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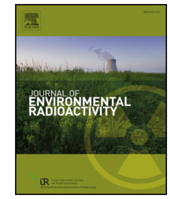

Temporal changes of the ambient dose rate in the forest environments of Fukushima Prefecture following the Fukushima reactor accident

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ABSTRACT

Approximately 70% of the total land area affected by the fallout from the Fukushima accident is forested, and therefore monitoring of the ambient dose rate in forest environments is essential to ensure that the population and natural habitats of these areas are protected from radiological hazards. However, there are little available data on the ambient dose rate for forest environments. This study investigated temporal changes in the ambient dose rate in different forest environments of Fukushima Prefecture. We conducted repeated measurements of the ambient dose rate in 2014 and 2016 at the same measurement points as those used by the Ministry of Agriculture, Fishery and Forestry of Japan (MAFF) in 2011. The measurements revealed that the decreasing trend in the ambient dose rate varied among the different forest types and time periods. The ambient dose rate in EGC decreased slower than that induced by the physical decay of radiocesium for the period of 2011–2014. However, such slow declining trend of ambient dose rate was likely followed by quick reduction during the following years (2014–2016 and 2011–2016). On the other hand, in MBL and DBF forests, the ambient dose rate decreased 10–20% faster than that induced solely by physical decay of radiocesium for the observation period 2011–2016.

1. Introduction

The Fukushima Dai-ichi Nuclear Power Plant accident resulted in the release of an enormous amount of radiocesium (~20 PBq for ^{137}Cs) into the atmosphere (Chino et al., 2011; Amano et al., 2012; Hirose, 2012; Aoyama et al., 2016). The subsequent atmospheric deposition of radiocesium contaminated large areas of the terrestrial environment in both Fukushima and the neighboring prefectures (Butler, 2011; MEXT, 2011; NRA, 2017a; b). The results of airborne monitoring surveys and model calculations simulating the atmospheric transport of contaminants estimated that approximately 22% of the total radiocesium released into the atmosphere was deposited onto the land area in Fukushima and its neighboring prefectures (Morino et al., 2011, 2013; MEXT, 2011). Fukushima Prefecture area accumulated 2.1 PBq of ^{137}Cs in total following the accident (Kato and Onda, 2018). Although the contaminated area included a wide range of environments and land uses (e.g., Kitamura et al., 2014), approximately 70% of the total contaminated land surface consisted of forest cover (Hashimoto et al., 2012). Therefore, monitoring radiocesium contamination and predicting the gamma radiation dose in forest environments following the accident are important tasks to assess external exposure to radiation for human and wildlife (e.g., Fesenko et al., 2005). However, the extent of the radiocesium contamination and temporal evolution of the ambient dose rate (ADR) in different types of forest have not been assessed sufficiently.

The ambient dose rate following the Fukushima Dai-ichi Nuclear Power Plant accident has been monitored across a large area of Fukushima and its neighboring prefectures by means of in-situ measurements (MEXT, 2011; Saito et al., 2015; Mikami et al., 2015a, 2015b) and airborne and car-borne surveys (e.g., NRA, 2015; Andoh et al., 2015; Sanada and Torii, 2015; Sanada et al., 2016). The results of those monitoring surveys have determined the spatial pattern of the ambient dose rate in the Fukushima landscape and its neighboring prefectures, with the measured ambient dose rate being closely related to the initial amount of ^{137}Cs deposition (Saito et al., 2015; Mikami et al., 2015a). The decreasing trend in the ambient dose rate has been assessed to determine the cumulative external radiation dose to local citizens and for long-term prediction of ambient dose rates in various land uses. The in-situ measurement of ambient dose rates at 1 m above the ground surface using a survey meter at flat and sparsely vegetated locations revealed that the relative percentage reduction in the air dose rate was 10% greater than that resulting solely from the radioactive decay of radiocesium between 2011 and 2012 (Mikami et al., 2015a). Such a rapid decrease in the ambient dose rate can be attributed to an

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increase in the relaxation depth of radiocesium in soil profiles rather than the loss of radiocesium due to natural weathering processes. On the other hand, the results of a car-borne survey indicated that the magnitude of the decreasing trend in the ambient dose rate was dependent on the land use in a particular area, with the ambient dose rate measured in forest areas decreasing more slowly than those in urban areas and over water (Kinase et al., 2014, 2017; Andoh et al., 2015). Most previous studies were based on the ambient dose rate measured from aircraft or along major roadways, with very little monitoring data available regarding the temporal changes in the ambient dose rate in forest environments.

The Ministry of Agriculture, Fishery and Forestry of Japan (MAFF) conducted regional measurements of the ambient dose rate from September to November of 2011, targeting forests within Fukushima Prefecture (MAFF, 2011a; b). A total of 391 locations, containing various forest types, were selected for the measurements. The extent of radioactive contamination and ambient dose rates in forest environments were thus determined during the early phases of the Fukushima accident. However, further detailed analyses and repeated measurements at the same location were not conducted, and consequently the temporal evolution of the ambient dose rate in forest environments has not been determined. Officials from Fukushima Prefecture have conducted repeated measurements of the ambient dose rate in the forests of Fukushima Prefecture (Fukushima Prefecture, 2016). The decreasing trend in the ambient dose rate determined in 362 locations was similar to the reduction expected due to the decay of radiocesium. The results obtained in Fukushima Prefecture have been presented as the average value of all forest types, i.e., evergreen, deciduous, and secondary mixed forests. The results of in-situ measurements of ambient dose rate suggest that temporal changes in the ambient dose rate in forests differ depending on the predominant tree species (NRA, 2015; Imamura et al., 2015). Further analysis is required to determine the influence of forest type on the long-term trend in the ambient dose rate in Japanese forest environments.

Radionuclides deposited in forested areas by either wet or dry processes encounter the forest canopy. Most radiocesium ($>$ 90%) deposited onto the canopy of evergreen conifers is intercepted and retained by tree needles and branches (Hoffman et al., 1995; Pröhl and Hoffman, 1996; Kinnersley et al., 1996, 1997). On the other hand, most of the atmospherically deposited radiocesium tends to deposit directly onto the forest floor, particularly during the leafless winter season in deciduous forests (e.g., Melin et al., 1994; Kato et al., 2017). The canopy-intercepted radiocesium is subsequently transferred to the forest floor as a result of weathering by rainwater and wind (Bunzl et al., 1989; Bonnet and Anderson, 1993; Pröhl, 2009). Some radiocesium is readily removed from plant surfaces by rainfall, but the remaining is strongly absorbed by leaf, branch, and bark surfaces (Rauret et al., 1994). The removal rate of radiocesium from plant tissue is affected by several factors, such as the elapsed time since the initial atmospheric deposition, tree species and age, and climatic conditions.

The ambient dose rate in forest environments is extremely variable in space and time. The vertical distribution of the measured ambient dose rate has been found to vary among different forest types (e.g., Yoshihara et al., 2013; Kato and Onda, 2014), representing differences in radiocesium accumulation in canopies. Furthermore, the decrease in the ambient dose rate at 1 m above the ground surface occurred more slowly than the decrease measured at canopy height in cedar stands (Kato and Onda, 2014). The ambient dose rate in a forest growing on a slope was found to be highly heterogeneous and influenced by topography (Atarashi-Andoh et al., 2015). These studies have suggested that the spatial distribution of atmospherically deposited radiocesium varies significantly among different forest stands; nevertheless, those differences in the initial distribution and subsequent transfer of radiocesium have not been linked to the temporal evolution of the ambient dose rate in forest environments.

A numerical assessment of air dose rates induced by radiocesium in the Fukushima terrestrial region was performed by Gonze et al. (2016) using dynamic, spatially distributed, and process-based models. Their results demonstrated that air dose rates, either within or above forests, were very sensitive to both the detector height and vertical location of radiocesium in the system. Therefore, airborne surveys might not reflect dose rates at ground level in forest systems. Thus, statistical analyses based on ambient dose rates measured in situ in various forests are necessary to determine the actual temporal evolution of the ambient dose rate in Japanese forest environments following the Fukushima accident.

The purpose of this study was to determine the temporal evolution of the ambient dose rate in various forest types. Repeated measurements of the ambient dose rate were conducted in 2014 and 2016 at the same measurement sites as those used by MAFF in 2011. The influence of forest type on the temporal evolution of the ambient dose rate was determined based on a statistical analysis of the regional measurements.

2. Materials and methods

2.1. Measurement of the ambient dose rate in forests

2.1.1. Data measured by MAFF in 2011 (MAFF, 2011a, 2011b)

MAFF measured the ambient dose rate in forests at 391 locations within Fukushima Prefecture (Fig. S-1 in the Supplementary Information document). It should be noted that white spot on the map is Lake Inawashiro. Each measurement site was designated to become part of the national survey of the biodiversity of forest ecosystems in Japan, with all sites distributed inside a 4-km grid within an 80-km radius of the power plant and inside a 10-km interval grid outside of the 80-km radius. The exact location of each measurement site was recorded using GPS, given a geographical coordinate, and marked with yellow or green poles (Fig. S-2 in the Supplementary Information document). The ambient dose rate at 1 m above the ground surface was measured using a NaI(TI) scintillation survey meter (TCS-172B, Hitachi, Ltd., Tokyo, Japan) at each measurement site. The measurements were conducted during between September 16 and November 9, 2011. The measured ambient dose rate was decay-corrected to the date of October 1, 2011.

2.1.2. Data measured by the Nuclear Regulation Authority (NRA) in 2014 (NRA, 2015)

Additional measurements of the ambient dose rate were conducted by authors as a part of the commission research project supported by NRA, at the same measurement sites in 2011. However, the measurements were reduced to 285 locations due to limited site accessibility caused by forest road collapse during typhoon event, deforestation and decontamination of the measurement site. The ambient dose rate at 1 m above the ground surface was measured using the same measurement protocol employed in 2011 by MAFF. It should be noted that the survey meters were checked and calibrated before field monitoring survey by a dosimeter company (Chiyoda Technol Corporation, Tokyo, Japan). The measurements were conducted between September and November 2014. The measured ambient dose rate was decay-corrected to the date of October 1, 2014.

2.1.3. Data measured in this study in 2016

Measurements of the ambient dose rate were conducted at 100 sites of the exact locations used by MAFF in 2011 and NRA in 2014. The number of measurement site was reduced to nearly one third of the measurements in 2014 due to the limitation of human resources and research fund. Criteria for the selection of repeated measurement site of ambient dose rate was as follows; 1) the ambient dose rate was measured in both 2011 and 2014, 2) the measurement location was easy to access, 3) the measurement site was covered by major forest type in Fukushima Prefecture (e.g., cedar (Cryptomeria japonica), konara oak (Quercus serrata), and secondary deciduous broad-leaved mixed forest