Journal of Environmental Radioactivity 145 (2015) 95–101

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

Changes in radiocesium concentrations in epigeic earthworms in relation to the organic layer 2.5 years after the 2011 Fukushima Dai-ichi Nuclear Power Plant accident

Motohiro Hasegawa [a, *], Shinji Kaneko [a], Shigeto Ikeda [a], Akio Akama [a], Masabumi Komatsu [a], Masamichi T. Ito [b]

[a] Forestry and Forest Products Research Institute, Tsukuba, Ibaraki 305-8687, Japan
[b] Surugadai University, Hanno, Saitama 357-8555, Japan

ARTICLE INFO

Article history:
Received 9 September 2014
Received in revised form
2 March 2015
Accepted 12 March 2015
Available online 15 April 2015

Keywords:
Earthworm
Radiocesium
Transfer factor
Accumulated litter
Soil

ABSTRACT

We reported previously that radiocesium (^{137}Cs) concentrations in earthworms increased with those in litter and/or soil in Fukushima Prefecture forests 0.5 y after the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident. This study provides further results for 1.5 and 2.5 y after the accident and discusses temporal changes in ^{137}Cs concentrations and transfer factors (TF) from litter to earthworms to better understand the mechanisms by which ^{137}Cs enters soil food webs. The concentration of ^{137}Cs in accumulated litter on the forest floor rapidly decreased, and the concentration in soil (0–5-cm depth) increased over time from 0.5 to 1.5 y, but changed only moderately from 1.5 to 2.5 y. The concentration of ^{137}Cs in earthworms consistently decreased during the study period; values 2.5 y after the accident were 18.8–68.5% of those 0.5 y after the accident. The TFs from accumulated litter to earthworms decreased over time: 0.24 ± 0.08 (mean ± SD) at 0.5 y and 0.16 ± 0.04 at 2.5 y. This decrease may be a result of decreases in the bioavailability of ^{137}Cs in litter and the surface soil layer. Changes in ^{137}Cs bioavailability should be continuously tracked to determine any changes in the relationship between radiocesium concentrations in earthworms and that in accumulated litter or soil.

1. Introduction

An accident at the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) exposed large areas of northeastern Japan to radioactivity (Yasunari et al., 2011; Hashimoto et al., 2012). Assessing the effects of radionuclides on natural flora and fauna is important not only because of their possible consumption by humans, but also because of the potential impact of contamination on forest ecosystems (Copplestone et al., 1999). 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; Koganezawa et al., 2013; Ayabe et al., 2014) have been reported after the accident at FDNPP. Approximately 70% of Fukushima Prefecture is covered by forest, and the biological cycle of radiocesium (^{137}Cs) is much larger in forests than in agricultural ecosystems (Nimis, 1996). Thus, long-term monitoring of ^{137}Cs throughout forest ecosystems must be performed after the Fukushima accident to estimate radionuclide pollution in the surrounding ecosystems. The majority of deposited ^{137}Cs has generally been maintained in litter and upper soil layers (Brückmann and Wolters, 1994; Melin et al., 1994; Rafferty et al., 1997; IAEA , 2006). Cesium-137 in the organic layer is thought to be exchangeable and highly available for various organisms because organic compounds do not strongly fix trace cesium compared with mineral or clay particles (Reichle and Crossley, 1969; Kruyts and Delvaux, 2002; Kruyts et al., 2004). The contamination status of biota in the forest ecosystem should be investigated in relation to changes in contamination of the forest floor layer to better understand the mechanisms by which ^{137}Cs enters food webs.

Highly contaminated litter in the organic layer is consumed by detritivores (e.g., earthworms, millipedes, and fly larvae), and thus these animals are heavily contaminated with ^{137}Cs (Mietelski et al.,

* Corresponding author. Tel.: +81 298 29 8251; fax: +81 298 73 1543.
E-mail addresses: motohiro@ffpri.affrc.go.jp (M. Hasegawa), kanekos@affrc.go.jp (S. Kaneko), ikedas@ffpri.affrc.go.jp (S. Ikeda), akama@ffpri.affrc.go.jp (A. Akama), kopine@ffpri.affrc.go.jp (M. Komatsu), itooc@surugadai.ac.jp (M.T. Ito).

http://dx.doi.org/10.1016/j.jenvrad.2015.03.015
0265-931X/

2010). The ^{137}Cs concentration in detritivorous invertebrates (including earthworms) is consistently higher than in all other invertebrate groups (Copplestone et al., 1999). Earthworms are considered one of the most appropriate biomonitors of radioactive pollution (Zaitsev et al., 2014). In addition, earthworms are considered ecosystem engineers (Lavelle, 1997) and are important food items for some vertebrates (Kålås et al., 1994; Yokohata, 2005; Minamiya et al., 2007). An increased ^{137}Cs concentration in detritivorous animals and earthworms was observed in the Fukushima area (Fukuda et al., 2013; Murakami et al., 2014; Ohte et al., 2013). We previously reported that ^{137}Cs accumulated in litter on the forest floor, and that earthworm ^{137}Cs concentrations increased with litter and/or soil concentrations (Hasegawa et al., 2013). The form and adsorption status of ^{137}Cs in the litter and soil layer tended to change with time after deposition (Kobayashi, 2014; Nakanishi et al., 2014). Therefore, long-term monitoring is required to estimate ^{137}Cs levels in earthworms together with environmental radioactivity data, such as ^{137}Cs concentrations in litter and soil.

In the present study, we investigated ^{137}Cs concentrations in earthworms as they relate to concentrations in the litter layer and soil (0–5 cm) of Fukushima Prefecture forests at 1.5 and 2.5 y after the FDNPP accident. By comparing our measurements with data collected at 0.5 y after the accident by Hasegawa et al. (2013), we additionally explored long-term changes. We compared ^{137}Cs concentrations among sampling years, and investigated relationship between concentrations in accumulated litter or soil and in earthworms. The ^{137}Cs concentration in earthworms is commonly shown as a value with or without gut contents (or both) (Rudge et al., 1993; Copplestone et al., 1999; Hasegawa et al., 2013). Gut contents are directly related to the ^{137}Cs levels in their food (accumulated litter). If the gut contents are highly contaminated, their inclusion in the measurement of ^{137}Cs must be clarified when discussing ^{137}Cs assimilation in earthworms (Rudge et al., 1993). In this study, we estimated the ^{137}Cs concentration of earthworms after removing gut contents and then discussed ^{137}Cs bioavailability in epigeic earthworms.

2. Materials and methods

2.1. Study sites

We established three study sites in forests in Kawauchi Village, Otama Village, and Tadami Town, Fukushima Prefecture, which were located at varying distances from the FDNPP (Fig. 1). Within these sites, we selected five rectangular plots of 1600–2400 m^2 according to the levels of ^{137}Cs contamination determined by previous monitoring studies (MAFF, 2011). Three plots were in Japanese cedar plantations (*Cryptomeria japonica*), and two plots were in mixed forests of oak (*Quercus serrata*) and pine (*Pinus densiflora*). Tree biomass of these plots ranged from 20 to 30 kg m^{-2}. Earthworms are generally scarce in the humus that develops beneath coniferous trees, but Japanese cedar plantations are known to have a high abundance of earthworms (Watanabe, 1973). At Kawauchi Village, the closest area to the FDNPP, two plots were established, in a 42-year-old Japanese cedar plantation (KC; 37°17′18″ N, 140°47′47″ E) and a 27-year-old mixed forest (KM; 37°17′22″ N, 140°47′30″ E) of oak mixed with deciduous trees. At Otama Village, 66 km from the FDNPP, two plots were established, in a 42-year-old Japanese cedar plantation (OC; 37°34′4″ N, 140°18′20″ E) and a 41-year-old mixed forest (OM; 37°34′14″ N, 140°18′30″ E) of oak mixed with pine. The final plot (TC) was established in a 40-year-old Japanese cedar plantation at Tadami Town (37°19′28″ N, 139°31′15″ E), the farthest site from the FDNPP. The deposition density of ^{137}Cs in 2013 was 734, 68, 67, and 14 kBq m^{-2} at KC, OC, OM, and TC, respectively. The

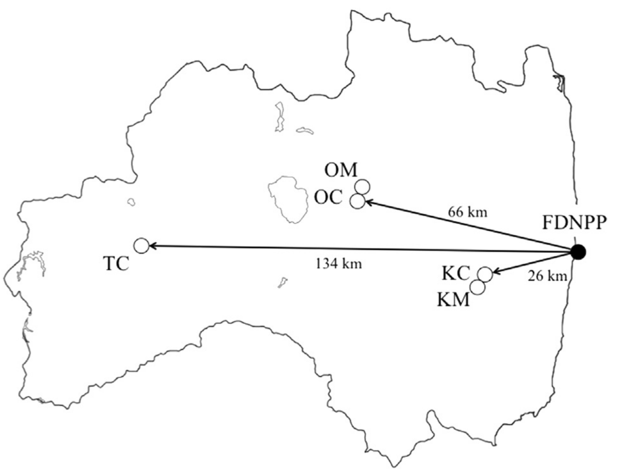

Fig. 1. Location of the study plots in Fukushima Prefecture, Japan and their distance from the Fukushima Dai-ichi Nuclear Power Plant (FDNPP).

method of tree and soil sampling used for the calculation of deposition density is described in Kuroda et al. (2013) and Fujii et al. (2014). At KM, the deposition density of $^{134+137}$Cs was estimated at 600–1000 kBq m^{-2} during a survey in November 2012 by MEXT (2013). Four of the five plots were used in a previous study (Hasegawa et al., 2013). The age of the forests in 2011 is provided here.

2.2. Accumulated litter and soil samples

Samples of accumulated litter and soil were collected during August or September 2011, 2012, and 2013 at 12 sampling points in KC, OC, OM, and TC, and at six points in KM. The method used to select the sampling points differed slightly among the three years. Samples were collected at four points around three trees in 2011 (Hasegawa et al., 2013), whereas sampling occurred at randomly selected points in a quadrat at every plot in 2012 and 2013. Accumulated litter samples on the forest floor were collected from a 25 × 25-cm quadrat. Soil layers were sampled at 5-cm intervals from the surface to depths of 20 cm using a 475-mL cylinder (95-cm^2 cross-sectional area × 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 using gamma-ray spectroscopy.

2.3. Earthworm sampling

Earthworms can be divided into three ecological groups (Bouché, 1977; Lee, 1985): epigeic (inhabiting the litter layer), anecic (inhabiting soil and feeding on litter), and endogeic (inhabiting soil and feeding on soil). In this study, we focused on epigeic earthworms, because the majority of radionuclides were expected to be in the litter and soil surface layer. We collected earthworms in the litter layer by hand sorting over a 2–4-h per person sampling period. Sampling was performed from August to September 2011–2013. However, at KM, sampling was performed in August 2012 and 2013. Sampling was conducted in the outskirts of each study plot to prevent disturbance of litter and soil layers caused by the earthworm collection. The distance from the edge of the plot to the sampling point was <30 m. Within the outskirts of plots, forest floor conditions appeared not to be different from those inside the plot. Each worm was individually weighed, identified, dissected to remove gut contents, and freeze-dried. After freeze-dried earthworm samples were homogenized with sodium