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The total amounts of radioactively contaminated materials in forests in Fukushima, Japan

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There has been leakage of radioactive materials from the Fukushima Daiichi Nuclear Power Plant. A heavily contaminated area ($\geq$ $^{134,\,137}$Cs 1000 kBq m^{-2}) has been identified in the area northwest of the plant. The majority of the land in the contaminated area is forest. Here we report the amounts of biomass, litter (small organic matter on the surface of the soil), coarse woody litter, and soil in the contaminated forest area. The estimated overall volume and weight were 33 Mm^3 (branches, leaves, litter, and coarse woody litter are not included) and 21 Tg (dry matter), respectively. Our results suggest that removing litter is an efficient method of decontamination. However, litter is being continuously decomposed, and contaminated leaves will continue to fall on the soil surface for several years; hence, the litter should be removed promptly but continuously before more radioactive elements are transferred into the soil.

A massive earthquake occurred in eastern Japan on March 11, 2011, and a very large earthquake-induced tsunami washed over the Fukushima Daiichi Nuclear Power Plant. The damage to the cooling system of the power plant resulted in several explosions. Radioactive materials leaked as a result of the explosions and the ventilation intended to avoid further explosions. Radioactive contamination has been widely but inhomogeneously found in eastern Japan, even in areas hundreds of kilometres away from the plant[1–4]. Airborne surveys revealed that the contamination spread widely, but areas northwest of the plant, from the immediate vicinity of the plant to approximately 60 km away, were found to be notably heavily contaminated (e.g. $\geq$ $^{134,\,137}$Cs 1000 kBq m^{-2})[1,2]. The two major radioactive elements found to be widely deposited are iodine (^{131}I) and cesium (primarily ^{134}Cs and ^{137}Cs). Because the half-lives of ^{131}I, ^{134}Cs, and ^{137}Cs are 8 days, 2 years, and 30 years, respectively, the decontamination of cesium (especially ^{137}Cs) is now the crucial issue.

The majority of the land in the contaminated area is forest. Forest ecosystems consist of tree biomass (aboveground: boles, branches, and leaves; belowground: roots), small dead organic matter on the soil surface (termed litter), dead trees on the soil surface (termed coarse woody litter), and soil. Litter includes fallen dead leaves and branches and their decomposed materials. Usually, several centimetres of litter cover the surface of the soil, whereas coarse woody litter is very sporadically distributed on the surface. Two independent, preliminary surveys conducted by the Forestry and Forest Products Research Institute and Forestry Agency of Japan (FFPRI and FAJ) and by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) revealed that radioactive materials primarily remain in the aboveground tree biomass, litter, and shallow soil (0–0.05 m) in forests[5,6]. Removing the contaminated components is a potential method of decontamination for forest ecosystems[7–9]. Although the amounts of contaminated forest components are unknown, this information is essential to reveal the extent of the contamination by this tragic, historic nuclear accident and guide decontamination efforts. Here we have estimated the volume and weight of contaminated forest components in the contaminated forest area by combining forest statistics, databases of the distributions of vegetation and soil types, and compilations of data from Japan's forests.

Results

The spatial distributions of forest and soil types are shown in Figure 1 and Table 1. The total extent of forest in the area that we defined as heavily contaminated ($\geq$ $^{134,\,137}$Cs 1000 kBq m^{-2}) was 428 km^2, 66% of the area (646 km^2), 4% of the forests in Fukushima prefecture, 0.17% of Japan's forests, and 0.11% of Japan's total area. The dominant forest types were deciduous broadleaf forests and evergreen needleleaf forests. The deciduous broadleaf forests were more distributed in the northern part of the region, and the evergreen needleleaf forests were more

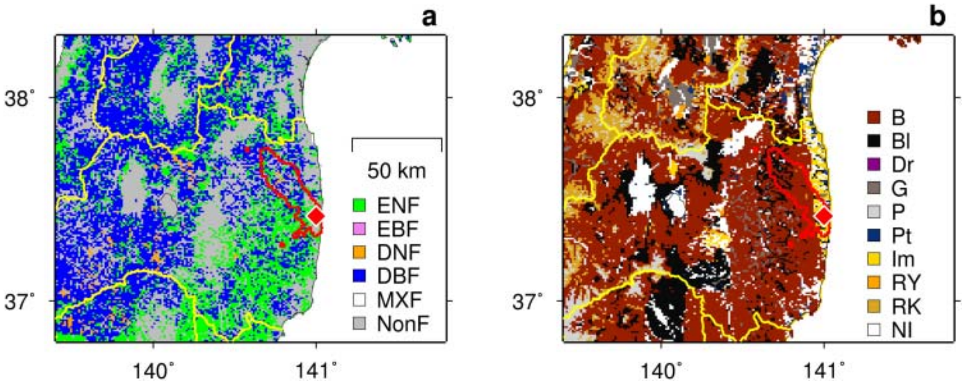

Figure 1 | Distributions of forest type (a) and soil type (b). Red diamond indicates the location of Fukushima Daiichi Nuclear Power Plant. Red line indicates the area that we defined as heavily contaminated. Yellow lines show the borders of the prefectures (local governmental unit in Japan). ENF: evergreen needleleaf forests, EBF: evergreen broadleaf forests, DNF: deciduous needleleaf forests, DBF: deciduous broadleaf forests, MXF: mixed forests, NonF: not forest. B: Brown forest soils, Bl: Black soils, Dr: Dark red soils, G: Gley soils, P: Podzolic soils, Pt: Peaty soils, Im: Immature soils, RY: Red and Yellow soils, RK: Rock and debris, NI: not classified.

distributed in the southern part. There was an additional small area of deciduous needleleaf forests. Brown forest soils (Cambisols and Andosols in the classification of the Food and Agriculture Organization), the most widely distributed soil type in Japan, were distributed most widely in this area, and Black soil (Andosols) and Immature soil (Regosols, Arenosols, Fluvisols, and Leptosols) were also found. The Black soil was distributed in the northern part of the region, and Immature soils were found in the southern part.

The estimated total volume and weight of all of the components were 33 Mm^3 and 21 Tg (dry matter), respectively (Table 2; note that only the weight was estimated for the branches, leaves, litter, and coarse woody litter because of the difficulty in estimating their volumes). The dominant components were soil and aboveground tree biomass (Fig. 2 and Table 2). The total volumes and weights of the aboveground tree biomass and soil were 11 and 21 Mm^3 and 6 and 13 Tg, respectively. Soil was the single largest component, 1.9 times greater in volume and 2.1 times greater in weight than the aboveground tree biomass. The weight of the litter was 0.5 Tg, and was the smallest component in weight, representing 4% of the soil and 3% of the total.

Discussion

The preliminary surveys conducted in August and September 2011 by FFPRI and FAJ revealed that the concentration of cesium (total of ^{134}Cs and ^{137}Cs) in the litter component ranged from 24.1 to 319 kBq kg^{-1} and the proportion of cesium in the litter component ranged from 22% to 66% of the total cesium in the forest ecosystems at this stage and suggest that removing litter could be an efficient method of decontamination, especially for deciduous forests (please note that the surveys were conducted in Fukushima but outside of our study site)[5]. According to the report, the contribution of the litter component was low for Japanese cedar forests (*Cryptomeria japonica*; evergreen needleleaf forests) and high for deciduous oak forests (*Quercus serrata*; deciduous broadleaf forests). This difference likely occurred because the trees in the deciduous forests did not have leaves (i.e., were at a stage prior to leafing) when the radioactive materials were discharged (March 2011). In terms of the amount of materials to be removed, our results indicate that removing the litter component from forest ecosystems is an efficient method of decontamination.

Table 1 | Forest types and soil types in forests in the radioactively contaminated area

Forest/soil type	Area
	km^2
Total forest area	428
Forest types	
Deciduous broadleaf forests	210
Evergreen needleleaf forests	201
Deciduous needleleaf forests	17
Soil types	
Brown forest soils	293
Black soils	70
Immature soils	51
Gley soils	5
Rock and debris	5
NI*	4

NI* denotes soils whose classification could not be identified.

However, we should note that the litter component is being continuously decomposed and that the decomposed litter is continuously transferred into the soil component. The average decomposition constant (exponential decay constant) of the litter in Japanese forests, determined through field experiments, is approximately 0.41 yr^{-1} (ref. 10). This value indicates that 30–40% of the litter on the soil surface will be decomposed each year. Thus, most of the trapped cesium in the litter component will move into the soil in a few years, and therefore, the litter component should be removed promptly[11]. Furthermore, the decomposition of the litter increases exponentially with increasing temperature[12]. During the winter, litter decomposition is inhibited by low temperatures, but the decomposition will accelerate with increasing temperatures during the spring. Such a transfer of cesium from litter to soil was reported in the Chernobyl forests[13–15]. In the evergreen needleleaf forests, the trapped cesium in the litter component is not currently as high as that in the deciduous broadleaf forests. The leaves on the trees still retain approximately 40% of the total cesium in the forests[5]. The average longevity of the leaves of the dominant species in evergreen needleleaf forests in Japan (Japanese cedar, *Cryptomeria japonica*) is approximately 5 years[16]. Hence, contaminated leaves will continue to fall on the soil surface during and after the next 5 years. In addition, the cesium trapped on the leaves would serve as a source of cesium transfer from the biomass to the forest floor via water flow[17]. To effectively decontaminate the forests by removing litter, prompt but continuous effort is needed.

When the contaminated components are removed, storage space for a substantial quantity of contaminated materials is required. The aboveground tree biomass, litter, and coarse woody litter components are incinerable, and incineration can reduce the volume and weight of these components. We estimated the volume and weight of the ash that would result if these three components are incinerated.

Table 2 | Estimated volumes and weights of the components

Component	Forest/soil type	Volume	Weight	Uncertainty
		Mm^3	Tg	%
Aboveground tree biomass	Deciduous broadleaf forests	4.3	3.4	-
	Evergreen needleleaf forests	6.5	2.5	-
	Deciduous needleleaf forests	0.5	0.3	-
	Total	11.3	6.1	NE*
Litter	Deciduous broadleaf forests	NE*	0.3	-
	Evergreen needleleaf forests	NE*	0.2	-
	Deciduous needleleaf forests	NE*	0.0	-
	Total	NE*	0.5	74
Coarse woody litter	Deciduous broadleaf forests	NE*	0.2	-
	Evergreen needleleaf forests	NE*	0.9	-
	Deciduous needleleaf forests	NE*	0.0	-
	Total	NE*	1.1	70
Soil	Brown forest soils	14.7	8.6	-
	Black soils	3.5	1.6	-
	Immature soils	2.6	2.3	-
	Gley soils	0.3	0.2	-
	Rock and debris	0.3	0.2	-
	NI	0.2	0.1	-
	Total	21.4	12.9	22
Total	Total	32.7	20.7	-

NE*: not estimated. The volumes of the branches, leaves, litter, and coarse woody litter were not estimated because of their complex shapes; thus, branches and leaves were not included in the volume of the aboveground tree biomass. The uncertainty of the aboveground tree biomass was not evaluated, as the uncertainty of the parameters used to calculate aboveground tree biomass was not reported.

The estimated weight was 0.1 Tg, approximately 1% of the soil component (see Supplementary Information). Furthermore, if the ash is compacted, the volume will be 0.3% of the volume of the soil component. For the soil component, the volume may be reduced; the surface soils in forests are in general looser (or have a lower bulk density) than compacted soils. If those loose soils can be compacted as dense soils, the volume will be reduced by 70% (see Supplementary Information).

The preliminary survey conducted by FFPRI and FAJ reported that approximately 20% of the radioactive cesium was already in the soil component[5]. This finding suggests that if we remove the aboveground tree biomass, litter, and coarse woody litter at this stage, we can decontaminate approximately 80% of the radioactive materials in the contaminated area. Our estimates demonstrate that storing these three components is more efficient than storing the soil component because these three components consume less space than the soil. Nevertheless, cutting the trees in such an extensive area would not be an easy task. In addition, cutting trees over an extensive area may cause serious soil erosion and landslides. In contrast, incinerating the contaminated components themselves could provide an energy source for performing the decontamination[18], although we are aware that the incineration of radioactively contaminated materials without leakage of radioactive elements to the atmosphere may not be feasible. Nevertheless, our results imply that the amount of litter is relatively very small. We therefore emphasise that the key component for efficient decontamination is the litter.

The distribution pattern of the contamination is very inhomogeneous; highly contaminated areas are located irregularly outside the area we focused on. However, we believe that our study provides approximate estimates of the amount of radioactively contaminated materials in forests. Depending on the balance of costs and benefits, our estimates may suggest that certain sites should be left without decontamination, and we believe that this choice is one of the options that should be courageously discussed. According to a report on the Chernobyl accident, forest decontaminations are potentially labour intensive and expensive[19]. Furthermore, it was indicated in studies of the forests contaminated by the Chernobyl accident that the circulation of radioactive elements (soil-plant) reached a quasi-equilibrium within a few years after the accident and that the forest retained radioactive elements, with only a small loss of radioactive elements from the forest ecosystems[20–22]. However, it is expected that the dynamics of radioactive elements differ depending on the level of contamination, ecosystems (tree species and soil types), climate, and topography[23,24]. Therefore, it should be emphasised that the detailed monitoring of the migration of the radioactive elements between the components in forest ecosystems and between different land types

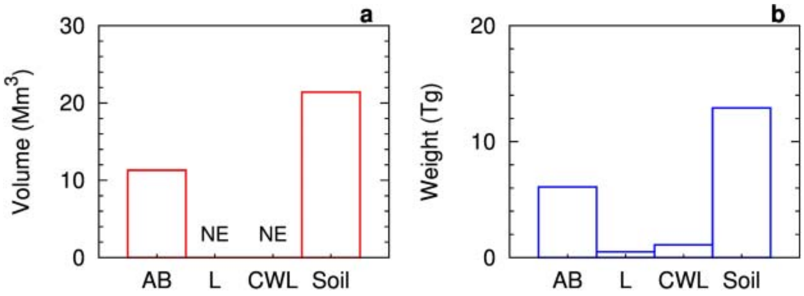

Figure 2 | Estimated total volumes and weights of radioactively contaminated components. AB: aboveground tree biomass, L: litter, CWL: coarse woody litter. NE: not estimated. Branches and leaves were not included in the volume of aboveground tree biomass.

(e.g., from forests to arable lands) is vital. We hope that our study facilitates the prompt and efficient decontamination of forests in Fukushima.

Methods

We combined forest statistics, databases of the distributions of the vegetation and soil types (1-km resolution), and compilations of data observed in Japan. The volumes and weights of the aboveground tree biomass, litter, coarse woody litter, and shallow soil (0–0.05 m) were estimated. From a radiation map from MEXT obtained by an airborne survey in November 2011, we defined the contaminated area ($\geq {}^{134,\,137}$Cs 1000 kBq m^{-2}) (ref. 1,2). We multiplied the area of each forest or soil type by the average stock per area of each component and summed the values. The distributions of the vegetation and soil types were derived from the Japan Integrated Biodiversity Information System (J-IBIS) (ref. 25) and the National Land Numerical Information[26]. The forest area and stock were obtained from forest statistics[27,28]. The parameters for calculating the aboveground tree biomass were derived from the National Greenhouse Gas Inventory Report of Japan 2011 (ref. 29). The average stocks of litter and coarse woody litter were obtained from a study representing a compilation of information on Japanese forest soils[30]. The bulk densities of soils were obtained from a soil data browsing system[31,32]. The equation for the uncertainty assessment is from the National Greenhouse Gas Inventory Report of Japan 2011 (ref. 29). The detailed equations are given below, and all parameters and calculations are included in the Supplementary Information.

For aboveground tree biomass,

$$V_{\mathrm{AB}} = \sum_i V_i\left(A_i \times 10^6\right)/10^6$$

$$W_{\mathrm{AB}} = \sum_i V_i\left(D_i \times 10^6\right) BEF_i\left(A_i \times 10^6\right)/10^{12}$$

where V_{AB} is the total volume of the aboveground bole biomass (Mm^3), V_i is the average bole biomass of forest type i (m^3 m^{-2}), and A_i is the area of forest type i (km^2). W_{AB} is the total weight of the aboveground tree biomass including boles, branches, and leaves (Tg), D_i is the wood density of the bole (Mg m^{-3}), and BEF_i is the biomass expansion factor (the factor to estimate the aboveground total biomass from bole biomass) of forest type i (ratio). We derived average bole stock data for artificial and natural forests in Fukushima from forest statistics[28]. The weight-based ash ratios of aboveground tree biomass are 0.5% for broadleaf forests and 0.4% for needleleaf forests[33].

For litter,

$$W_{\mathrm{L}} = \sum_i \left(ML_i \times 10^3\right)\left(A_i \times 10^6\right)/10^{12}$$

where W_{L} is the weight of litter (Tg) and ML_i is the mean stock in litter of forest type i (kg m^{-2}). The volume of litter was not estimated due to its complex shape. The ash ratios of litter were assumed to be 14.7% for deciduous broadleaf forests and 23.6% for evergreen and deciduous needleleaf forests[34].

For coarse woody litter,

$$W_{\mathrm{CWL}} = \sum_i \left(MC_i \times 10^3\right)\left(A_i \times 10^6\right)/10^{12}$$

where W_{CWL} is the weight of coarse woody litter (Tg) and MC_i is the mean stock in coarse woody litter of forest type i (kg m^{-2}). The volume of coarse woody litter was not estimated because of its complex shape. The ash ratio for coarse woody litter was assumed to be 0.4% (Y. Sakai (Forestry and Forest Products Research Institute, Japan), personal communication).

The compacted volumes of the ash were calculated as follows:

$$CAV_{\mathrm{AB}} = \left(AW_{\mathrm{AB}} \times 10^{12}\right)/\left(d_{\mathrm{AB}} \times 10^6\right)/10^6$$

$$CAV_{\mathrm{L}} = \left(AW_{\mathrm{L}} \times 10^{12}\right)/\left(d_{\mathrm{L}} \times 10^6\right)/10^6$$

$$CAV_{\mathrm{CWL}} = \left(AW_{\mathrm{CWL}} \times 10^{12}\right)/\left(d_{\mathrm{CWL}} \times 10^6\right)/10^6$$

where CAV_{AB}, CAV_{L}, and CAV_{CWL} are the compacted volumes of the ash of the aboveground tree biomass, litter, and coarse woody litter, respectively (Mm^3), AW_{AB}, AW_{L}, and AW_{CWL} are the weights of the ash of the aboveground tree biomass, litter, and coarse woody litter, respectively (Tg), and d_{AB} , d_{L}, and d_{CWL} are the bulk densities of the respective compacted ash (Mg m^{-3}). We used a bulk density of 2 Mg m^{-3} based on the bulk density of the compacted soils.

For soil,

$$V_{\mathrm{Soil}} = \sum_j Z\left(A_j \times 10^6\right)/10^6$$

$$W_{\mathrm{Soil}} = \sum_j \left(BD_j \times 10^3\right) Z\left(A_j \times 10^6\right)/10^{12}$$

where V_{Soil} and W_{Soil} are the volume (Mm^3) and weight (Tg) of the soil component, Z is the depth (0.05 m), and BD_j is the bulk density of each soil type (kg m^{-2}).

The compacted volume of the soil was calculated as follows:

$$CV_{\mathrm{Soil}} = \left(W_{\mathrm{Soil}} \times 10^{12}\right)/\left(d_{\mathrm{Soil}} \times 10^6\right)/10^6$$

where CV_{Soil} is the compacted volume of the soil (Mm^3) and d_{Soil} is the bulk density of the compacted soil (Mg m^{-3}). We assumed a bulk density of 2 Mg m^{-3} based on the maximum bulk density of the soil.

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Author contributions

S.H. designed the study and wrote the manuscript with input from all other authors. S.H. and S.U. collected data and conducted the calculations. K.N. conducted the GIS analyses.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

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