Overview of Environmental Impact Assessment Studies on Radioactive Contamination after the Fukushima Daiichi Nuclear Power Plant Accident

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Abstract

The radioactive environmental contamination that resulted from the Fukushima Daiichi nuclear power plant accident has clearly been declining during the nearly 10 years that have passed since the accident. Many studies, however, have indicated prolongation of radioactive contamination in natural ecosystems, probably arising from non-decontaminated forested areas, so a more detailed examination is needed on the environmental dynamics of bioavailable radiocesium and its transfer to ecosystems. Also, regarding the influences of radiation on organisms, the effects on wild organisms of the evacuation of humans have been more pronounced than the direct effects from radiation, especially in the Fukushima evacuation zones.

Key words : dissolved Cs, radiation effect, transfer to ecosystem, wild organism

1. Introduction

As shown by the time change in radiation air dose rates measured by airborne surveys (Nuclear Regulation Authority, 2020), serious environmental radioactive contamination occurred widely as a result of the Fukushima Daiichi nuclear power plant (FDNPP) accident. The air dose rate has clearly been declining during the nearly 10 years that have passed since the accident thanks to decontamination operations in the living sphere of the affected areas as well as the natural decay of Cs-134, the half-life of which is 2.0 years, and weathering of radiocesium.

On the other hand, the forested areas that cover over 80% of the evacuated zones remain mostly non-decontaminated. Considering the reported behavioral properties of radiocesium in forests such as its high adsorption in clay particles in the soil (Takahashi et al., 2019) and limited runoff ratios even during rain events (Tsuji et al., 2016; Iwagami et al., 2017a), it is assumed that large amounts of the deposited radiocesium will be retained in the surface soil layer over a long period of time. Serious radioactive contamination of forested areas and subsequent long-term contamination of natural ecosystems were reported after the Chernobyl nuclear power plant (CNPP) accident in 1986 in the former Soviet Union (Belli & Tikhomirov, 1996; Bulgakov et al., 2002). The same situation is of increasing concern in the area affected by the FDNPP accident. Additionally, since long-term retention of radiocesium in the forest floor means prolonged conditions of high dose rates in the part of the forest environment near the ground, we cannot overlook the effects of radiation doses on organisms over the mid to long term.

In this paper, we focus especially on radiocesium transfer to natural ecosystems and the various effects of radiation on organisms in an attempt to assess the environmental effects of the FDNPP accident through the accumulated scientific knowledge from previous research papers. Concretely, we first give an overview of the behavioral properties of dissolved radiocesium with high bio-availability, which plays an important role in its transfer to natural ecosystems in forests and river systems. Then we describe the state of radiocesium transference to forest trees, freshwater fish and wild animals. In addition, the actual state of radiation doses' influence on organisms and the influence on biota of the absence of humans due to evacuation are described respectively as direct and indirect effects of serious environmental radioactive contamination.

2. Migration Behavior of Dissolved Cs in Terrestrial Areas

In a previous review (Hayashi, 2016), the following points were indicated as future issues regarding the behavior of Cs in the environment around Fukushima:

- Organization of scientific knowledge on managing radiocesium runoff from forests based on many case studies,
- Detailed investigations of dissolved radiocesium in river systems in terms of generation mechanisms, particularly the contribution of highly contaminated organic matter (leaf litter) and seasonal fluctuations in concentrations,
- Investigations on the behavior of sediments with high concentrations of radiocesium through direct deposition and initial inflow to clarify the actual state of bottom sediment contamination in dam reservoirs, and
- Investigations on the possibility of dam reservoirs acting as a source of dissolved radiocesium.

In this chapter, we review recent investigations on the behavior of dissolved radiocesium in river systems and forests, which are considered to be two sources.

2.1 Sources of Dissolved Cs in River Systems

Highly contaminated organic litter, such as leaf litter, is considered one of the possible sources of dissolved radiocesium in river systems. This possibility is supported by both seasonal fluctuation, with high levels in summer and low in winter (Tsuji et al., 2016; Nakanishi & Sakuma, 2019), and a rapid but extremely temporary increase in concentration immediately after rainfall starts (Tsuji et al., 2016; Iwagami et al., 2017b; Sakuma et al., 2019). According to phenomenological model calculations, these trends in dissolved radiocesium concentration cannot be expressed by traditional adsorption-desorption distribution models, so it is thought that the kinetically controlled dissolution of radiocesium during the decomposition of organic matter might contribute (Sakuma et al., 2019). Dissolved radiocesium concentrations are correlated with water temperature (Nakanishi & Sakuma, 2019), dissolved organic carbon (DOC) and potassium (K^+) concentrations (Tsuji et al., 2016), also suggesting contribution of organic matter decomposition. However, since the width of fluctuation decreases with time (Nakanishi & Sakuma, 2019), the contribution of this process might be decreasing.

Desorption from forest soil or river sediments is another possible source. In the case of forest streams, the declining trend of dissolved radiocesium in stream water is similar to that in groundwater (Iwagami et al., 2017b). The level of radiocesium dissolved in water contained in soil layers was found to be quite high in July 2011 and declined after that, and could be fit with a two-component exponential model (Iwagami et al., 2017c). The faster decline rate showed a good correlation with the radiocesium interception potential (RIP), suggesting that desorption from clay minerals contributed to generation of dissolved radiocesium in forest soil. In the case of river sediments, the cation exchange capacity (CEC) is influenced by both clay minerals and organic matter content (Tachi et al., 2020a). The adsorption behavior at 10^{-9} M of the initial concentration of radiocesium can be expressed by a first-order reaction, but the rate constant decreases with an increase in organic matter content, indicating that organic matter inhibits radiocesium access to frayed edge sites (FESs) (Tachi et al., 2020b). In particular, the dissolved radiocesium concentration in output water from one of the dam reservoirs in Fukushima has shown slightly higher concentrations and slower decline than that of the input water (Funaki et al., 2020). It is thought that radiocesium that has accumulated in the reservoir sediments may partly be desorbed by ammonium ions, dissolving into the reservoir's water. The conditions in the reservoir sediment are likely to remain in a reducing condition under which ammonium ions are easily generated and can desorb cesium ions.

2.2 Behavior of Cs in the Forest Floor

Most of the radiocesium deposited in forests has moved from the canopy to the forest floor. Throughfall is the dominant pathway of radiocesium transfer in the first year, and the contribution of litterfall gradually increases with time (Kato et al., 2017). The trend of radiocesium decreasing in the canopy is expressed by a double exponential field-loss model. In the six months after the accident, 82% of the initially deposited radiocesium was present on the forest floor in mixed forests and broad-leaved forests, and 78-56% in the case of cedar forests (Komatsu et al., 2016). The ratio of radiocesium on the cedar forest floors to the initially deposited amount was also reported to be 80% three years after the accident (Gonze et al., 2017) and 94% four years after it (Yoschenko, 2017).

On the forest floor, radiocesium in the litter layer migrates to the lower mineral layer, and is strongly adsorbed by the minerals. It has been reported that the radiocesium concentration in the mineral layer located a few centimeters below the surface gradually increased and became higher than that in the litter layer after two or three years (Takahashi et al., 2019). The exchangeable fraction of radiocesium was of 10% in the organic layer and 6% in mineral layer after five months, and constant at 2−4% in two to four years in both layers, showing that radiocesium could not easily move to deeper parts (Manaka et al., 2019). Throughfall dominates as the source of radiocesium migrating downward from the litter layer in the case of cedar forests, while decomposition of litter dominates in the case of broad-leaved forests (Kurihara et al., 2018).

Litter from forests and elution from the litter/organic soil layer are likely contributors to the dissolved radiocesium concentrations in river systems. Based on a compartment model analysis Kurikami et al. (2019) reported that the origination of dissolved radiocesium concentration in river water and freshwater fish could be explained by a combination of these three sources. Further investigations to clarify the dissolution mechanism and behavior of radiocesium in forests are desired, which would enable the establishment of models for estimating future concentrations.

3. Radiocesium Transfer to Natural Ecosystems

Most of the radiocesium emitted in large quantities into the environment by the FDNPP accident was deposited in the mountainous forested areas of Fukushima Prefecture and its surroundings. Many studies after the accident suggest that although most of the deposited radiocesium remains in the surface soil layer because it is strongly bound with clay particles in the soil, the runoff ratio from forest catchments is limited to less than 1.0% annually even when large storms occur (Tsuji et al., 2016; Iwagami et al., 2017a). Therefore, forested areas would not be involved with re-contamination in the downstream catchment area as the source of radiocesium migration. However, this situation implies that radiocesium deposited on the forest floor, especially Cs-137 with a long half-life (30.1 yrs.) stays nearly retainable in the surface soil layer, which is biologically active (Takahashi et al., 2019). Therefore, understanding radiocesium transfer in natural ecosystems is essential for inferring future trends.

In this chapter, we outline the current state of radiocesium distribution and properties of its transfer in the natural ecosystems of forested areas, freshwater bodies and wild animals, based on reports from previous studies after the FDNPP accident.

3.1 Forest Ecosystems

As for the state of radiocesium transfer into forest products, which is of most concern regarding radioactive contamination of forest ecosystems, the main research that has been conducted has targeted evergreen needle-leaved trees like Japanese cedar and cypress which have been utilized as timber products (Kanasashi et al., 2015; Kajimoto et al,. 2015; Kato et al., 2017; Nishikiori et al., 2019). Since uptake followed by translocation from the above-ground parts, mainly foliage, where it was deposited soon after the accident, and root uptake are assumed as the transfer processes of radiocesium to wood, this is of most interest. Several attempts have been made to quantitatively evaluate the respective contributions (Mahara et al., 2014; Nishikiori et al., 2015; Yoschenko et al., 2018). Imamura et al. (2020) conducted a source analysis utilizing the ratio of Cs-137 activity concentration to stable cesium (Cs-133) concentration in several components of Japanese cedar and soil pore water. They estimated that root uptake had contributed to about 50% of the increment in Cs-137 in the stemwood of a 40-year-old tree from Jul. 2011 to Aug. 2017 at a maximum, although the size of this contribution was highly uncertain. Thiry et al. (2020) applied of their comprehensive modeling of radiocesium cycling in forests to pine trees in Belarus and Ukraine after the CNPP accident using the observed data. They proved that root uptake contributed to the transfer of Cs-137 to wood more strongly than uptake from foliage since 10 years after the accident. Even in Fukushima, continuous observation will be needed to see if the contribution of root uptake to the Cs -137 transfer to the wood of Japanese cedar and Japanese cypress increases in the future, although it will depend on how much bio-available Cs-137 is generated in the soil, corresponding to forest environment conditions.

Based on a five-year study starting from Aug. 2011, five months after the FDNPP accident, Imamura et al. (2017) estimated the initial deposition of Cs-137 onto the above-ground parts of *konara* oak to be less than one-third of those of Japanese cedar or Japanese cypress, due to lack of foliage at the time of the accident in the case of deciduous broad-leaved trees. Surprisingly, Cs-137 activity concentrations in deciduous *konara* oak leaves did not change over the five years, although the Cs-137 activity concentrations in the wood significantly increased year by year. Kanasashi et al. (2020) showed that Cs-137 activity concentrations in growing coppiced shoots of *konara* oak have had a significant positive correlation with exchangeable Cs-137 in soil in Fukushima after the FDNPP accident. It may be necessary to examine the contribution of root uptake as one of the main controlling factors in determining Cs-137 activity concentrations in the leaves and stemwood of deciduous broad-leaved trees as well as translocation from the deposited bark and branches. Generally, many deciduous broad-leaved trees have shallower root systems than Japanese cedars and Japanese cypresses, suggesting that they may be able to take up exchangeable Cs-137 in soil supplied by leaching from litter more easily.

Since radiocesium cycling caused by transfer to deciduous broad-leaved trees via root uptake will be a strong concern regarding long-term radioactive contamination of forest ecosystems, countermeasures to this issue should be considered in future research.

3.2 Freshwater Ecosystems

Since radioactive contamination of fish is a big concern from the viewpoint of inland water fisheries and the leisure industry in freshwater ecosystems, the Ministry of the Environment; Ministry of Agriculture, Forestry and Fisheries; and Fukushima Prefecture have been conducting respective monitoring projects to elucidate the state of radiocesium concentrations in fish. By utilizing these monitoring data, Ishii et al. (2020) showed that the state of Cs-137 transfer to fish clearly differed by habitat (river or lake) or feeding habit of fish using the concentration factor (CF: CF = Cs-137 activity concentration in fish (Bq/kg-fw)/Cs-137 in water (Bq/L)), which serves as an indicator of the present state of radiocesium transfer from the aqueous environment to aquatic organisms. It has also been confirmed that larger fish show higher radiocesium concentrations than smaller ones even in the same habitat or among the same species (Wada et al., 2019; Ishii et al., 2020). Freshwater fish usually supplement cations including radiocesium through feeding and have a lower excretion rate during osmoregulation compared to marine fish (Wada et al., 2019). Consequently, since their radiocesium activity concentration varies depending largely on what they eat, clarifying the flow of radiocesium via the food-web is clearly essential to understanding the mechanism of transfer to fish.

Generally, radiocesium activity concentrations in omnivorous or carnivorous fish are higher than that in herbivorous or planktotrophic fish (Wada et al., 2016; Ishii et al., 2020), so how radiocesium is transferred to fish by the detritus food chain via insects feeding on forest litter is being examined. As an example, it has been confirmed that differences in radiocesium concentrations in litter, which is the basal food of forest and stream ecosystems, are reflected in radiocesium concentrations in communities of aquatic organism (Sakai et al., 2016). Factors inhibiting lower of radiocesium activity concentrations in fish need to be investigated and effective countermeasures to prevent radiocesium from transferring to fish need to be examined as much as possible based on scientific knowledge obtained from an evaluation of transfer properties through the food web in order to promote the recovery of industries related to freshwater fish.

3.3 Wild Animals

As for the transfer of radiocesium originating from the FDNPP accident to wild animals, the current and transition states have been examined mainly with regard to game animals from the viewpoint of food-safety. From the reported Cs-137 activity concentrations in game meat data from Asian black bears (*Ursus thibetanus*), wild boars (*Sus scrofa*), sika deer (*Cervus nippon*), green pheasants (*Phasianus versicolor*), copper pheasants (*Syrmaticus soemmerringii*), and wild ducks (*Anas poecilorhynch* and *Anas platyrhynchos*) in more than 10 prefectures after the FDNPP accident between 2011 and 2015, Tagami et al. (2016) confirmed that the concentrations in wild boars were the highest of all, but were lower than those reported after the CNPP accident. Also from a comparison between Cs-137 activity concentrations in the meat of Asian black bears or wild boars between 2011 and 2016 and Cs-137 inventories in the areas where they had been trapped, estimated by airborne surveys (Nuclear Regulation Authority 2020), Nemoto et al. (2018) reported that each concentration was proportional to the inventory and the concentration in wild boars was higher than in Asian black bears if they had been trapped in the same area.

As for the aggregated Cs-137 transfer factor (Tag = activity concentration in meat (Bq/kg-fw)/inventory in soil (Bq/m^2)), which is an indicator of transfer properties from radioactive contaminated land to game animals, the geometric means (GM) for green pheasant and wild duck remained on the order of 10^{-4} during the monitoring period, while those for Asian black bear, wild boar, sika deer and copper pheasant were one order higher (Tagami et al., 2016; Nemoto et al., 2018). Compared with the Tag after the CNPP accident, directly comparable data obtained for wild boars were in the same range of the GM values (4×10^{-3} to 6.7×10^{-2}) collected within five years after the CNPP accident by International Atomic Energy Agency (IAEA; Howard et al., 1996).

The annual change in Tag depends on the species. While it decreases slightly in some species (wild boar, green pheasant and wild duck), no significant change has been found in other species (Asian black bear, sika deer and copper pheasant). Although clear seasonal changes in Cs-137 activity concentration were found in wild animals after the CNPP accident (Semizhon et al., 2009), a uniform opinion has yet to be formed in the case of the FDNPP accident. While Tagami et al. (2016) concluded that no seasonal trends could be found in any species from the collected data, Nemoto et al. (2018) stated that muscle Cs-137 varied seasonally and that this seasonal variation also differed between Asian black bears and wild boars. It might be necessary to conduct more successive sample collections and detailed analyses considering differences in feeding among species or differences in environment between the areas affected by the FDNPP and CNPP accidents to gain a clearer understanding of the properties. Concretely, progress will be needed in studies focused on gastric contents of wild animals to elucidate increases in concentrations according to when and what they eat (Saito et al., 2020). This pertains especially to the most contaminated wild boars whose numbers are confirmed to have increased due to the effects of evacuation orders affecting seriously contaminated areas (Lyons et al. 2020). More detailed research on ranging behavior, dietary habits and the long-term behavior of radiocesium in forest ecosystems will be needed in Fukushima Prefecture and surrounding areas (Hinton et al., 2015).

4. Effects of Radiation and Human Evacuation on Wild Organisms and Ecosystems in Fukushima

As a result of the FDNPP accident, all of the wild animals and plants have been left behind in high radiation-dose areas, so they are still exposed to radiation in Fukushima. It is, therefore, of high concern whether any adverse effects have been found in wild organisms in the Fukushima area resulting from long-term, low-dose exposures to radiation. In the first half of this chapter, we focus on radiation effects in wild organisms found in Fukushima, where small but serious adverse effects of radiation have been detected. However, the risks from radiation on wild organisms will diminish because radiation doses in Fukushima have been decreasing through natural decay, weathering and efforts for decontamination. The area covered by the evacuation zones has been steadily decreasing, from 1,150 km^2 in August 2013 to 340 km^2 in April 2019, as air dose rates have decreased. With the lifting of evacuation orders, about 58,000 former residents of the evacuation zones, have been permitted to return to their hometowns, but the area's population is only 28% of its total before the accident. Thus, changes in land use with the cessation of daily life activities, such as agricultural and horticultural work, continue, and these significantly affect the wild organisms and ecosystems in the evacuation zones. In the Fukushima evacuation zones, because the air dose rates are gradually decreasing with time, it will be necessary to pay more attention to the effects of the evacuation on wild organisms and ecosystem rather than direct effects from radiation hereafter. Therefore, the impacts of rapid changes in human activities on wild organisms and ecosystems are also described in the second half of this chapter.

4.1 Estimated Levels of Exposure of Wild Organisms to Radiation

Levels of contamination with radioactive materials and estimated radiation exposure doses in marine and terrestrial organisms living in Fukushima were initially predicted to exceed the derived consideration reference levels (DCRLs) determined by ICRP and reported during first month after the accident (ICRP, 2008; Garnier-Laplace et al., 2011; Strand et al., 2014). According to the prediction, marine organisms including seaweed, benthic invertebrates and benthic flatfish were expected to have suffered severe effects from radiation categorized as "reduction in life span" in ICRP's DCRLs (Tamaoki, 2016). However, very few adverse effects were found in marine organisms living in Fukushima.

The only exception was reported by Horiguchi et al. (2015), in which the abundance and diversity of intertidal species decreased significantly with decreasing distance from the FDNPP in 2012, and no rock shells (*Thais clavigera*) were observed within a radius of 20 km of the FDNPP. Unfortunately, whether the decrease or disappearance of these species was caused directly by the increase of radiation doses or not remains unclear at this moment.

4.2 Radiation Effects in Wild Organisms in Fukushima

In contrast to marine organisms, only rodents were expected to suffer from radiation at the level categorized as "reduced production" in ICRP's DCRLs for terrestrial organisms (Tamaoki, 2016). Onuma et al. (2020) calculated exposure dose rates for large Japanese field mice (*Apodemus speciosus*) captured in the "difficult-to-return zones" in Fukushima Prefecture from 2012 to 2016, and they found that the total dose rate (sum of internal and external dose rates) was estimated at less than 1.0 mGy/day. Exposure exceeding 1.0 mGy/day could reduce fertility in male and female field mice according to ICRP's DCRLs, indicating that the present dose rates of the field mice living in the capture sites were lower than the dose rates that would reduce fertility. Accordingly, no significant differences in apoptotic cell frequencies or frequencies of morphologically abnormal sperm were observed in field mice captured in Fukushima as compared to the results from two control sites, in Aomori and Toyama prefectures, in 2013 and 2014 (Okano et al., 2016).

Among organisms living in Fukushima, morphological abnormalities were detected in some species such as the pale grass butterfly (*Pseudozizeeria maha*) (reviewed by Hiyama et al., 2015), gall-forming aphids (*Tetraneura sorini and T. nigriabdominalis*) (Akimoto 2014) and conifer tree species (Japanese fir tree; Watanabe et al., 2015, Japanese red pine; Yoschenko et al., 2016). It is noteworthy that no abnormal morphologies in the butterfly and aphid have been observed since 2013 (Akimoto, 2014; Hiyama et al., 2015). This indicates that the abnormal phenotypes in these small insects only occurred within two years after the FDNPP accident, and severely malformed individuals were eliminated by natural selection.

In addition, there is no evidence of genetic mutations causing abnormal morphologies. Further studies are needed to obtain positive proof that these abnormal phenotypes occurred due to radiation, and reproductive experiments such as irradiation of butterflies, aphids and conifer tree species for long periods at low doses would also be effective for advancing our knowledge on radiation effects in wild organisms.

4.3 Effects of Radiation on Abundance of Wild Populations in Fukushima

Radiation effects on population sizes in insect and birds were also investigated in the Fukushima evacuation zones. Møller et al. (2013) took a census of spiders, grasshoppers, dragonflies, butterflies, bumblebees and cicadas at 300 sites in forested areas of the evacuation zones. They found that the abundance of butterflies and cicadas declined significantly with increasing levels of radiation doses. Interestingly, the abundance of spiders showed a positive correlation to the radiation doses at the sites where they were collected. Such positive correlations observed in spiders were not observed in particular in the case of Chernobyl, where all of the arthropods showed negative correlations between their abundance and radiation dose rates.

The effects of radiation on the abundance of common birds were also studied in Fukushima and the results obtained were compared to those in Chernobyl (Møller et al., 2012). Fourteen bird species common to both Fukushima and Chernobyl showed abundance negatively correlated to radiation doses at the two sites, but the tendency toward negative effects differed between Fukushima and Chernobyl. Interestingly, the negative correlation between the abundance of these 14 common bird species and radiation doses was more pronounced in Fukushima than in Chernobyl. The reasons for these differences in radiation-dose-dependent change in abundance of spiders and bird species between Fukushima and Chernobyl are unclear. Some research evidence indicates that wild organisms living in Chernobyl have already finished undergoing adaptation to and/or selection for high radiation environments because the investigations in the area started 20 years after the Chernobyl accident. Thus, it will be very important to study whether adaptation and/or selection is occurring in the Fukushima evacuation zones.

4.4 Effects of Human Non-residence by Evacuation on Population Size in Wild Organisms

To clarify the effect of evacuation on wild organisms, biota monitoring targeting mammals, birds, frogs and flying insects inside and outside the evacuation zones in Fukushima has been undertaken since 2014 (Yoshioka et al., 2016). As reviewed previously, the abundance of carpenter bees (*Xylocopa appendiculata*) was lower in the evacuation zone than outside it (Yoshioka et al., 2015; Tamaoki 2016). Moreover, some small bees, wasps and beetles were more common inside the evacuation zone. The causes of these population changes in some insect species are unclear, but changes in human activities such as abandonment of cultivation and/or gardening may affect them. Among frogs, eight species have been observed during the monitoring, but the frequency of observation of each frog species has not yet been compared inside and outside of the evacuation zones. The two-year data sets (2014–2015) obtained were published as a data paper for enabling its use by other researchers (Yoshioka et al., 2020).

Mammals have been monitored at 46 sites in nine municipalities inside and outside the evacuation zones (locations can be seen at http://www.nies.go.jp/biowm/map/en_mafu.html). Infrared camera traps were employed, which automatically respond to infrared radiation from homothermic animals. Sixteen different mammal species have been observed through camera trapping (Fukasawa et al., 2016). Among these, wild boars (*Sus scrofa*) were caught on camera most often and at the largest number of sites (78% of the monitored sites). A statistical analysis showed that wild boars were more abundant in the evacuation zone than outside it, indicating that decreased human activity may help the wild boar population increase. The same tendency was also found to a lesser extent in other species such as badgers (*Meles meles*), Japanese macaques (*Macaca fuscat*a) and Japanese hares *(Lepus brachyurus*). The same result was also reported by Lyons et al. (2020) in which they found no evidence of impact on population size in mammals or gallinaceous birds, and showed that several species were most abundant in the evacuation zones, despite the presence of high radiation doses.

Among them, increased wild boar populations in Fukushima have resulted in damage to agricultural operations and require control by state-funded hunting programs. Radiocesium levels in wild boar meat often exceed government guidelines for food consumption, not only in and around the evacuation zones but also in the Aizu area in western Fukushima Prefecture, more than 100 km from the FDNPP. Moreover, wild boars are considered a pest animal in farmland, and are a major mediator of classical swine fever which can seriously damage the pork industry. Indeed, about half of the animal damage to crop yields in Fukushima is due to wild boars, and wild boars infected by swine fever virus have been found in Aizu-Wakamatsu City as of September 2020. Thus, it is important to clarify the population dynamics and migratory movements of wild boars in Fukushima to develop an efficient plan for helping residents return to the evacuation zones.

5. Summary

In this paper, we have provided an overview of recent progress in investigations of the environmental impact induced by the FDNPP accident, focusing especially on radiocesium transfer to natural ecosystems and the effects of deposited radioactive materials on organisms.

Litter from forests and desorption from the litter/organic soil layer are likely contributors to dissolved radiocesium concentrations in river systems. The origins of the dissolved radiocesium will evolve with time in accordance with the source of radiocesium migrating downward from the litter layer to the mineral layer. In forest ecosystems, radiocesium is thought to migrate into wood by root uptake and/or uptake from deposits on above-ground parts followed by translocation. The contribution of root uptake, however, has not been evaluated as of this time. As a source of dissolved radiocesium affecting river systems and forest ecosystems, the behavior of litter decomposing and leading to the dissolution of radiocesium in forests is a key issue to be investigated in the future.

The transfer of Cs-137 to freshwater fish is affected by habitat (river or lake), feeding habit, body size and so on. It has also been pointed out that the concentration of radiocesium in litter is related to that in communities of aquatic organism. Among wild animals, wild boars showed relatively higher radiocesium concentrations, but the tendencies of concentrations to evolve, such as through seasonal variation, are still under discussion. To predict future concentrations in these ecosystems, it would be desirable to clarify dominant pathways of transfer of radiocesium via the food-web through continuous systematic sample collection and detailed analysis.

Direct effects of increased radiation doses have not been clearly observed among marine organisms, while morphological abnormalities have been detected in some species of terrestrial organisms, such as small insects and coniferous trees. However, further investigation will be needed to obtain evidence as to whether or not genetic mutations caused these abnormalities. Negative effects of radiation on population size in insects and birds have also been observed in areas affected by the FDNPP and CNPP accidents, respectively, though the tendencies differed in some cases. Conversely, the decrease in human activities caused by conditions of high radiation are thought to lead to increased wild boar populations. In future work, it will be important to investigate whether adaptation and/or selection occur in the Fukushima evacuation zones and to elucidate the population dynamics and migratory movements of wild boars.

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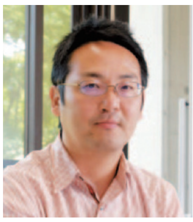

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