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Effects of local-scale decontamination in a secondary forest contaminated after the Fukushima nuclear power plant accident☆

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ABSTRACT

We investigated whether local-scale decontamination (removal of the litter layer, superficial soil layer, and understory) in a secondary forest contaminated by the Fukushima nuclear power plant accident reduced ^{137}Cs contamination of the soil and litter. We also measured ^{137}Cs concentrations in plants and in the web-building spider *Nephila clavata* (Nephilidae: Arachnida), as an indicator species, to examine ^{137}Cs contamination in arthropods. One month after decontamination, the total ^{137}Cs contamination (soil + litter) was reduced by 20% (100 $kBq \cdot m^{-2}$) relative to that in an adjacent untreated (i.e., contaminated) area, which was however not statistically significant. Four months after decontamination, ^{137}Cs in the decontaminated area had increased to a level similar to those in the untreated area, and the air radiation dose in the decontaminated area was about 2.1 $\mu Sv \cdot h^{-1}$, significantly higher than that in the untreated area (1.9 $\mu Sv \cdot h^{-1}$). This may have been attributed to a torrential rain event. Although no statistically significant reduction was observed, most spiders had a lower ^{137}Cs contamination than that before the decontamination. This implied that the decontamination may have reduced ^{137}Cs transfer from soil via litter to *N. clavata* through the detrital food chains, but may not have reduced the amount of ^{137}Cs transfer through grazing food chains because the concentration of ^{137}Cs in living tree leaves was not reduced by the decontamination. In autumn, about 2 $kBq \cdot m^{-2}$ of ^{137}Cs was supplied from foliage to the ground by litterfall. The results suggested that removal of the litter and superficial soil layers in a contaminated forest may be ineffective. The present study suggests that the local-scale decontamination in a secondary forest had no effect on the reduction of ^{137}Cs contamination in the treated area.

1. Introduction

The accident at the Fukushima Dai-ichi Nuclear Power Plant following the Tōhoku Earthquake of 2011 contaminated a large area in northeastern Japan with large amounts of radioactive materials (Saito et al., 2015; Yasunari et al., 2011). Among those materials, ^{137}Cs is particularly significant because it has a relatively long half-life (30.2 years) and therefore remains and circulates in the environment for a long time; it will therefore affect both human health, through external and internal exposure, and local economic activity, through contamination of various forest products. Japan's Ministry of the Environment (MOE) has classified the contaminated areas that extended northwest of the Fukushima plant into three categories according to the contamination levels: areas where residents will have difficulty for many years in returning home, areas where residents are not permitted to enter and live, and areas where residents are permitted to enter but not to stay overnight (Ministry of the Environment, 2014). For the last category, decontamination has been actively carried out.

Decontamination methods differ among the types of land use: For residences and buildings, this involves washing the roof and walls with high-pressure washers, cleaning gutters, and removing topsoil and vegetation from yards. For agricultural land, removal and replacement of the topsoil to a depth of 5 cm is carried out, whereas for forest edges beside residences, roads, and agricultural land, removal of the litter layer is performed (Yasutaka et al., 2013a). In aquatic environments, radiocesium adsorbents such as hybrid grafted ion exchanger have been suggested as an effective method to remove dissolved radiocesium (Iwanade et al., 2012). These decontamination activities were assumed to reduce not only

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the soil ^{137}Cs inventory (Japan Atomic Energy Emergency, 2012a), but also radiocesium concentrations in animals that live in decontaminated areas (Sakai et al., 2014). Decontamination is believed to have a certain efficacy in reducing the long-term external radiation exposure in the Fukushima evacuation zone (Yasutaka et al., 2013a).

However, GIS-based studies predicted that decontamination of forest areas would not be effective in reducing air radiation dose (ARD; Yasutaka et al., 2013a). This is an important problem because forest occupies 70% of Fukushima Prefecture (Hashimoto et al., 2012; Yasutaka et al., 2013b), which makes decontamination activities extremely difficult (Yasutaka and Naito, 2015; Yasutaka et al., 2013b). Japan's MOE has prioritized local-scale decontamination of forest around residential areas (area A), typically to a distance of 20 m inside the edge of the forest. Their second priority is areas where people have daily access (area B), such as mushroom farms and recreation areas. The last priority is the whole areas of contaminated forest outside of areas A and B, which they refer to as area C (Ministry of the Environment, 2014).

Although radiocesium tends to remain in the forest and appears unlikely to flow out (Nishikiori et al., 2015a; Ueda et al., 2013; Yoshimura et al., 2015), forests can nonetheless be a source of contamination: leaf litter and animals in forests are mobile and can carry radiocesium to both unaffected and decontaminated areas, thus causing new contamination. In one study, a decontamination operation conducted to a distance of 30 m inside the edge of a forest reduced the ARD at the forest boundary (Japan Atomic Energy Emergency, 2012b) just after the operation, but whether their result was stable is not yet known. Furthermore, a decontamination operation should be evaluated both for ARD and for ^{137}Cs contamination of components of the forest habitat, such as plants and animals. To establish a future scientifically supported system for the management of radiocesium contamination in forests, it is essential to understand the effectiveness of the present decontamination methods in forests and the stability of the effect.

The purpose of the present study was to investigate whether current forest decontamination operations can reduce the levels of ^{137}Cs contamination in the soil, plants, and animals in a treated area and whether the effects are stable and persistent. In a contaminated secondary forest, where decontamination was performed along a mountain trail, we monitored changes in the ARD and the levels of ^{137}Cs contamination in the soil, in living plants, and in the web-building spider *Nephila clavata* L. Koch (Nephilidae: Arachnida). We compared values before and after the decontamination and between a decontaminated area and the adjacent non-treated area (as a control). *Nephila clavata* is a useful indicator species for evaluating radiocesium contamination because spiders occupy a key position in the material circulation and ecological interactions within forest ecosystems through both grazing and detrital food chains, in part because they constitute a large proportion of forest arthropod biomass (up to 30%; Hijii, 1989). In addition, spiders are linked to a wide range of arthropod species as predators (Wise, 1993), but are also prey for insectivorous birds (Mizutani and Hijii, 2002). *Nephila clavata* overwinters as eggs, disperses as juveniles in April to May, feeds on prey arthropods captured in a web and then matures in September to October. Female adults deposit the sack on trees or shrubs in October to November and then die. Therefore monitoring by using such an univoltine spider with no carry-over of ^{137}Cs would be reasonable to evaluate year-to-year changes in ^{137}Cs concentrations in arthropods. Although there is a possibility that some out-of-habitat prey insects flying from a distance could be captured on webs of *N. clavata*, our previous study revealed that ^{137}Cs contamination in *N. clavata* was significantly positively correlated with ^{137}Cs contamination in the spider's habitat (Ayabe et al., 2014). Moreover, ^{137}Cs contamination in *N. clavata* was associated with transfers of alkali metals (potassium and sodium) within the food chain (Ayabe et al., 2015b). These results suggest the suitability of *N. clavata* as an indicator species.

At the site of the present study, ^{137}Cs contamination in *N. clavata* has been monitored since 2012 (Ayabe et al., 2015a, b). This permits an exact evaluation of the decontamination efficacy by examination of changes in ^{137}Cs concentrations after the decontamination. Furthermore, we compared contamination levels 1 month and 4–5 months after the decontamination to reveal temporal changes (i.e., stability of the decontamination process). If a decontamination operation effectively reduced ^{137}Cs in the soil and litter layers, the ^{137}Cs contamination levels in plants and arthropods inhabiting in the decontaminated area may also have been reduced through the ^{137}Cs cycling in the habitat. In addition, we measured the litter ^{137}Cs activity to evaluate the post-decontamination supply of ^{137}Cs from the foliage to the ground. On the basis of these results, we discuss the efficacy and stability of local-scale decontamination of the forest, the processes responsible for radiocesium circulation in forests after decontamination, and the risks of re-contamination of decontaminated areas.

2. Materials and methods

2.1. Site description

The research was conducted in a contaminated secondary forest at 620 m elevation, and the site was located about 33 km northwest of the Fukushima nuclear power plant, in the Yamakiya district of Kawamata Town in Fukushima Prefecture (Fig. 1a). At the study site, a trail extends uphill toward Mt. Kotaishi. The forest consists of broadleaved trees, such as *Quercus serrata* and *Quercus crispula* (Fagaceae), of *Pterostyrax hispida* (Styracaceae), and of coniferous trees, such as *Cryptomeria japonica* (Cupressaceae) and *Pinus densiflora* (Pinaceae). The original understory vegetation consisted mainly of the bamboo grass *Sasa nipponica* (Poaceae), but these plants were mostly removed during decontamination and had not recovered by the end of the study period. The annual precipitation at the nearest weather station in Tsushima Town (400 m elevation, 5.9 km southwest from the study site) averaged 1455 ± 183 (mean ± SD) mm from 2006 to 2015, ranged from 1148 mm in 2009 to 1705 mm in 2010, and was 1658 mm in 2015, the year of our study. At another station in Iitate Village (446 m elevation, 10.6 km north-northwest from the study site), the annual precipitation averaged 1417 ± 237 mm from 2006 to 2015, ranged from 1084 mm in 2011 to 1824 mm in 2006, and was 1522 mm in 2015 (Japan Meteorological Agency, 2015). The average slope of the trail to Mt. Kotaishi is 4.2°. In May 2015, the MOE decontamination operation was conducted in an area 20–40 m wide centered along the trail. The study site was decontaminated between the beginning to middle of May, but the exact dates were unknown. In this area, the litter layer, including the humus layer to the superficial mineral soil (according to the interview with operation workers) were removed by scraping off using broom and rakes, and understory vegetation were also removed. Large trees were left intact. We defined a 200-m-long decontaminated area and included the adjacent untreated area on the forest side of the trail (Fig. 1b). These two areas are on a gentle slope, with no steep areas, and the untreated area was at the same elevation as the decontaminated area. The decontaminated area was the same one used in our previous studies (site PS in Ayabe et al., 2014, 2015a, 2015b), so we used the ^{137}Cs contamination levels in soils, plants, and arthropods before the decontamination operation as the basis for comparison with the data from the present study.