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Changes in radiocesium contamination from Fukushima in foliar parts of 10 common tree species in Japan between 2011 and 2013

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ABSTRACT

Yearly changes in radiocesium (^{137}Cs) contamination, primarily due to the Fukushima accident of March 2011, were observed in the foliar parts of 10 common woody species in Japan (*Chamaecyparis obtusa*, *Cedrus deodara*, *Pinus densiflora*, *Cryptomeria japonica*, *Phyllostachys pubescens*, *Cinnamomum camphora*, *Metasequoia glyptostroboides*, *Prunus* × *yedoensis*, *Acer buergerianum*, and *Aesculus hippocastanum*). The samples were obtained from Abiko (approximately 200 km SSW of the Fukushima Dai-ichi Nuclear Power Plant) during each growing season between 2011 and 2013, and the foliar parts were examined based on their year of expansion and location in each trees. The radiocesium concentrations generally decreased with time; however, the concentrations and rates of decrease varied among species, age of foliar parts, and locations. The radiocesium concentrations in the 2012 current-year foliar parts were 29%–220% of those from 2011, while those from 2013 fell to between 14% and 42% of the 2011 values. The net decontamination in the foliage was higher in evergreen species than in deciduous species. The radiocesium concentrations in the upper foliar parts were higher than those in the lower parts particularly in *C. japonica*. In addition, the radiocesium concentrations were higher in the current-year foliar parts than in the 1-year-old foliar parts, particularly in 2013. Thus, the influence of the direct deposition of the fallout was reduced with time, and the translocation ability of radiocesium from old to new tissues became more influential. Similar to the behavior of potassium in trees, Cs redistribution probably occurred primarily due to internal nutrient translocation mechanisms.

1. Introduction

After the major earthquake and tsunami that occurred on March 11, 2011, the Fukushima Dai-ichi Nuclear Power Plant (FDNPP; located at 37.41868° N, 141.02215° E) experienced a severe accident, causing widespread contamination by radionuclides, primarily ^{131}I, ^{134}Cs, and ^{137}Cs (Yamamoto et al., 2012; Endo et al., 2012; Amano et al., 2012). Areas relatively far from the FDNPP were contaminated, including our institute in Abiko (located at 35.87815° N, 140.02487° E; approximately 200 km SSW from the FDNPP). The initial radionuclide fallout in Abiko was observed on March 16, 2011, as dry-deposition, and majority of the fallout was observed on March 21, 2011, with rainfall; in total, 60–100 kBq m^{-2} of radiocesium (^{134}Cs, and ^{137}Cs) were observed at Abiko after the latter deposition (Morino et al., 2011; Terada et al., 2012; Doi et al., 2013).

Forests are effective aerosol interceptors (Bunzl and Kracke, 1988; Petroff et al., 2008; Pröhl, 2009). Radiocesium in aerosol form would therefore also be effectively trapped by forests. Indeed, after the Chernobyl accident, a nearby spruce forest trapped 20% more radiocesium than a similarly located grassland (Bunzl and Kracke, 1988). Many parts of Fukushima are covered with forest vegetation (forests cover 71% of Fukushima; 984,000 ha of 1,378,000 ha), and 44% (430,000 ha) of this area is contaminated with radiocesium at more than the level recommended by the ICRP for constraining the optimization process in long-term post-accident situations (i.e., 1.0 mSv y^{-1} without normal background radiation. Areas showing this level of air dose rate are mostly overlapped to the areas contaminated with 10–30 kBq m^{-2} of ^{137}Cs deposition density; ICRP, 1991; Forestry Agency, 2013, 2012; MOE, 2012a; Hashimoto et al., 2012). Similarly contaminated forest areas outside Fukushima comprise 360,000 ha in total (Forestry Agency, 2012; MOE, 2012a). Although drastic reductions in the radiocesium inventory of the canopy (e.g., one-third of the initial fallout per year) and as well

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as the translocation of radiocesium to the forest floor soils have recently been reported, the canopy is still heavily contaminated (Forestry Agency, 2013, 2012; Kato et al., 2012; Akama et al., 2013; Yoshihara et al., 2014b). However, forest areas are excluded from the governmental decontamination plan (MOE, 2012b). This omission has raised concerns about the potential contamination of forest products, such as mushrooms, timber, and compost. Possible discharges of radionuclides into drainage basins and/or drifts from decomposed particles of plant debris in flowing water are also a large concern. Although an ordinary rainfall event discharges radiocesium from forests to river systems at a negligible level (e.g., 0.009–0.098 Bq L^{-1}), a heavy rainfall event, such as a typhoon, increases the discharge rate by one or two orders of magnitude (Forestry Agency, 2012; Nagao et al., 2013).

Early reductions in the radionuclide dynamics of forests (i.e., acute phase reductions) are expected to bottom out within 5 y, followed by a comparatively stable phase, in which the reductions occur mainly from the physical decay of long-lived radionuclides (e.g., ^{137}Cs), as based on observations after the Chernobyl accident (Goor and Thiry, 2004; Hashimoto et al., 2013). This pattern may alleviate the previously discussed concerns; however, such tentative predictions are uncertain regarding the role of trees, particularly in relation to regional characteristics such as vegetation, geology, topography, and meteorology (Likuku, 2003). Thus, the fate of long-lived radionuclides in forests cannot be understood without recognizing the specific roles of trees in radionuclide cycling: uptake, translocation, and leaching by throughfall and litterfall (Myttenaere et al., 1993). The proportion of the uptake retained in the annual woody increment is also important. These tree roles are closely related to yearly/seasonal variations in specific nutritional elements inside and outside of the trees (Myttenaere et al., 1993). However, most previous studies have targeted only one or several plant species per observation site and measured bulk samples, ignoring physiological differences such as leaf longevity, age, and maturity. Here, as a preliminary to long-term observations and an assessment of acute phase reductions from the Fukushima accident, we provide data showing clear and specific changes in the radiocesium concentrations between 2011 and 2013 in the foliar parts of 10 common woody species, with precise classifications of each part's year of expansion and growing position. Furthermore, particularly in Japanese cedar, we analyzed the distributions of three stable nutritional elements, including potassium (the metabolism of which is most closely related to cesium metabolism in trees), for comparison with radiocesium distribution (Ronnneau et al., 1991; Myttenaere et al., 1993; Kaunisto et al., 2002).

2. Materials and methods

2.1. Study site and sample trees

The study site was located at the Laboratory of Environmental Science in Abiko (total area 17.3 ha), approximately 200 km SSW of the FDNPP. Abiko has a moderate monsoon climate, with an average annual precipitation and daily average air temperature of 1375.2 mm and 14.4 °C, respectively, between 2011 and 2013 (Japan Meteorological Agency, http://www.jma.go.jp/jma/menu/report.html). Further details of the location can be found in previous reports (Yoshihara et al., 2013, 2014a,b). In brief, the gamma radiation dose rate at the site was approximately 0.2–0.5 μSv h^{-1} during the observation period. In August 2011, surface soils at depth of 0–5 cm around the sample trees contained 0.82–3.4 kBq kg-DW^{-1} of $^{134+137}$Cs. The basal soil type was a pale Andosol overlaid with a thin organic layer (National Land Agency, 1983). The sample trees stood alone or as parts of colonnades/small forests and grew on bare ground (Table 1).

The samples consisted of the foliar parts of 10 woody species (*Chamaecyparis obtusa*, *Co*; *Cedrus deodara*, *Cd*; *Pinus densiflora*, *Pd*; *Cryptomeria japonica*, *Cj*; *Phyllostachys pubescens*, *Pp*; *Cinnamomum camphora*, *Cc*; *Metasequoia glyptostroboides*, *Mg*; *Prunus* × *yedoensis*, *Py*; *Acer buergerianum*, *Ab*; and *Aesculus hippocastanum*; *Ah*; Table 1). All of these species are commonly used in Japan for landscape gardening and/or forestation. Notably, although *P. pubescens* is not technically a woody species, it was treated as an evergreen woody species in this study. The ages of the individual trees were not specifically known. The trees heights were 8.8–20.1 m, and the diameters at breast height were 40–140 cm, with the exception of those of *Pp* (9–15 cm).

2.2. Sampling procedure and radionuclide analysis

Samples were collected once in each growing season on August 6–7, 2011, May 24–25, 2012, and June 1, 2013. Some of the samples for 2011 had also been used in our previous study (Yoshihara et al., 2013). Several foliar samples, each weighing a total of approximately 1.0 kg-FW (leaves of broadleaf species and needles of coniferous species), were collected from each of two (upper and lower in 2012 and 2013) or three relative positions (upper, middle, and lower in 2011) in the canopy. The same one to four trees per species were observed in each year from 2011 through 2013 (Table 1). The samples of some coniferous species, such as *Co*, *Pd*, and *Cj*, contained woody tissues. The absolute sampling heights were different for each plant, although the relative sampling positions were the same. The absolute height of each sample location

Table 1
A list of the target woody plant species.

Classification		Common name (*Scientific name*), abbreviation	Number of observed samples (trees)			Surrounding conditions[b]
			2011	2012	2013	
Evergreen species	Coniferous	1) Hinoki cypress (*Chamaecyparis obtusa*), *Co*	3 (1)[a]	6 (3)	6 (3)	M
		2) Himalayan cedar (*Cedrus deodara*), *Cd*	3 (1)	6 (3)	6 (3)	C
		3) Japanese red pine (*Pinus densiflora*), *Pd*	4 (2)	7 (4)	6 (3)	M/A
		4) Japanese cedar (*Cryptomeria japonica*), *Cj*	9 (3)	4 (2)	6 (3)	M
		5) Moso bamboo (*Phyllostachys pubescens*), *Pp*	3 (1)	4 (4)	3 (3)	M
	Broadleaf	6) Camphor tree (*Cinnamomum camphora*), *Cc*	3 (1)	6 (3)	6 (3)	M
Deciduous species	Coniferous	7) Metasequoia (*Metasequoia glyptostroboides*), *Mg*	6 (2)	6 (3)	6 (3)	M/A
	Broadleaf	8) Japanese flowering cherry (*Prunus* x *yedoensis*, cv. Somei-yoshino), *Py*	12 (4)	6 (3)	8 (4)	C/M
		9) Trident maple (*Acer buergerianum*), *Ab*	6 (2)	6 (3)	6 (3)	C/M
		10) Horse chestnut (*Aesculus hippocastanum*), *Ah*	6 (2)	6 (3)	6 (3)	C/M

[a] In cases for only one/two tree(s) was provided for the observation, at least three samples grown at different foliar positions were averaged per individual trees.
[b] M, trees grow at a margin of a small forest; C, trees grow as a part of colonnade; A, trees grow independently from the other trees.