii/S0265931X12001038*

147 Fujiwara, T., et al., *op. cit.* (2012)

148 Nimis, P.L., *op. cit.* (1996) pg. 17.

Endnotes

149 Teramage, M.T., et al., *op. cit.* (2014)

150 Koarashi, J., et al. (2012). “Factors affecting vertical distribution of Fukushima accident-derived radiocesium in soil under different land-use conditions.” *Science of the Total Environment.* Vol. 431: 392-401. *http://www.sciencedirect.com/science/article/pii/S0048969712007231*

151 Teramage, M.T., et al. (2014). “Vertical distribution of radiocesium in coniferous forest soil after the Fukushima nuclear power plant accident.” *Journal of Environmental Radioactivity.* Vol. 137: 37-45. *http://www.sciencedirect.com/science/article/pii/S0265931X14001817EndFragment*

152 Nakanishi, T., et al., *op. cit.* (2013)

153 *Ibid.*

154 *Ibid.*

155 *Ibid.*

156 *Ibid.*
Ohno, T., et al., *op. cit* (2012)
See also, Tanaka, K., et al. (2012). “Vertical profiles of Iodine-131 and Cesium-137 in soils in Fukushima Prefecture related to the Fukushima Daiichi Nuclear Power Station Accident.” *Geochemical Journal.* Vol. 46: 73 - 76.
See also, Fujiwara, T., et al., *op. cit*. (2012)
See also, Fujii, K., et al., *op. cit.* (2014)

157 Nimis, P.L. *op. cit.* (1996). pg. 10

158 *Ibid.*

159 *Ibid.* pg. 11.

160 *Ibid.*

161 *Ibid.*

162 *Ibid.* pg. 10

163 *Ibid.* pg. 30

164 *Ibid.* pg. 31

165 Yuan, L., et al. (2004). “Biological mobilization of potassium from clay minerals by ectomycorrhizal fungi and eucalypt seedling roots.” *Plant and Soil.* 262: 351–361. *https://www.researchgate.net/profile/Peter_Christie3/publication/226746783_Biological_mobilization_of_potassium_from_clay_minerals_by_ectomycorrhizal_fungi_and_eucalypt_seedling_roots/links/5582e8dd08ae1b14a0a28e79.pdf*

166 Nimis, P.L., *op. cit.* (1996)

167 Scheck, J. (December 23, 2010). “Bunnies Are in Deep Doo-Doo When They 'Go Nuclear' at Hanford: Detectives at Old A-Bomb Plant Track Radioactive Critters, Rogue Tumbleweeds.” *The Wall Street Journal. http://www.wsj.com/articles/SB10001424052748704694004576019280235026892*

168 Mousseau, T.A., et al. (2014). “Highly reduced mass loss rates and increased litter layer in radioactively contaminated areas.” *Oecologia. http://cricket.biol.sc.edu/chernobyl/papers/Mousseau-et-al-Oecologia-2014.pdf*

169 Evangeliou, N., et al., *op. cit.* (2015)

170 Mousseau, T.A., et al. (2014)

171 Evangeliou, N., et al., *op. cit.* (2015)

172 *Ibid.*

173 Hao, W.M., et al. (2009). “Vegetation fires, smoke emissions, and dispersio of radionuclides in the Chernobyl Exclusion Zone.” Developments in Environmental Science. Vol. 8. Pgs. 265– 275. *http://www.fs.fed.us/rm/pubs_other/rmrs_2009_hao_w001.pdf*

174 Evangeliou, N., et al., *op. cit.* (2015)

175 *Ibid.*

176 Fukushima Prefecture. 林野火災の防止について *https://www.pref.fukushima.lg.jp/sec/16025b/saigai-rinyakasai.html*

177 *Ibid.*

178 Stankevich, S., et al. (2015). “Risk assessment of adsorbed radionuclide emission by fire within Fukushima exclusion zone using multispectral satellite imagery.” Український журнал дистанційного зондування Землі 4: 4–9. *https://www.researchgate.net/publication/276028384_Risk_assessment_of_adsorbed_radionuclide_emission_by_fire_within_Fukushima_exclusion_zone_using_multispectral_satellite_imagery*

179 Møller, A.P. & Mousseau, T.A. (2015). “Strong effects of ionizing radiation from Chernobyl on mutation rates.” *Scientific Reports 5.* Article 8363. *http://www.nature.com/articles/srep08363*

180 *Ibid.*

181 *Ibid.*

182 Institute for Radiological Protection and Nuclear Safety (24 November 2015). “Information Note: Realistic dose reconstruction for non-human species to assess the ecological consequences of chronic exposure to ionizing radiation in the contaminated territories after the Fukushima accident.” *http://www.irsn.fr/EN/newsroom/News/Documents/IRSN_Information-Note_Fukushima-Impact-Birds_20151124.pdf*

183 Møller, A.P. & Mousseau, T.A., *op. cit.* (2015).

184 *Ibid.*

185 Garnier-Laplace, J., et al. (2013). “Are radiosensitivity data derived from natural field conditions consistent with data from controlled exposures? A case study of Chernobyl wildlife chronically exposed to low dose rates.” *Journal of Environmental Radioactivity.* Vol. 121: 12-21 *http://www.sciencedirect.com/science/article/pii/S0265931X12000240*

186 *Ibid.*

187 *Ibid.*

188 *Ibid.*

189 Garnier-Laplace, J., et al. (2015). “Radiological dose reconstruction for birds reconciles outcomes of Fukushima with knowledge of dose-effect relationships.” *Scientific Reports 5.* Article 16954. *http://www.nature.com/articles/srep16594*

190 Director General of the International Atomic Energy Agency. *op. cit.* 2015. pg. 136.

191 ICRP. J. Valentin, ed. (2003). “A Framework for Assessing the Impact of Ionising Radiation on Non-human Species.” *Annals of the ICRP.* International Commission on Radiological Protection. 33 (3). *http://www.icrp.org/publication.asp?id=ICRP Publication 91*

192 Director General of the International Atomic Energy Agency. *op. cit.* 2015. pg. 136.

193 Radioecologists habitually use ERICA or other ‘tools’ for estimating doses to wildlife. These are almost all based on lab studies. In addition, the findings are often based on small sample sizes, which is not taken into account when estimating overall effects. Radioecological communities are trying to move past this traditional approach, given its demonstrated inadequacy. The main recognized inadequacy is in the principle that protection of humans would automatically imply protection of the environment.

194 Nimis, P.L., *op. cit.* (1996).

195 Garnier-Laplace, J., et al., *op. cit.* (2013).

196 Watanabe, Y. et al., *op. cit.* (2015).

Endnotes

197 Garnier-Laplace, J., et al., *op. cit.* (2015) See also, Møller, A.P. et al. (2015).“Cumulative effects of radioactivity from Fukushima on the abundance and biodiversity of birds.” *Journal of Ornithology.* DOI 10.1007/s10336-015-1197-2, http://cricket.biol.sc.edu/chernobyl/papers/Moller-et-al-JO-2015b.pdf

198 *Ibid.*

199 *Ibid.*

200 Bonisoli-Alquati, A., et al. (2015). “Abundance and genetic damage of barn swallows from Fukushima.” *Scientific Reports 5,* Articl: 9432. http://www.nature.com/articles/srep09432

201 *Ibid.*

202 *Ibid.*

203 *Ibid.*

204 Garnier-Laplace, J., et al., *op. cit.* (2015)
See also, Møller, A.P., et al., *op. cit.* (2015)

205 Hiyama, A., et al. (2012). “The biological impacts of the Fukushima nuclear accident on the pale grass blue butterfly.” *Scientific Reports 2,* Article: 570. http://www.nature.com/articles/srep00570

206 *Ibid.*

207 *Ibid.*

208 Aliyu, A.S., et al. (2015). “Current Knowledge Concerning the Impacts of the Fukushima Daiichi Nuclear Power Plant accident on the environment.” *Environment International.* Vol. 85: 213–228. http://www.sciencedirect.com/science/article/pii/S016041201530060X

209 Fujita, Y., et al. (2014). “Environmental radioactivity damages the DNA of earthworms of Fukushima Prefecture, Japan.” *European Journal of Wildlife Research.* Vol. 60(1): 145-148. http://link.springer.com/article/10.1007%2Fs10344-013-0767-y

210 Akimoto, S., (2014). "Morphological abnormalities in gall-forming aphids in a radiation-contaminated area near Fukushima Daiichi: selective impact of fallout?” *Ecology and Evolution*; 4(4): 355–369. http://onlinelibrary.wiley.com/doi/10.1002/ece3.949/full

211 *Ibid.*

212 Taira, W., et al. (2014). “Fukushima’s Biological Impacts: The Case of the Pale Grass Blue Butterfly.” *Journal of Heredity.* 105(5):710–722. https://jhered.oxfordjournals.org/content/105/5/710.full

213 Møller, A.P. & Mousseau, T.A. (2016). “Are Organisms Adapting to Ionizing Radiation at Chernobyl?” *Trends in Ecology and Evolution*. http://www.sciencedirect.com/science/article/pii/S0169534716000197

214 Taira, W., et al. *op. cit.* (2014)

215 Møller, A.P. & Mousseau, T.A., *op. cit.* (2016)

216 Møller, A.P. & Mousseau, T.A. *op. cit.* (2015)

217 Taira, W., et al., *op. cit.* (2014)

218 *Ibid.*

219 Møller, A.P. & Mousseau, T.A., *op. cit.* (2016)

220 *Ibid.*

221 Deryabina, T.G., et al. (2015). “Long-term census data reveal abundant wildlife populations at Chernobyl.” *Current Biology.* Vol. 25(19): R824–R826. http://www.sciencedirect.com/science/article/pii/S0960982215009884

222 Møller, A.P. & Mousseau, T.A., *op. cit.* (2016)

223 Møller, A.P., et al. (2011) “Chernobyl Birds Have Smaller Brains.” PLoS ONE 6(2): e16862. doi:10.1371/ journal.pone.001686. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0016862

224 *Ibid.*

225 Mousseau, T.A. & Møller, A.P. (2013). “Elevated Frequency of Cataracts in Birds from Chernobyl.” PLoS ONE 8(7): e66939. doi:10.1371/journal.pone.0066939. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0066939

226 *Ibid.*

227 *Ibid.*

228 *Ibid.*

229 *Ibid.*

230 Møller, A.P., et al. (2013). “High frequency of albinism and tumours in free-living birds around Chernobyl.” *Mutation Research/Genetic Toxicology and Environmental Mutagenesis.* Volume 757, Issue 1, Pages 52–59. http://www.sciencedirect.com/science/article/pii/S1383571813001848

231 *Ibid.*

232 Boratynski, Z., et al. (2014). “Increased radiation from Chernobyl decreases the expression of red colouration in natural populations of bank voles (Myodes glareolus).” *Scientific Reports 4,* Article: 7141. http://www.nature.com/articles/srep07141?trendmd-shared=0
See also, Lehmann, P., et al. (2015). “Fitness costs of increased cataract frequency and cumulative radiation dose in natural mammalian populations from Chernobyl.” *Scientific Reports 6,* Article: 19974. http://www.nature.com/articles/srep19974

233 Lehmann, P., et al., *op. cit.* (2015)

234 Pratama, M.A., et al. (2015). “Future projection of radiocesium flux to the ocean from the largest river impacted by Fukushima Daiichi Nuclear Power Plant.” *Scientific Reports 5,* Article: 8408. http://www.nature.com/articles/srep08408

235 Lepage, H., et al. (2016). “Investigating the source of radiocesium contaminated sediment in two Fukushima coastal catchments with sediment tracing techniques.” *Anthropocene.* http://www.sciencedirect.com/science/article/pii/S2213305416300042

236 Yamashiki, Y., et al. (2014). “Initial flux of sediment-associated radiocesium to the ocean from the largest river impacted by Fukushima Daiichi Nuclear Power Plant.” *Scientific Reports 4,* Article: 3714. http://www.nature.com/articles/srep03714
See also, Evrard, O. et al., *op. cit.* (2015)

237 Evrard, O. et al., *op. cit.* (2015)

238 Eyrolle-Boyer, F., et al. (2015). “Behaviour of radiocaesium in coastal rivers of the Fukushima Prefecture (Japan) during conditions of low flow and low turbidity e Insight on the possible role of small particles and detrital organic compounds.” *Journal of Environmental Radioactivity.* 151: 328-340. https://www.researchgate.net/publication/283896408_Behaviour_of_radiocaesium_in_coastal_rivers_of_the_Fukushima_Prefecture_Japan_during_conditions_of_low_flow_and_low_turbidity_-_Insight_on_the_possible_role_of_small_particles_and_detrital_organic_com

239 Pratama, M.A., et al., *op. cit.* (2015)

240 *Ibid.*

241 *Ibid.*

242 Evrard, O. et al., *op. cit.* (2015)

243 *Ibid.*
See also, Konoplev, A., et al., *op. cit.* (2015)

244 Konoplev, A., et al., *op. cit.* (2015)

Endnotes

245 Tanaka, K., et al. (2015). “Size-dependent distribution of radiocesium in riverbed sediments and its relevance to the migration of radiocesium in river systems after the Fukushima Daiichi Nuclear Power Plant accident.” *Journal of Environmental Radioactivity.* Journal of Environmental Radioactivity Vol. 139: 390–397. http://www.sciencedirect.com/science/article/pii/S0265931X14001337

246 Evrard, O. et al., *op. cit.* (2015)
See also, Lepage, H., et al., *op. cit.* (2016)

247 Konoplev, A., et al., *op. cit.* (2015).

248 Yamashiki, Y., et al., *op. cit.* (2014)

249 *Ibid.*

250 *Ibid.*

251 Nagao, S., et al. (2013). “Export of 134Cs and 137Cs in the Fukushima river systems at heavy rains by Typhoon Roke in September 2011.” *Biogeosciences.* 10: 6215–6223. https://www.researchgate.net/publication/258758074_Export_of_134Cs_and_137Cs_in_the_Fukushima_river_systems_at_heavy_rains_by_Typhoon_Roke_in_September_2011

252 Eyrolle-Boyer, F., et al., *op. cit.* (2015)

253 Sakai, M., et al. (2015). "Radiocesium leaching from contaminated litter in forest streams." *Journal of Environmental Radioactivity* 144: 15-20. http://www.sciencedirect.com/science/article/pii/S0265931X1500065X

254 Nemoto, K. & Abe, J. (2013). “Radiocesium Absorption by Rice in Paddy Field Ecosystems.” Chapter 3. T.M. Nakanishi and K. Tanoi (eds.), Agricultural Implications 1of the Fukushima Nuclear Accident, DOI 10.1007/978-4-431-54328-2_3, © The Author(s) 2013. http://www.springer.com/us/book/9784431543275

255 *Ibid.*

256 *Ibid.*

257 *Ibid.*

258 *Ibid.*

259 *Ibid.*

260 Wakahara, T., et al. (2014). “Radiocesium discharge from paddy fields with different initial scrapings for decontamination after the Fukushima Dai-ichi Nuclear Power Plant accident. *Environmental Sciences: Processes and Impacts.* 16: 2580 - 2591. https://www.researchgate.net/publication/265137254_Radiocesium_discharge_from_paddy_fields_with_different_initial_scrapings_for_decontamination_after_the_Fukushima_Dai-ichi_Nuclear_Power_Plant_accident

261 Avery, S. (1996). “Fate of caesium in the environment: Distribution between the abiotic and biotic components of aquatic and terrestrial ecosystems.” Journal of Environmental Radioactivity, 30(2): 139-171. http://www.sciencedirect.com/science/article/pii/0265931X96892769

262 Arai, T (2014). “Radioactive cesium accumulation in freshwater fishes after the Fukushima nuclear accident.” SpringerPlus. 3:479 http://www.springerplus.com/content/3/1/479

263 *Ibid.*

264 *Ibid.*
See also, Yamamoto, S., *op. cit.* et al. (2015)

265 Wada, T. et al. (2016). “Radiological impact of the nuclear power plant accident on freshwater fish in Fukushima: An overview of monitoring results. *Journal of Environmental Radioactivity.* 151: 144-155. http://www.sciencedirect.com/science/article/pii/S0265931X15301119

266 Yamamoto, S., et al., *op. cit.* (2015)

267 Davidson, W. et al. (1993). “The transport of Chernobyl-derived radio-caesium through two freshwater lakes in Cumbria, UK.” *Journal of Environmental Radioactivity.* 19(2):125-153. 10.1016/0265-931X(93)90073-G

268 Bryant, C.L., et al. (1993). “Distribution and behaviour of radiocaesium in Scottish freshwater loch sediments.” *Environmental Geochemistry and Health.* Vol. 15(2):153-161 http://link.springer.com/article/10.1007/BF02627833

269 For an illustration see: Lake Turnover. National Geographic Education. http://education.nationalgeographic.org/media/lake-turnover/

270 Sternberg, D. “Clearing Up the Fall Turnover: That murky water tells you it's time to change techniques.” *Field & Stream*. http://www.fieldandstream.com/articles/fishing/more-freshwater/1998/06/clearing-fall-turnover

271 Avery, S., *op. cit.* (1996)

272 Yamamoto, S., et al., *op. cit.* (2015)
See also, T. Mizuno & H. Kubo (2013). “Overview of active cesium contamination of freshwater fish in Fukushima and Eastern Japan.” *Scientific Reports 3,* Article: 1742. http://www.nature.com/articles/srep01742
See also, Matsuda, K. et al. (2015). “Comparison of radioactive cesium contamination of lake water, bottom sediment, plankton, and freshwater fish among lakes of Fukushima Prefecture, Japan after the Fukushima fallout.” *Fisheries Science.* Vol 81(4): 737-747. http://link.springer.com/article/10.1007%2Fs12562-015-0874-7
See also, Arai, T., *op. cit.* (2014)

273 Avery, S., *op. cit.* (1996)

274 Covich, A.P., et al. (1999). “The Role of Benthic Invertebrate Species in Freshwater Ecosystems.” *BioScience.* Vol. 49(2): 119-127. http://www.palmerlab.umd.edu/Publications/Covich et al 1999.pdf

275 Avery, S., *op. cit.* (1996)

276 Bergan T.D., *op. cit.* (1995)

277 Rowan, D. J., et al. (1998). "The fate of radiocesium in freshwater communities—Why is biomagnification variable both within and between species?." *Journal of Environmental Radioactivity* 40.1 (1998): 15-36. http://www.sciencedirect.com/science/article/pii/S0265931X97000660

278 Mayumi, Y., & Akio, A. (2014). “Radioactive contamination of aquatic insects in a stream impacted by the Fukushima nuclear power plant accident.” *Hydrobiologia,* 722(1), 19-30. http://link.springer.com/article/10.1007%2Fs10750-013-1672-9

279 *Ibid.*

280 *Ibid.*

281 Sakai, M., et al. (2015). "Radiocesium leaching from contaminated litter in forest streams." *Journal of Environmental Radioactivity* 144: 15-20. http://www.sciencedirect.com/science/article/pii/S0265931X1500065X

282 Bergan T.D., *op. cit.* (1995)

283 Bergan T.D., *op. cit.* (1995)

284 Matsuda, K. et al., *op. cit.* (2015)
See also, Yamamoto, S., et al., *op. cit.* (2015)

285 Yamamoto, S., et al., *op. cit.* (2015)
See also, Arai, T., *op. cit.* (2014)

286 Wada, T. et al., *op. cit.* (2016)
See also, Matsuda, K. et al., *op. cit.* (2015)
See also, Yamamoto, S., et al., *oop. cit.* (2015)

287 Rowan, D. J., et al., *op. cit.* (1998).

288 Wada, T. et al., *op. cit.* (2016)

Endnotes

289 Arai, T. *op. cit.* (2014)
See also, Wada, T. et al., *op. cit.*(2016)
See also, Matsuda, K. et al., *op. cit.*(2015)
See also, Yamamoto, S., et al., *op. cit.* (2015)

290 Wada, T. et al., *op. cit.* (2016)

291 *Ibid.*

292 *Ibid.*

293 *Ibid.*

294 *Ibid.*

295 Yamamoto, S., et al., *op. cit.* (2015)

296 *Ibid.*

297 *Ibid.*

298 *Ibid.*

299 *Ibid.*

300 Lepage, H., et al., *op. cit.* (2016)

301 *Ibid.*

302 Evrard, O., et al. (2014). “Renewed soil erosion and remobilisation of radioactive sediment in Fukushima coastal rivers after the 2013 typhoons.” *Scientific Reports 4.* *http://www.nature.com/articles/srep04574*

303 Evrard, O. et al., *op. cit.* (2015)

304 Evrard, O. et al. (2013). “Evolution of radioactive dose rates in fresh sediment deposits along coastal rivers draining Fukushima contamination plume.” Scientific Reports 3. Article 3079. *http://www.nature.com/articles/srep03079*

305 For basic information on estuaries, visit: *http://omp.gso.uri.edu/ompweb/doee/science/descript/whats.htm*

306 For example, see: Kakehi, S., et al. (2016). “Radioactive cesium dynamics derived from hydrographic observations in the Abukuma River Estuary, Japan.” *Journal of Environmental Radioactivity.* Vol. 153: 1–9. *http://www.sciencedirect.com/science/article/pii/S0265931X15301600*

307 Iwasaki, T., et al. (2014). “Computational modeling of 137Cs contaminant transfer associated with sediment transport in Abukuma River.” *Journal of Environmental Radioactivity.* Vol.139: 416–426 *http://www.sciencedirect.com/science/article/pii/S0265931X14001520*

308 Kakehi, S., et al., *op. cit.* (2016)

309 *Ibid.*

310 Chartin, C. et al. (2013). “Tracking the early dispersion of contaminated sediment along rivers draining the Fukushima radioactive pollution plume.” *Anthropocene* 1: 23–34. *http://www.sciencedirect.com/science/article/pii/S2213305413000088*

311 *Ibid.*

312 Yamasaki, S., et al. (2016). “Radioactive Cs in the estuary sediments near Fukushima Daiichi Nuclear Power Plant.” *Science of The Total Environment.* Vol. 551–552: pgs.155–162 *http://www.sciencedirect.com/science/article/pii/S0048969716301541*

313 *Ibid.*

314 Kakehi, S., et al., *op. cit.* (2016)
See also, Yamasaki, S., et al., *op. cit.* (2016)

315 Yamasaki, S., et al., *op. cit.* (2016)

316 Takata, H., et al. (2015). "Remobilization of radiocesium on riverine particles in seawater: The contribution of desorption to the export flux to the marine environment." *Marine Chemistry.* 176: 51-63. *http://www.sciencedirect.com/science/article/pii/S0304420315300219*

317 *Ibid.*

318 *Ibid.*

319 *Ibid.*

320 Fan, Q., et al. (2014). “Factors controlling radiocesium distribution in river sediments: Field and laboratory studies after the Fukushima Dai-ichi Nuclear Power Plant accident.” *Applied Geochemistry.* 48: 93–103. *http://www.sciencedirect.com/science/article/pii/S088329271400167X*

321 Kakehi, S., et al., *op. cit.* (2016)

322 F. Eyrolle-Boyer, et al., *op. cit.* (2015)

323 “Final Report: The Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi Nuclear Power Plant”, *Tokyo and Fukushima Prefecture,* Japan 14 – 21 October 2013. *https://www.iaea.org/sites/default/files/final_report230114_0.pdf,* accessed July 13 2015.

324 The teams are made up of Greenpeace radiation experts who have been trained in radiation monitoring and the use of sophisticated measuring devices. Radiation surveys - Fukushima October 30th, 2014, *http://www.greenpeace.org/international/en/campaigns/nuclear/safety/accidents/Fukushima-nuclear-disaster/Radiation-field-team/*, accessed February 11th 2015.

325 The total Cs 134 inventory was almost equivalent to Cs 137 at the time of initial deposition (year 0) but will become less than 10% of the total initial inventory after 5 years due to the fact that Cs 134 has a half-life of 2.1 years. The total Cs 137 and Cs 134 combined inventory will decrease to approximately half of the initial fallout after approximately 10 years, primarily because of the radioactive decay of Cs134. However, the rate at which the total radiocesium inventory decreases will slow after 10 years, when Cs 137 remains as the dominant nuclide, see “Predicted spatio-temporal dynamics of radiocesium deposited onto forests following the Fukushima nuclear accident”, Shoji Hashimoto, Toshiya Matsuura, Kazuki Nanko, Igor Linkov, George Shaw & Shinji Kaneko, *http://www.nature.com/srep/2013/130902/srep02564/full/srep02564.html*

326 Long-term Assessment of Transport of Radioactive Contaminate in the Environment of Fukushima (F-TRACE). *Japan Atomic Energy Agency.* Caesium Workshop. 2013. *http://fukushima.jaea.go.jp/initiatives/cat01/pdf00/20__Iijima.pdf*

327 “Gov't plans not to decontaminate Fukushima forests away from residential areas.” *The Mainichi.* December 22, 2015. *http://mainichi.jp/english/articles/20151222/p2a/00m/0na/012000c*

328 「森林・木材と放射性物質　福島の森林・林業再生に向けて
2014年」　発行：林野庁
http://www.ringyou.or.jp/publish/detail_1270.html

329 Forestry Agency, (2014). “Annual Report on Forest and Forestry in Japan Fiscal Year 2014 (Summary).” Ministry of Agriculture, Forestry and Fisheries, Japan. Pg 24. *http://www.maff.go.jp/e/pdf/2014_summary.pdf*

330 “About shipment restriction on mushrooms or/and wild vegetables.” Website of Ministry of Agriculture, Forestry and Fisheries. *http://www.rinya.maff.go.jp/j/tokuyou/kinoko/syukkaseigen.html*

331 *Ibid.*

Endnotes

332 Bird, W.A. & Little, J.B. (2013). "A Tale of Two Forests: Addressing Postnuclear Radiation at Chernobyl and Fukushima." *Environmental Health Perspectives.* 121(3) *http://ehp.niehs.nih.gov/121-a78/*

333 Forestry Agency, (2014). op. cit.

334 *Ibid.*

335 Ministry of Education, Culture, Sports, Science and Technology, Japan. *http://www.mext.go.jp/b_menu/shingi/chousa/kaihatu/016/shiryo/__icsFiles/afieldfile/2015/01/28/1354739_5.pdf*

336 Recommendation of the Environmental Ministry's expert panel on decontamination on December 21, 2015. See, *http://josen.env.go.jp/material/session/pdf/016/mat05.pdf*

337 "Forests will not be decontaminated." December 20, 2015. NHK. *http://www3.nhk.or.jp/nhkworld/english/news/20151221_09.html*

A clean-up operation in the center of Iitate village. The top soil en vegetation are removed, then put into plastic containers in the hope it will lower the level of radiation of the contaminated fields.
© Robert Knoth/Greenpeace

Greenpeace is an independent campaigning organisation. Founded in 1971, it acts to change attitudes and behavior, to protect and conserve the environment, and promote peace and sustainability.

Greenpeace Japan
〒160-0023 Tokyo, Shinjuku,
Nishishinjuku, 8 Chome–13–11,
エヌエフビル 2F

For more information contact:
kendra.ulrich@greenpeace.org

www. greenpeace.org/japan/ERJ