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Estimation of radioactive 137-cesium transportation by litterfall, stemflow and throughfall in the forests of Fukushima

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ABSTRACT

Since the Fukushima Dai-ichi Nuclear Power Plant accident in March 2011, large areas of the forests around Fukushima have become highly contaminated by radioactive nuclides. To predict the future dynamics of radioactive cesium (^{137}Cs) in the forest catchment, it is important to measure each component of its movement within the forest. Two years after the accident, we estimated the annual transportation of ^{137}Cs from the forest canopy to the floor by litterfall, throughfall and stemflow. Seasonal variations in ^{137}Cs transportation and differences between forests types were also determined. The total amount of ^{137}Cs transported from the canopy to the floor in two deciduous and cedar plantation forests ranged between 3.9 and 11.0 kBq m^{-2} year^{-1}. We also observed that ^{137}Cs transportation with litterfall increased in the defoliation period, simply because of the increased amount of litterfall. ^{137}Cs transportation with throughfall and stemflow increased in the rainy season, and ^{137}Cs flux by litterfall was higher in cedar plantation compared with that of mixed deciduous forest, while the opposite result was obtained for stemflow.

1. Introduction

The Great East Japan Earthquake of 11 March 2011, with its epicenter offshore of Japan's Miyagi Prefecture, triggered a devastating tsunami along the coastline and destroyed the cooling system of the Fukushima Dai-ichi Nuclear Power Plant (FDNPP). Because of the explosions at the plant, a large amount of radioactive nuclides, especially iodine (^{131}I and ^{133}I) and cesium (^{134}Cs and ^{137}Cs), were released into the environment (Chino et al., 2011; Steinhauser et al., 2014). Half-lives of ^{131}I and ^{133}I are only 8.03 days and 20.8 h, but those of ^{134}Cs (2.07 years) and ^{137}Cs (30.1 years) are longer. Because of the long half-life of ^{137}Cs, it is expected that 137Cs will pollute the surrounding natural environment for many years to come. Thus, it is important to understand the distribution and dynamics of 137Cs in the environment.

More than 70% of Fukushima Prefecture is covered by forest. Natural forests, dominated by oak, maple and pine trees, account for 60% of the forest area, and cedar and cypress plantations for timber production account for 35% (Japanese Forestry Agency, 2012). This means that most of the radioactive nuclides released by the FDNPP accident have contaminated the forests. Therefore, understanding the dynamics of radioactive Cs in the contaminated forests is essential for predicting its future behavior in Fukushima.

Radioactive nuclides released into the atmosphere generally deposit on land surfaces both as a wet deposition (e.g., precipitation) and dry deposition (e.g., aerosols and gases). Most of the deposited radioactive material is then washed out with rainfall or falls onto the ground when plants die or litter is deposited onto the soil surface (Kinnersley et al., 1997). Since the above ground parts of trees are much larger than those of crops and herbs, many of the radioactive materials deposited in Fukushima have been captured by trees in the forests (Hashimoto et al., 2012). Radioactive materials captured by the trees subsequently move to the forest floor under natural influences such as precipitation and

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defoliation (Bunzl et al., 1989; Kato et al., 2012; Hisadome et al., 2013). It is expected that the movement of radioactive Cs from the forest canopy to the soil surface will decrease over time, but it is now an active process as only a few years have passed since the accident (Hashimoto et al., 2013). To understand the processes of accumulation and dynamics of radioactive Cs in the Fukushima forests, such as transport from above ground to the forest floor, uptake from the soil to above ground or efflux from the forest ecosystem, it is necessary to quantify current radioactive Cs transportation by litterfall and rainfall. In the Chernobyl NPP accident (26 April, 1986 in Ukraine), a larger amount of radioactive material was dispersed more widely compared with the FDNPP accident (Steinhauser et al., 2014). Schimmack et al. (1993) reported that 5–6 years after the Chernobyl accident, the amount of 137Cs in a German beech forest was highest in throughfall, followed by litterfall and stemflow. However, no study to date has evaluated the amount of Cs transportation by multiple pathways in the Fukushima forests.

Two previous studies reported radioactive Cs transportation after the FDNPP accident. Hisadome et al. (2013) studied the amount of 137Cs transported by litterfall and found it was smaller in conifer–deciduous mixed forest compared with cedar plantation. They reported that the 137Cs concentration was higher in the needles, bark and branches that were on the canopy of evergreen trees at the time of the accident. They also showed that the seasonality of litterfall amount and species components affected the amount of 137Cs transfer. In broad-leaf deciduous forest, the transportation of 137Cs increased in autumn because of defoliation. In contrast, the seasonal pattern of 137Cs transportation in cedar plantation differed from deciduous forests, because evergreen trees such as cedar and pine also defoliate in spring (Hisadome et al., 2013). Transportation of ^{137}Cs by throughfall and stemflow in Fukushima forests was reported by Kato et al. (2012), where throughfall contribution to the movement of ^{137}Cs was 100-fold greater than stemflow contribution in cedar and cypress plantation forest. Schimmack et al. (1993) reported that the radioactive Cs transportation by stemflow and throughfall increased in the rainy season after the Chernobyl accident. From these reports, it was shown that the amount of ^{137}Cs transportation was different among litter components and water pathways, and was affected by seasonal variations. Therefore, to correctly evaluate the amount of ^{137}Cs flux from canopy to forest floor, continuous monitoring of each component (litterfall, throughfall and stemflow) is required.

In this study, we aimed to estimate the annual amount of ^{137}Cs descending from the canopy to the forest floor in a Fukushima Prefecture forest watershed. Observations were carried out in two types of forests (deciduous–pine mixed forest and cedar plantation), which are both commonly found in this area. The seasonal variations of ^{137}Cs fluxes were determined from the monthly amount of litterfall, throughfall and stemflow and the seasonal changes in ^{137}Cs concentration in each pathway. For litterfall, the flux for each component (leaf, branch, bark, seed and insect) was determined.

2. Materials and methods

2.1. Study site

The study was conducted in the Kami-Oguni River catchment in Ryozencho, Date City, 10 km east of Fukushima City in Fukushima Prefecture (Fig. 1). It is located about 50 km northwest of the FDNPP. According to a radioactivity survey report using an aircraft survey device, the air dose rate and total deposition of ^{137}Cs in December 2012 were 1.0–1.9 μSv h^{-1} and 100–300 kBq m^{-2}, respectively (Ministry of Education, Culture, Sports, Science and Technology Japan.(MEXT), 2011, 2012). The accumulations of ^{137}Cs in the soil of Mixed deciduous-1, Mixed deciduous-2 and Cedar plantation were 50,000, 15,100 and 21,200 Bq m^{-2} in A_0 layer and 4,900, 13,700 and 4600 Bq m^{-2} in A_1 and A_2 layers (sampled between 16 May and 27 July 2012, Murakami et al., 2014).

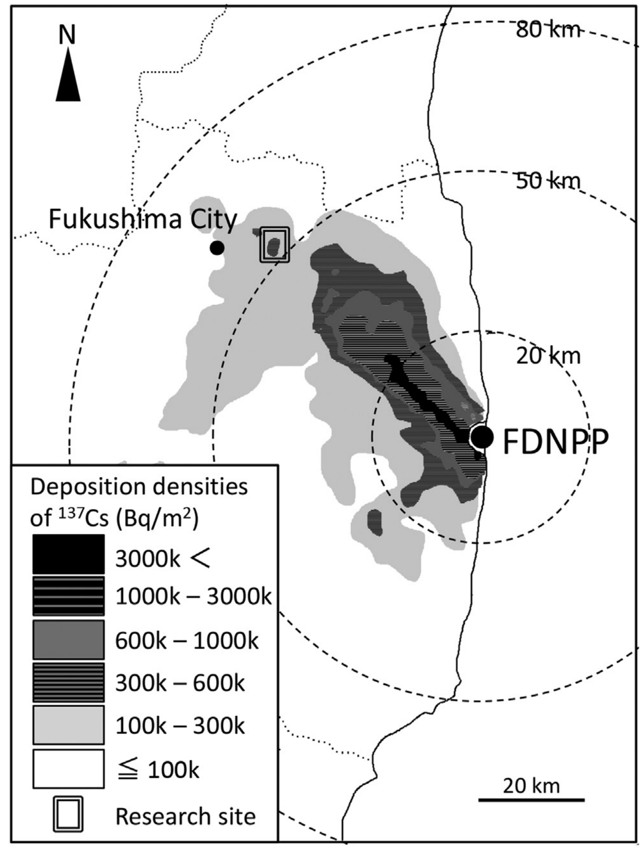

Fig. 1. Locations of the study site, Fukushima city and Fukushima Dai-ichi Nuclear Power Plant (FDNPP). Distribution of ^{137}Cs deposition densities map was modified from the report of 6th Airborne Monitoring and Survey Outside 80 km from the FDNPP in November 16, 2012 (MEXT, the Sixth Airborne Monitoring, 2013).

Mean annual temperature in this area was 13.4 °C in 2012–2013 (Japan Meteorological Agency, 2012–2013). The monthly mean temperature varied from 0.6 °C to 26.6 °C (Fig. 2). The annual rainfall was 912 mm in 2012–2013 in Kami-Oguni research site. The highest rainfall was recorded in July (304.3 mm) and the lowest in March (0 mm, Fig. 2). In winter (December–March), there is snowfall in the area. The mean annual snowfall was 189 cm for 1981–2010 (National Astronomical Observatory of Japan, 2013).

The study site consisted of two deciduous (Mixed deciduous-1, Mixed deciduous-2) and one cedar stand (Cedar plantation), which were common forest types in this area. We established a rectangle plot with a total size of 400 m^2 in each stand. The deciduous forest stand consisted of a mixture of broad leaf species, such as oaks (*Quercus* spp.) and maples (*Acer* spp.). The cedar plantation was about 50-year-old with 2100 ha^{-1} tree density. The average diameter at breast height (DBH) was 27 cm in 2013. Mixed deciduous forests were used as firewood forests for more than 50 years. In 2004, they were designated as a protection forest and thereafter it has not been used as firewood forest. Stand density of trees with >10 cm DBH was 1300 ha^{-1} and 800 ha^{-1} in the Mixed deciduous-1 and -2, respectively.