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Radiocesium concentrations in epigeic earthworms at various distances from the Fukushima Nuclear Power Plant 6 months after the 2011 accident

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ABSTRACT

We investigated the concentrations of radiocesium in epigeic earthworms, litter, and soil samples collected from forests in Fukushima Prefecture 6 months after the Fukushima Dai-ichi Nuclear Power Plant accident in 2011. Radiocesium concentrations in litter accumulated on the forest floor were higher than those in the soil (0–5 cm depth). The highest average $^{134+137}$Cs concentrations in earthworms (approximately 19 Bq g^{-1} of wet weight with gut contents and 108 Bq g^{-1} of dry weight without gut contents) were recorded from a plot that experienced an air dose rate of 3.1 μSv h^{-1}, and earthworm concentrations were found to increase with litter and/or soil concentrations. Average ^{134}Cs and ^{137}Cs concentrations (with or without gut contents) were intermediate between accumulated litter and soil. Different species in the same ecological groups on the same plots had similar concentrations because of their use of the same habitats or their similar physiological characteristics. The contribution of global fallout ^{137}Cs to earthworms with gut contents was calculated to be very low, and most ^{137}Cs in earthworms was derived from the Fukushima accident. Transfer factors from accumulated litter to earthworms, based on their dry weights, ranged from 0.21 to 0.35, in agreement with previous field studies.

1. Introduction

In March 2011, an accident at the Fukushima Dai-ichi Nuclear Power Plant (NPP) exposed large areas of northeastern Japan to radioactivity (Yasunari et al., 2011). Forests and woody plants were the major recipients of the terrestrial fallout. Hashimoto et al. (2012) combined forest statistics from databases of the vegetation and soil type distributions with 1 km areal resolution and a radiation map from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan, obtained by an airborne survey in November 2011 (MEXT, 2012a,b). They estimated the overall volume and weight of the exposed forest ($\geq^{134+137}$Cs 1000 kBq m^2) to be 33 × 10^6 m^3 (not including branches, leaves, litter, and coarse woody litter) and 21 × 10^{12} g dry matter, respectively (Hashimoto et al., 2012). Assessing the effects of radionuclides on indigenous natural flora and fauna is important not only because of their possible human consumption, but also because of the potential impact of contamination on forest ecosystems (Copplestone et al., 1999). The contamination of forest ecosystems by radionuclides (Kato et al., 2012; Yoshihara et al., 2013), estimation of dose rates (Garnier-Laplace et al., 2011), and risks to wildlife (Hiyama et al., 2012; Møller et al., 2012) in the Fukushima area have been reported. Radionuclide concentrations in boar, black bear, and some birds have been periodically monitored (Fukushima Prefecture, 2012), but little information is available on soil invertebrates. Most of the radionuclides deposited have likely existed in the litter and soil surface layers (Brückmann and Wolters, 1994; Rafferty et al., 1997). At other locations, detritivore invertebrates or soil invertebrates in the litter layer have been reported to have higher concentrations of various radionuclides (e.g., ^{137}Cs, $^{239+240}$Pu, ^{241}Am, and ^{90}Sr) than other animal groups (Copplestone et al., 1999; Maksimova, 2002; Mietelski et al., 2010).

As representative soil macrofauna, earthworms are considered ecosystem engineers (Lavelle, 1997) and are important food items for some vertebrates (Kålås et al., 1994). Earthworms have been extensively used to monitor contaminated soils (Cortet et al., 1999) and to assess the potential impacts of contaminants in controlled

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laboratory studies (Sheppard et al., 1997). The effects of exposure to radionuclides or gamma-rays on earthworms have been reported in field studies following the Chernobyl (Russia) accident (Krivolutzkii and Pokarzhevskii, 1992; Jackson et al., 2005) and under experimental conditions (Hertel-Aas et al., 2007; Nakamori et al., 2009). The mechanisms of radionuclide transfer from litter or soil to earthworms have been investigated in laboratory experiments (Brown and Bell, 1995; Janssen et al., 1996a, b; Badot, 2008; Fritsch et al., 2008). The concentrations of radiocesium in earthworms have also been investigated in the field (Rudge et al., 1993; Copplestone et al., 1999). However, further field study is required to estimate radiocesium levels in earthworms from environmental radioactivity data, such as radiocesium concentrations in the litter and soil.

In the present study, we investigated the radiocesium concentrations in earthworms in forests of Fukushima Prefecture 6 months after the Fukushima NPP accident. The concentrations were compared among four plots at three sites, and we assessed the relationship between the contamination of accumulated litter or soil and earthworm radiocesium concentrations. Japan has a high diversity of terrestrial earthworms, especially those in the family Megascolecidae (Ishizuka, 1999). Minamiya et al. (2007) recorded 11 species of Megascolecidae at a university campus in Miyagi Prefecture. Different species of earthworm may have different radiocesium concentrations even in the same environment because of their ecological and physiological characteristics (Janssen et al., 1996a,b). Therefore, we identified earthworms at the species level before measuring radiocesium concentrations. The difference in radiocesium concentrations between species was also investigated.

2. Materials and methods

2.1. Study sites

We established four plots in three forest sites in Fukushima Prefecture that were different distances from the Fukushima Daiichi NPP. We selected these plots by considering the different contamination levels of radiocesium expected from previous monitoring data. Three plots were Japanese cedar plantations (*Cryptomeria japonica*), and one plot was a mixed forest of oak (*Quercus serrata*) and pine (*Pinus densiflora*). Tree biomass of these sites ranged between 20 and 30 kg m^{-2}. Earthworms are typically scarce in the types of humus that develop beneath coniferous trees, but Japanese cedar plantations are known to have a rich abundance of earthworms (Watanabe, 1973). The area of each plot ranged from 1600 m^2 to 2400 m^2. Four plots at different distances from the Fukushima NPP were selected in Fukushima Prefecture (Fig. 1). One plot (KC) was established at Kawauchi Village (37°17′18″N, 140°47′47″E), the nearest from the NPP; it consisted of a 42-year-old Japanese cedar plantation. At Otama, 66 km away from the NPP, two plots were established; these consisted of a 42-year-old Japanese cedar plantation (OC) (37°34′4″N, 140°18′20″E) and 41-year-old mixed forest (OM) (37°34′14″N, 140°18′30″E) of oak and pine. A final plot (TC) was established at Tadami Town (37°19′28″N, 139°31′15″E), the farthest from the NPP; it consisted of a 40-year-old Japanese cedar plantation. The average gamma-ray dose rates on the date of sampling were 3.11 (KC), 0.33 (OM), 0.31 (OC) and 0.12 (TC) μSv h^{-1} (Table 1). Cesium-134 and ^{137}Cs concentrations in accumulated litter and soil samples from each plot, based on dry weight, decreased with gamma-ray dose rates (Table 1). The $^{134}Cs/^{137}Cs$ ratio ranged from 0.835 to 0.879 in the accumulated litter and was lower in the soil at each plot. It decreased with decreasing air dose rates and reached 0.577 at TC.

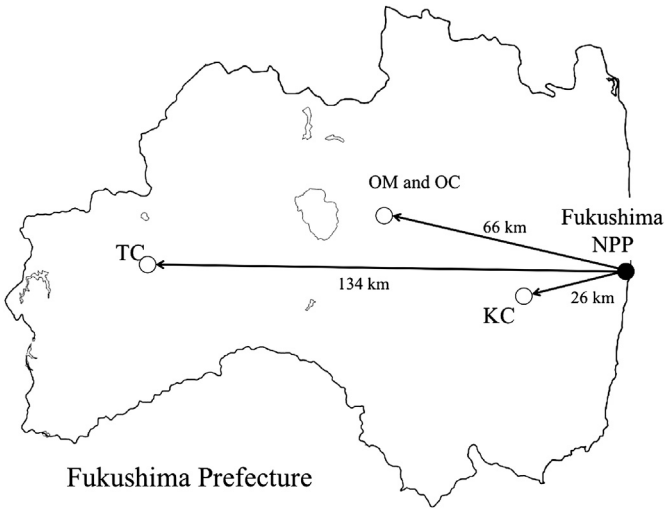

Fig. 1. Map of the study site in Fukushima Prefecture, Japan.

2.2. Air dose rate measurements

Gamma-ray dose rates were measured using a NaI scintillation survey meter (TCS-172B: Hitachi Aloka Medical, Ltd., Tokyo, Japan) in August 2011. The meter was left operational until the values were stable at 1 m above the ground at each sampling point. The measurement points were on the cross points of a 10 m × 10-m grid for each plot. At least 36 measurement points were set.

2.3. Accumulated litter and soil samples

We selected three (large, medium, and small) trees at each plot. Samples of accumulated litter and soil were collected at four points around each tree at KC on 8–12 August 2011, at OC on 30–31 August 2011, and at TC on 6–7 September 2011. At OM, we selected three oak (*Q. serrata*) and three pine (*P. densiflora*) trees, and collected samples for accumulated litter and soil at four points around each tree. Accumulated litter samples on the forest floor were collected from each 25 cm × 25-cm area. Soil samples from the surface to 20 cm depth were collected at 5-cm-depth intervals using a 475-mL cylinder (95 cm^2 cross-sectional area and 5 cm depth). The accumulated litter and soil samples were air-dried and then oven-dried for 24 h at 70 °C and 105 °C respectively. The oven-dried samples were analyzed by gamma-ray spectroscopy.

2.4. Earthworm sampling

Earthworms are divided into three ecological groups (Bouché, 1977; Lee, 1985): epigeic (inhabiting the litter layer), anecic (inhabiting soil and feeding on litter), and endogeic (inhabiting and feeding on soil). In this study, we focused on epigeic earthworms because most of the radionuclides were expected to be in the litter layer and soil surface layer. We collected the earthworms in the litter layer by hand-sorting over a 2–4 h per person sample period. Sampling events at KC, OM, and OC were carried out on 31 August 2011, and sampling at TC was conducted on 21 September 2011. Sampling was conducted in the outskirts of each study plot to prevent disturbance of the litter and soil layers caused by earthworm collection. The distance from the edge of the plot to the sampling point was less than 30 m. Each collected worm was individually weighed, identified, and freeze-dried, and its radionuclide concentration was then measured. We separated the samples collected at KC, OC, and TC into groups with and without gut contents and processed both groups as noted