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Six-year monitoring of the vertical distribution of radiocesium in three forest soils after the Fukushima Dai-ichi Nuclear Power Plant accident

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ABSTRACT

After the Fukushima Dai-ichi Nuclear Power Plant accident on March 2011, several studies showed that the downward migration of ^{137}Cs from litter to mineral soil is more rapid in forests in Fukushima than in forests affected by the Chernobyl accident. Therefore, the downward migration within mineral soil layers is more important for predicting long-term dynamics of ^{137}Cs in forest ecosystems in Fukushima. In the present study, we monitored the detailed vertical distribution of ^{137}Cs in litter and soil layers for 6 y (2011–2017) following the previous study (2011–2012), and found that temporal changes in those distributions were different among mixed forest (MF), mature cedar (MC) and young cedar (YC) forests. The ^{137}Cs concentrations and inventories in the litter layer exponentially decreased with time for all sites, with more than 80–95% of the deposited ^{137}Cs on the forest floor distributed in mineral soil layers by 2017. The percentage of ^{137}Cs inventory in the litter layer to the total ^{137}Cs inventory in litter and mineral soil layers was well fitted by a single exponential equation with decreasing rate of 0.22–0.44 y^{-1}. The slower migration was observed in the YC site, probably because of higher initial interception of ^{137}Cs fallout by dense canopy. As the downward migration from litter to mineral soil progressed, the ^{137}Cs concentration in the first few cm of mineral soil surface gradually increased and became higher than the ^{137}Cs concentration in the litter within 2–3 y of the accident. The ^{137}Cs concentration in mineral soil layers exponentially decreased with depth throughout survey period, and an exponential equation fitted well. The relaxation depth of ^{137}Cs concentration in mineral soil layers estimated by the exponential equation were constantly increasing in the MC and YC sites with 0.08 cm y^{-1}. In contrast, there was no temporal increase in the relaxation depth in the MF site, indicating little migration to subsurface soil layer from not only litter layer but also surface soil layer. Further studies are necessary to identify the forests prone to the downward migration of ^{137}Cs and its factors regarding both forest and soil characteristics.

1. Introduction

A massive amount of radiocesium (primarily ^{134}Cs and ^{137}Cs) was released into the atmosphere after the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident on March 2011. About 20% of the atmospheric release was deposited terrestrially in Japan, of which 70% was in forested areas (e.g., Evrard et al., 2015). Hashimoto et al. (2012) estimated that about 428 km^2 of forest area was heavily contaminated with more than 1 MBq m^{-2} of radiocesium. Forestry is a major industry in Fukushima Prefecture and has suffered serious damage, as the output of forest products has decreased to two-thirds after the FDNPP accident (Ministry of Agriculture, 2017). As of the end of March 2017, 58 km^2 of the forest around residential areas was decontaminated (removal of litter layer and cutting of branches and leaves as needed) in order to reduce the radiation in daily living areas (Ministry of the Environment, 2017). In contrast, other extensive and remote forests have untreated because this kind of decontaminations are not only labor-intensive and expensive but also can damage the ecological functioning of the forest (IAEA, 2011). However, an appropriate forest management such as thinning is necessary to prevent radiocesium wash-off by soil erosion and use forest products in the future. Recently, Komatsu et al. (2017) reported that potassium fertilization could suppress the radiocesium root uptake by planted cypress seedlings in a highly contaminated forest due to the FDNPP accident. In order to achieve the practical use of this technique, it is essential to provide information on not only effective amounts and frequency of the potassium fertilization but also radiation protection for forest workers. Therefore, long-term prediction of the radiocesium dynamics and distribution in the forest ecosystem is

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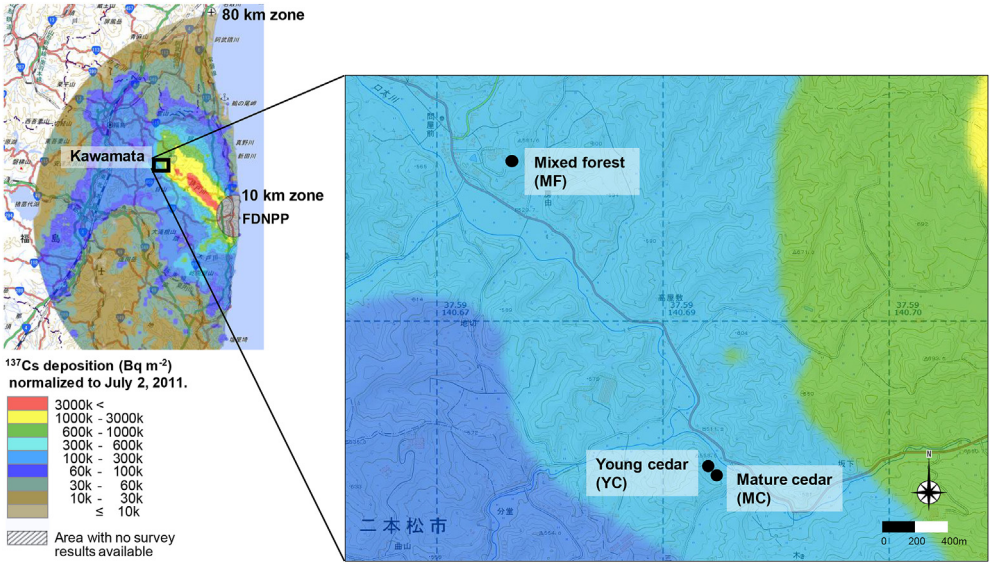

Fig. 1. Location of the study sites. The ^{137}Cs deposition density map normalized to July 2, 2011 is based on the third airborne monitoring survey of radioactivity by MEXT (2011).

required to estimate the ambient dose rate and to assess the effect on forest products.

Numerous studies after the Chernobyl accident revealed that forest ecosystems tend to accumulate and preserve radiocesium for a long time, and the behavior of radiocesium in forest ecosystems is very specific and differs from that in natural meadow and agricultural ecosystems owing to the internal cycling of nutrients in them (Shcheglov et al., 2001). In particular, forest litter and surface soil retain most of the deposited radiocesium and play important roles as a long-term sink and as a source of radiocesium for uptake by roots and microbes and its further transfer up food chains. Although the uptake by forest vegetation is limited, a major portion of the radiocesium taken up by vegetation is annually recycled towards the soil by litterfall and throughfall (Goor and Thiry, 2004). Therefore, the greatest proportion of the deposited ^{137}Cs inventory, or the maximum ^{137}Cs concentration, was frequently found in litter layers even a decade after the Chernobyl fallout (e.g., Shcheglov et al., 2001; Fesenko et al., 2001b).

However, our previous monitoring study of the 2 y following the FDNPP accident showed that the percentage of ^{137}Cs inventory in the litter layer to the total inventory (litter layer plus 0–10 cm soil layers) gradually decreased from 48 to 91% in summer 2011 to 18–41% in winter 2012, i.e., less than 50%, for three forest sites in Fukushima Prefecture (Takahashi et al., 2015). Hashimoto et al. (2013) also reported that the majority of radiocesium had already migrated to the mineral soil layer in 2012, pointing out that the downward migration from litter layers to soil layers is more rapid than that in the forests affected by the Chernobyl accident, most likely because the relatively warm climate and heavy rainfall in Japan lead to rapid litter decomposition and substantially thinner litter layers. Similar trends were observed in several studies (e.g., Fujii et al., 2014; Nakanishi et al., 2014; Takada et al., 2017). Such rapid migration from litter to mineral soil is one of the important radioecological differences between the Fukushima and Chernobyl accident. In other words, understanding and quantifying the downward migration within mineral soil layers is more important in the case of Fukushima for predicting long-term dynamics of ^{137}Cs in forest ecosystems and for developing strategies for radiation protection and forest management.

To understand the downward migration of ^{137}Cs in forest soils, various studies were conducted after the FDNPP accident. Koarashi et al. (2016b) monitored the downward fluxes of ^{137}Cs using field lysimeters in deciduous forests, but it had become difficult to measure ^{137}Cs flux because the ^{137}Cs concentration rapidly decreased with time. Imamura et al. (2017) reported that temporal changes in the ^{137}Cs distribution in each component in nine forest sites for 5 y, however it showed only rough distribution of ^{137}Cs in mineral soil layers. Most of the investigations regarding the detailed vertical distribution of ^{137}Cs in mineral soil layers were performed in one-off or short-term (e.g., Konoplev et al., 2016; Teramage et al., 2014, 2016), midterm monitoring has been little investigated in forest soils. Meanwhile, new models emerged to estimate the redistribution of ^{137}Cs in Japanese forest ecosystems (e.g., Calmon et al., 2015; Ota et al., 2016) and the detailed distribution of ^{137}Cs in soils (Mishra et al., 2015, 2016). In order to evaluate and improve these models, the quantifying of the downward migration of ^{137}Cs based on the practical monitoring is important.

In this paper, we present midterm (6 y) monitoring of the detailed vertical distribution of ^{137}Cs in soils under three forest sites on which we previously reported (Takahashi et al., 2015). The Japanese cedar and Konara oak that are dominant species in these sites are valuable forest products as lumber and raw timber for culturing mushrooms, respectively. In addition, the initial interception of ^{137}Cs by canopy and the secondary deposition of ^{137}Cs from canopy to forest floor were different among these sites (Kato et al., 2017). The differences in the initial and secondary deposition to forest floor would cause different temporal changes in the vertical distribution in soils. Therefore, temporal chenges in vertical distribution of ^{137}Cs concentration and inventory were quantified using simple regression analyses to compare the trends in the downward migration of ^{137}Cs for three forest sites. In addition, we discussed the differences between this study and the Chernobyl studies.

2. Materials and methods

2.1. Study sites

We established the monitoring sites in three forests in the town of Kawamata, Yamakiya District, located roughly 40 km northwest of the FDNPP (Fig. 1). These are the same sites that were used in a previous study (Takahashi et al., 2015), other five sites in a previous study were decontaminated by 2015. Several investigations, such as ^{137}Cs fluxes in throughfall, stemflow, and litterfall (Loffredo et al., 2014; Kato et al., 2018; in this issue), ^{137}Cs distribution in forest components (Coppin et al., 2016), dissolved ^{137}Cs in soil water (Iwagami et al., 2017), sideward migration of ^{137}Cs through soil erosion (Wakiyama et al.,