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Input and output budgets of radiocesium concerning the forest floor in the mountain forest of Fukushima released from the TEPCO's Fukushima Dai-ichi nuclear power plant accident

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ABSTRACT

Estimations of radiocesium input and output concerning the forest floor within a mountain forest region have been conducted in the north and central part of the Abukuma Mountains of Fukushima, northeast Japan, after a 2–3 year period following the TEPCO Fukushima Dai-ichi nuclear power plant accident. The radiocesium input and output associated with surface washoff, throughfall, stemflow, and litterfall processes at experimental plots installed on the forest floor of evergreen Japanese cedars and deciduous Konara oaks have been monitored. Despite the high output potential in the mountainous forest of Fukushima, the results at both monitoring locations show the radiocesium input to be 4–50 times higher than the output during the summer monsoon in Fukushima. These results indicate that the radiocesium tends to be preserved in the forest ecosystem due to extremely low output ratios (0.05%–0.19%). Thus, the associated fluxes throughout the circulation process are key issues for the projecting the environmental fate of the radiocesium levels, along with the subsequent reconstruction of life emphasized within the setting.

1. Introduction

TEPCO's Fukushima Dai-ichi nuclear power plant (FDNPP) accident is one of the most severe accidents that has ever been experienced in the history of nuclear energy. Most of the contaminated area via the radioactive material released from the FDNPP is a mountainous forest, which covers approximately 70% of the land area of Fukushima Prefecture (MAFF, 2014). Compared with the physical geography among Belarus, Ukraine, and Fukushima, the latter is characterized by a high precipitation and mountainous landform (National Astronomical Observatory of Japan, 2014). This implies a high potential for an outflow of land-forming surface materials such as soil and litter layers. An understanding of the environmental dynamics of radiocesium is, hence, one of the most crucial issues for a recovery of the living environment in and around the subject forested mountain region. ^{137}C is a primary contributor to radiation dose (following the decay of short-lived radionuclides) because of its long half-life of 30 years.

Immediately after the accident, with strong support by local and national governing bodies, an association of universities, and research institutes, a field investigation and monitoring study of the radionuclides released by the accident to characterize their initial distribution and dynamics was launched. Several months after the accident had transpired, investigation results on the contamination levels and environmental dynamics of radiocesium in nearby forested lands had been made open to the public through Internet and scientific publications (e.g., Forestry Agency, 2012). The distribution of radiocesium in the nearby forest ecosystem had evidently changed between 2011 and 2012; concentrations of radiocesium in branches and bark decreased between the two years due to washing-off, with concentrations in leaves notably decreasing from 2011 to 2013. Concentrations in bark, however, remained at the same level between 2012 and 2013. Investigation and monitoring results have altogether shown that the amount of radiocesium in the forest has been essentially constant from 3 years onward subsequent to the accident. This indicates that the radiocesium deposited in the forest has steadily remained within the forest ecosystem (Forestry and Forest Products Research Institute,

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2015). Detailed studies have also been performed, which focused on the initial transfer of radiocesium from a canopy to the forest floor via throughfall, stemflow, and litterfall processes (Hisadome et al., 2013; Kato et al., 2012; Teramage et al., 2014; Loffredo et al., 2014) and outflow from a forested mountainous region (Yoshimura et al., 2015; Nishikiori et al., 2015). In addition to the above field-based investigation studies, a modeling assessments of radiocesium fate in a forest ecosystem have been conducted (Hashimoto et al., 2013; Mahara et al., 2014). Hashimoto et al. (2013) simulated the spatiotemporal dynamics of radiocesium deposited in evergreen needle leaf and deciduous broadleaf forests in Japan using of the RIFE model (Shaw and Belli, 1999) developed after the Chernobyl accident in 1986, with its analytical results characterizing radiocesium migrations from trees and surface organic soils to mineral soils over a period of 1–2 years after the accident. Furthermore, Mahara et al. (2014) proposed a numerical model to predict changes in the concentration of ^{137}Cs in tree rings of Konara oak and Sugi (Japanese cedar). Modeling results showed the difference in temporal changes of the concentration profiles between the xylem of Konara and Sugi after the accident. Concentrations were ultimately found unaffected by root uptake if an active root system occurred 10 cm below the soil.

The aforementioned studies treated the migration and transfer processes of radiocesium in a forest ecosystem separately, thus the aggregate behavior of radiocesium in the ecosystem, as a whole, maintains an appreciable degree of ambiguity. As such, an “integrated” understanding of the total behavior of radiocesium (i.e., the input and output budgets of radiocesium and its temporal changes in the ecosystem) can only provide a sound scientific basis for effective remediation of the subject contaminated land area and promotion of an effective intervention strategy to regain the forest ecosystem as a viable setting wherein biota, production, and recreation once again thrive.

The radiocesium initially deposited in a forested area will reach and accumulate on a forest floor via throughfall, litterfall, and stemflow processes. Subsequently, the material will be transported from the forest floor through surface washoff as dissolved and particulate-bond state. Therefore, an assessment is provided herein with regard to input and output budgets of radiocesium within a forested area with the forest floor of particular emphasis to clarify whether the forest floor behaves as a sink (input greater than output) or a source (output greater than input) of the contamination.

2. Materials and methods

2.1. Study area

The subject investigation and monitoring have been conducted at two separate districts (Sakashita and Ogi) of cool-temperate mountainous forests within the Abukuma Mountains, the east of Fukushima Prefecture, Japan. Levels of radioactive contamination in both districts measured 1000–3000 kBq m^{-2} in total radiocesium deposition (^{134}Cs + ^{137}Cs, as of July 2, 2011) via airborne monitoring results (Ministry of Education, Culture, Sports, Science & Technology in Japan, 2015).

The Sakashita district, which is located near the ridge of the Abukuma Mountains, is 34.5 km northwest of the FDNPP (Fig. 1). The mean annual precipitation in this district over the past 30 years (1981–2010) is 1221.7 mm yr^{-1} at the Yamakiya meteorological station, located 2.7 km northwest of the district (Ministry of Land, Infrastructure, Transport and Tourism, 2015). The district is mainly covered by deciduous broad-leaved trees of Konara oak (*Quercus serrata*), Mizunara oak (*Quercus cripspula*), and Japanese chestnut (*Castanea crenata*), except on the southern edge of the forest where Japanese red pine (*Pinus densiflora*) trees are dominant. The average tree height and tree density of canopy layers are 11.2 m and 790 ha^{-1}, respectively. Most of the forest floor is covered with litter composed mainly of fallen branches and leaves of deciduous broad-leaved trees. The thickness of the litter layer is usually 1–3 cm, but is typically over 5 cm around the trunk of a tree. The undergrowth cover, such as mountain azalea (*Rhododendron kaempferi*) and bamboo grass (*Sasa nipponica*), ranged from 35% to 60%. Brown forest soil (andosol and cambisol in IUSS Working Group WRB, 2014) is most common in the Sakashita district with an organic horizon of 3.2 cm (range of 1.0–9.0 cm) and an A horizon of 9.5 cm (range 4.0–12.5 cm) in the average thickness. Andosols with a thick A horizon (range 12.5–40.0 cm thick) were consistently present at the foot of the mountain slope. The soil down to a 5 cm depth is sandy-loam to loam in conventional textural classes.

The Ogi district, which is located on the eastern mountainside slope of the Abukuma Mountains, is 14 km southwest of the FDNPP (Fig. 1). The mean annual precipitation over the past 30 years (1981–2010) is 1465.1 mm yr^{-1} at the Kawauchi meteorological station, 8.7 km west of the Ogi district (JMA, 2015). Evergreen coniferous trees (Japanese cedar; *Cryptomeria japonica*), which prominently exist within an evenly aged mature plantation display a tree density of 740 ha^{-1} and an average 21.3 m tree height for the canopy layer. Almost the entire forest floor is covered with litter such as fallen needle leaves, bark fragments, and cedar tree cones. The thickness of the litter layer is usually 3–4 cm with sparsely development of undergrowth, such as mulberry (*Morus australis*) and lindera (*Lindera praecox*), widely observed throughout the area except on the edge of the forest. The most common soil type in the Ogi district is Brown forest soil (andosol and cambisol in IUSS Working Group WRB, 2014) with an organic horizon of 4.4 cm (range 2–8 cm) and an A horizon of 19.0 cm (range 10–29 cm) in average thickness. The textural class of the soil down to a level of 5 cm is silt-loam to loam.

2.2. Monitoring and sampling

Two experimental plots for monitoring were installed in the mountain forest of the Sakashita district, on a crest slope (KE-plot) and a side slope (KW-plot) of a valley-head area that face west (Fig. 1). Both experimental plots are located on rectilinear and straight slopes, and have common features of a physical geography except for slope angle (Table 1). The 86%–99% of the forest floor in the two plots is covered with litter layer. In the mountain forest of the Ogi district, one plot of KA-plot was installed on a west-facing side slope of a valley-head area (Fig. 1, Table 1). The 91%–97% of the forest floor in the KA-plot surface is covered with a litter layer. The geomorphic feature of the KA-plot is similar to that of the KW-plot, but the forest type is markedly different.

Each experimental plot has a rectangular shape, whose long side orients to the dip direction of the slope, and is surrounded with stainless-steel boards to prevent the transportation of particulate matter and the flow of surface runoff water into the plot from the outside (Fig. 2). The particulate matter, which is composed of soil particles and fine litter fragments, accumulated in an 18 L stainless-steel catchment box installed at the bottom end of the plot. Surface runoff water that drained from the plot likewise flowed into the box with its associated overflow running into a 200 L catchment tank connected to the box via a pipe. After removal of a large litterfall from the catchment box, the relatively coarser particulate matter was collected by a trowel, with finer matter collected as turbid water mixed within the box. The turbid water was filtered through a 0.45 μm pore size Durapore® hydrophilic PVDF membrane filter (HVLP04700, Merck Millipore, Massachusetts, USA) in a laboratory. The particulate matter collected from the catchment box was