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 ($^{134,137}$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. 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. $^{134,137}$Cs 1000 kBq m$^{-2}$). 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 (above-ground: boles, branches, and leaves; below-ground: 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. Removing the contaminated components is a potential method of decontamination for forest ecosystems. 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 ($^{134,137}$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
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). 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.

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$^9$. 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 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.

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.
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. 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, 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. 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. 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. 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 is necessary to develop effective decontamination strategies.

### Table 2 | Estimated volumes and weights of the components

| Component                  | Forest/soil type                | Volume (Mm³) | Weight (Tg) | Uncertainty (%) |
|----------------------------|--------------------------------|--------------|-------------|-----------------|
| 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         | -               |
|                            | NE                            | 0.2          | 0.1         | -               |
|                            | Total                          | 21.4         | 12.9        | 22              |
| 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.
and leaves (Tg), CAV

SCIENTIFIC

V

where

CAV

W

where

The compacted volume of the soil was calculated as follows:

CV_{\text{Soil}} = \left( \frac{W_{\text{Soil}} \times 10^5}{d_{\text{Soil}} \times 10^3} \right) / 10^6

where CV_{\text{Soil}} is the compacted volume of the soil (Mm$^3$) and $d_{\text{Soil}}$ 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.

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