(Attachment 1)

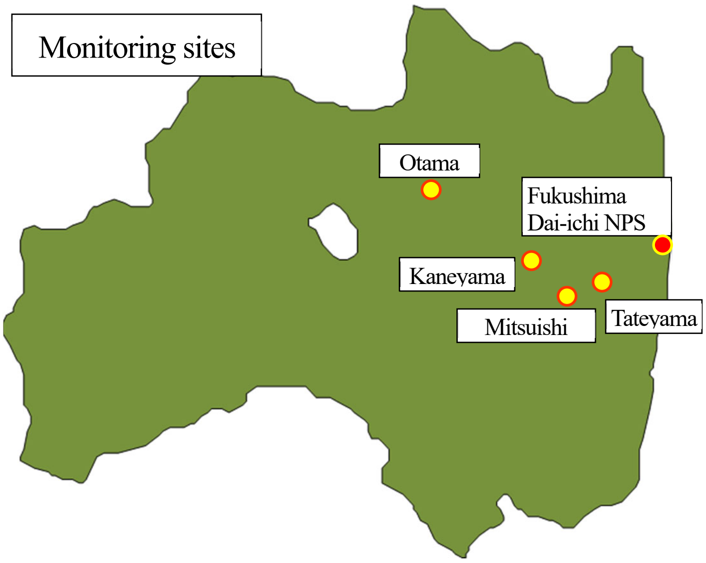
[Survey 1] Result of FY2020 Survey on Radioactive Cesium Distribution in Forests

1. Background and Objective

In 2011, the Forestry Agency set monitoring sites in three municipalities (Kawauchi Village, Otama Village, and Tadami Town) in Fukushima Prefecture in order to clarify the distribution of radioactive cesium within forests. Since then, the Agency has investigated the concentrations and accumulated quantities of radioactive cesium in soil, fallen leaves, and sections of trees such as leaves and trunks, and published the results.

In response to a decrease in radioactive cesium concentrations and the lifting of areas under evacuation orders, the Agency reviewed the monitoring sites and added some sites in FY2017. From July to December 2020, the Agency surveyed the concentrations and accumulated quantities of radioactive cesium for six forests at four monitoring sites in two villages (Figure 1), for which the Agency is reporting the results.

2. Monitoring Sites



Distance from Fukushima Dai-ichi NPS	
Tateyama	19 km
Mitsuishi	26 km
Kaneyama	28 km
Otama	66 km

Figure 1 Monitoring Sites and Distance from Fukushima Dai-ichi NPS.

The monitoring sites are located from 19 to 66 km from the Fukushima Dai-ichi Nuclear Power Station, where an accident occurred, as measured in a straight line. This fiscal year, in addition to measuring the air dose rates at five monitoring sites in Kawauchi Village (Tateyama Japanese red pine forest, Mitsuishi cedar forest, Mitsuishi Japanese cypress forest, Mitsuishi konara oak forest, Kaneyama cedar forest) and one monitoring site in Otama Village (Otama cedar forest), the Agency investigated the concentrations of radioactive cesium in soil, in litter layer, and in the leaves, trunks, and other parts of trees in the forests and estimated the distribution and accumulated quantities of radioactive substances for the entire forest area (Table 1).

Note that the "konara oak forest" in Mitsuishi actually is deciduous broad-leaved forest but is named "konara oak forest" in this document since the survey target is konara oak trees.

Table 1 Location of Monitoring Site and Survey Period

Monitoring site	**Location**	**Survey period**
Tateyama Japanese red pine forest	Tateyama, Kawauchi Village, Futaba District, Fukushima Prefecture (National forest under the jurisdiction of Iwaki District Forest Office)	August 28, 31, and September 1, 2020
Mitsuishi cedar forest	Shimo-Kawauchi, Kawauchi Village, Futaba District, Fukushima Prefecture (National forest under the jurisdiction of Iwaki District Forest Office)	August 20 and 25, 2020
Mitsuishi Japanese cypress forest	Shimo-Kawauchi, Kawauchi Village, Futaba District, Fukushima Prefecture (Village forest)	August 21, 25 to 26, 2020
Mitsuishi konara oak forest	Kami-Kawauchi, Kawauchi Village, Futaba District, Fukushima Prefecture (Village forest)	August 21, 25 to 26, 2020
Kaneyama cedar forest	Kami-Kawauchi, Kawauchi Village, Futaba District, Fukushima Prefecture (Village forest)	August 24 and 27, December 3, 2020
Otama cedar forest	Tamanoi, Otama Village, Adachi District, Fukushima Prefecture (National forest under the jurisdiction of Fukushima District Forest Office)	July 30, August 3 to 4, 2020

Photo 1 Japanese red pine forest at Tateyama monitoring site

Photo 2 Cedar forest at Mitsuishi monitoring site

Photo 3 Japanese cypress forest at Mitsuishi monitoring site

Photo 4 Konara oak forest at Mitsuishi monitoring site

Photo 5 Cedar forest at Kaneyama monitoring site

Photo 6 Cedar forest at Otama monitoring site

Table 2 Tree Type, Forest Age, Forest Type and Air Dose Rate of Monitoring Sites

Monitoring site	Forest age (years)	Forest type	Air dose rate (μSv/h)*
Tateyama Japanese red pine forest	54	Planted	1.23
Mitsuishi cedar forest	52	Planted	0.91
Mitsuishi Japanese cypress forest	35	Planted	1.20
Mitsuishi konara oak forest	35	Natural regenerated	0.90
Kaneyama cedar forest	64	Planted	0.41
Otama cedar forest	51	Planted	0.10

* Average of measurements at a height of 1 m from the ground during the survey period in 2020

3. Method

The tree type, forest age, etc., of monitoring sites are shown in Table 2. The Forestry Agency conducted the survey and analysis by the method shown below, which is the same as the method applied in the previous fiscal year. Air dose rates were measured in monitoring sites at an interval of 10 meters. A basic survey of monitoring sites was conducted including the growth of forest, and the trunk xylem volume, leaf weight and branch weight were estimated from the trunk diameter and tree height.

For the samples of litter layer and soil for analysis, the litter layer (organic litter layer consisting of fallen leaves and branches on soil and their humus) was sampled first, and then soil was sampled from four layers (depths of 0-5, 5-10, 10-15, and 15-20 cm) using a tube for sampling soil (height 5 cm, inner diameter 11 cm). As for trees at four monitoring sites (Mitsuishi cedar forest, Mitsuishi Japanese cypress forest, Mitsuishi konara oak forest, and Kaneyama cedar forest), six trees were selected to survey, their bark was sampled, and then xylem was sampled using an increment borer. As for sampling leaves and branches, at three monitoring sites (Mitsuishi cedar forest, Mitsuishi Japanese cypress forest and Kaneyama cedar forest) among the four monitoring sites, four trees from which branches and leaves could be sampled (some trees in Mitsuishi Japanese cypress forest and Kaneyama cedar forest are the same as those from which xylem was sampled using an increment borer) were selected to survey. Samples were collected from both the upper and lower layers of the forest canopy by means of tree climbing and use of high branch pruning shears. At the Mitsuishi konara oak forest, six trees were selected as trees to survey, and branches and leaves were sampled from all layers of the forest canopy. Meanwhile, at the Otama cedar forest and Tateyama Japanese red pine forest, the same as the surveys conducted in the past, three target trees were selected near each of the monitoring sites, felled, and leaves, branches, bark, and xylem were sampled. The xylem was separated into sapwood and heartwood indoors.

The tree section samples, litter layer and soil were dried, crushed and then subjected to gamma-ray spectrometry using a germanium semiconductor detector to measure the radioactive cesium (Cs-134, Cs-137) concentrations per dry weight. The accumulated quantities of radioactive cesium per unit area were derived by multiplying the weight of litter layer, soil and tree sections per unit area with the respective radioactive cesium concentration. For samples in which the radioactive cesium concentration was at or below the detection limit, the detection limit value was used if both Cs-134 and Cs-137 were undetectable. If only Cs-134 was undetectable, the Cs-134 concentration was estimated from the Cs-137 concentration using the concentration ratio of Cs-134 and Cs-137 calculated from theoretical estimation formula based on physical decay, assuming that the concentration ratio of Cs-134 and Cs-137 as of March 15, 2011was 1:1. For the radioactive cesium concentrations, the average and standard deviation were derived for all samples. Hereinafter radioactive cesium concentration refers to the sum of Cs-134 and Cs-137 concentrations. This year's measurements were normalized to September 1, 2020.

4. Results

(1) Air dose rate

In 2020, the air dose rate at a height of 1 m from the ground was 1.23 μSv/h for Tateyama Japanese red pine forest, 0.91 μSv/h for Mitsuishi cedar forest, 1.20 μSv/h for Mitsuishi Japanese cypress forest, 0.90 μSv/h for Mitsuishi konara oak forest, 0.41 μSv/h for Kaneyama cedar forest, and 0.10 μSv/h for Otama cedar forest, exhibiting smaller values at locations farther from the NPS (Figure 2). The values for 2020 ranged from 94% to 106% of those measured in 2019. The air dose rates at the Mitsuishi cedar forest and Otama cedar forest, monitoring sites at which survey has been continued since 2011, were 30% and 32%, respectively, of the values in 2011.

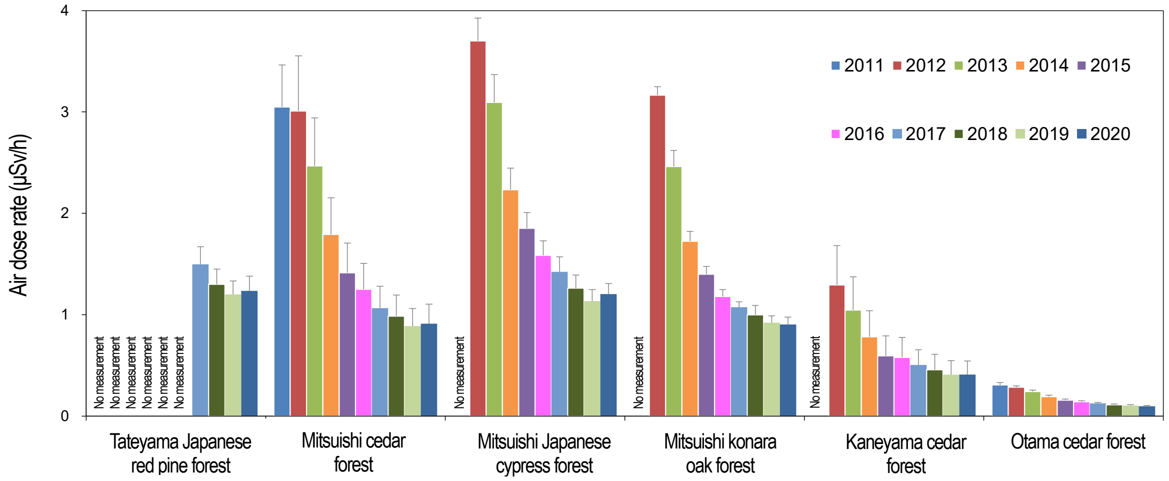


Figure 2 Changes in Air Dose Rates (Average) at Monitoring Sites from 2011 to 2020
(Fine lines indicate standard deviation.)

(2) Changes in radioactive cesium concentration by section

The radioactive cesium concentrations of sections such as leaf, branch and bark continue to fall in general since the commencement of the survey in 2011 (Figure 3). In FY2020, the radioactive cesium concentrations in leaves were lower than the previous survey results at the monitoring sites in the Mitsuishi cedar forest and Tateyama Japanese red pine forest, and the concentrations in branches were lower than the previous survey results at the monitoring sites except the Mitsuishi konara oak forest. Compared to the periods immediately after the accident at the Fukushima Daiichi NPS, it is now apparent that the reduction in the radioactive cesium concentrations has slowed down in both branches and leaves. As for the radioactive cesium concentrations in heartwood and sapwood inside the trees, no major changes have been observed for the Mitsuishi cedar forest and Mitsuishi Japanese cypress forest in both heartwood and sapwood since around 2015 to 2016. On the other hand, the radioactive cesium concentrations in heartwood had been gradually increasing in those from Kaneyama cedar forest until around 2018. However, the concentrations in FY2019 and FY2020 were lower than the FY2018 survey results. In addition, in all monitoring sites, the concentrations in sapwood and heartwood were lower than the concentrations in other sections.

In some areas, the concentrations in the litter layer were slightly higher than in the previous survey and, in general, the reduction in the concentrations had slowed down.

For soil, similar to the survey results up to the previous fiscal year, the concentrations were highest in the surface layer soil with the depth of 0-5 cm. In the layers deeper than 5 cm, the concentration values were 27% of the concentrations at the surface layer soil at most, and the deeper layers showed lower values as a trend. The concentrations at the depth of 0-5 cm significantly increased from 2011 over to 2012 at some sites, but the trend was a mixture of increases and decreases from 2013 to 2020, and did not exhibit any clear trend. The concentrations at the depth of 5-10 cm in the Mitsuishi cedar forest and Otama cedar forest exhibited the highest values in the survey to date with a gradually increasing trend.

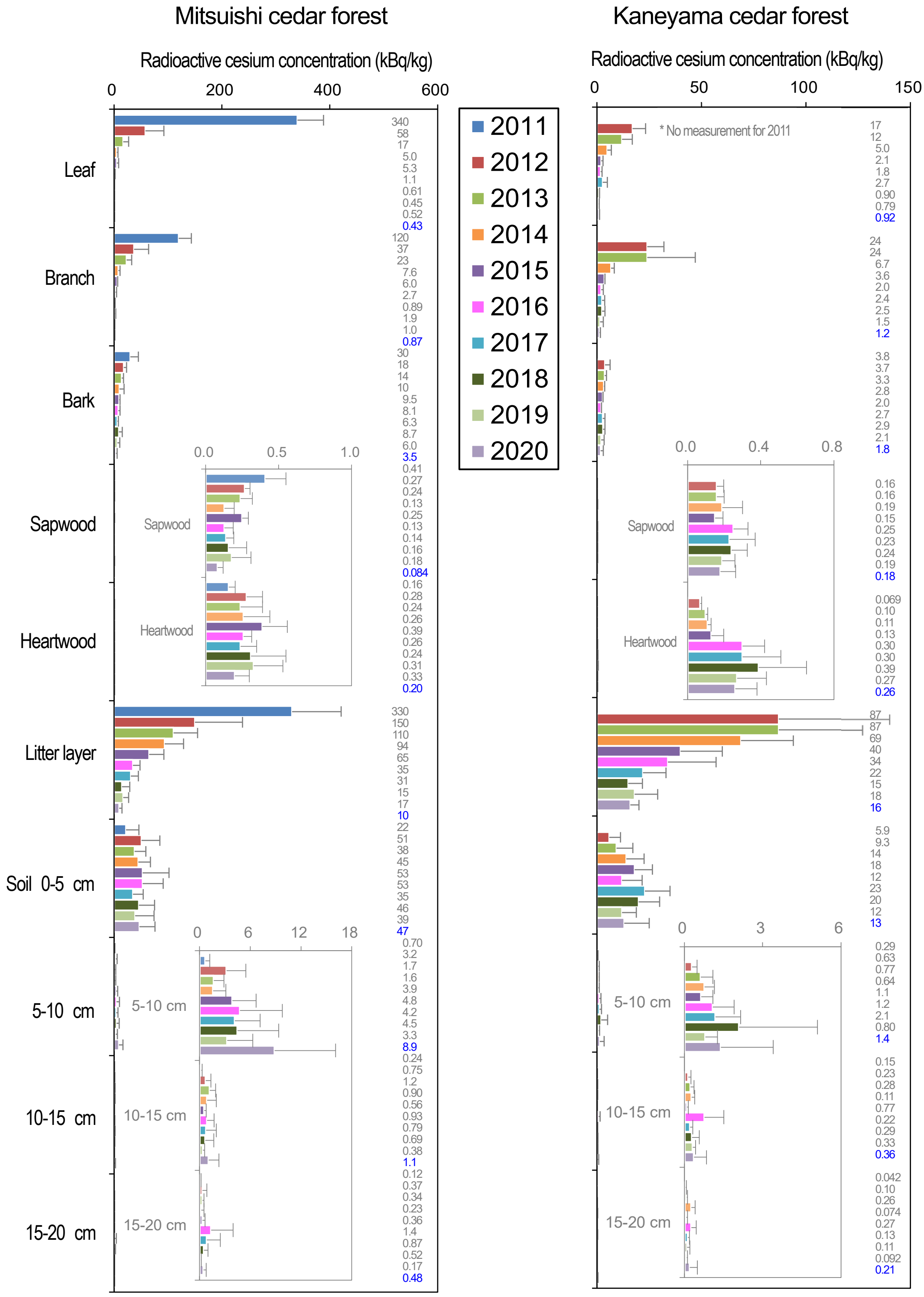


Figure 3 Changes in Radioactive Cesium Concentrations by Section at Each Monitoring Site (kBq/kg, average, 2 significant digits)
(Fine lines indicate standard deviation. No measurement for Kaneyama cedar forest in 2011. Concentrations by section of trees are those of the dominant species.

Measurement results in the current fiscal year are shown in blue.)

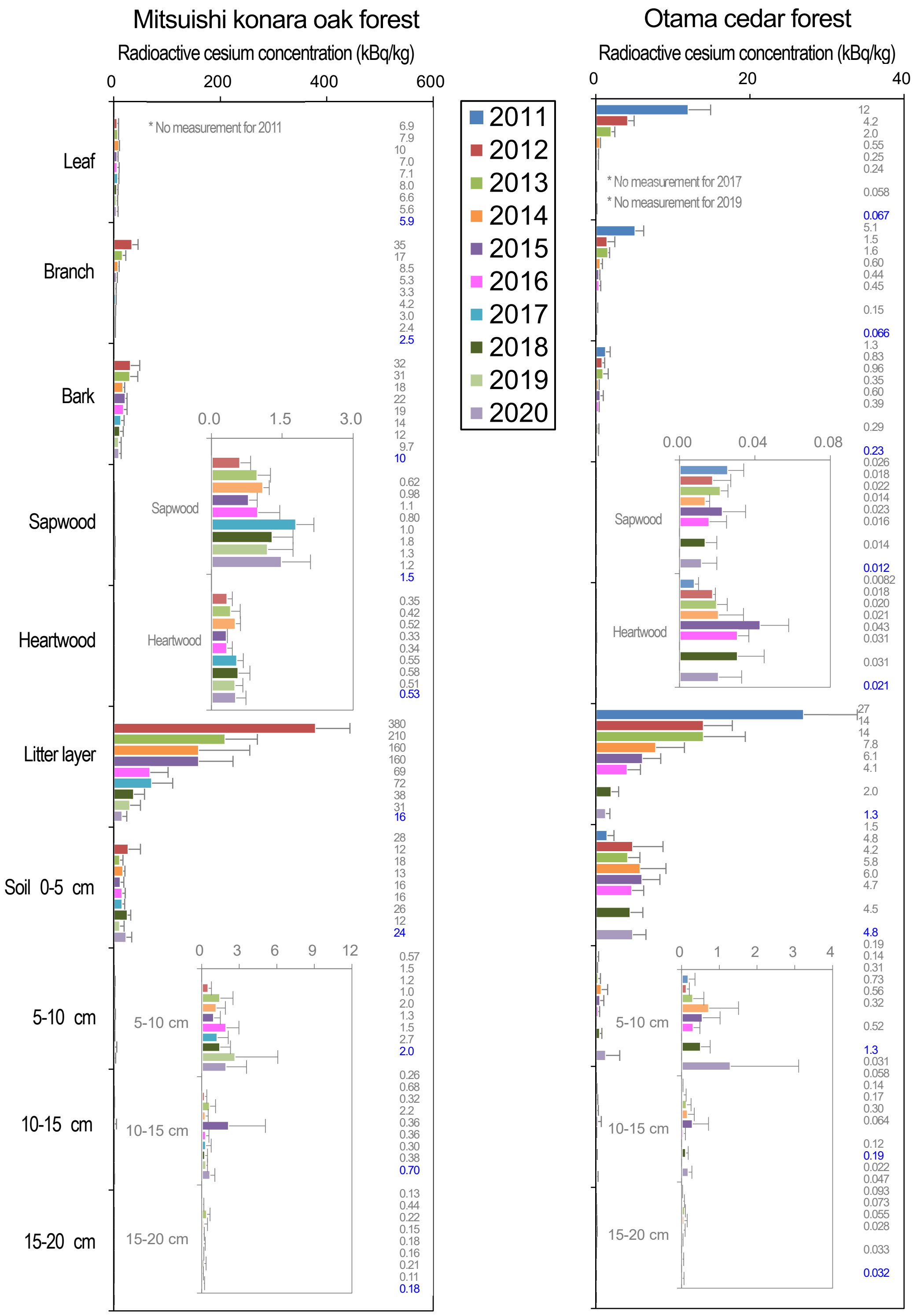


Figure 3 Changes in Radioactive Cesium Concentrations by Section at Each Monitoring Site (kBq/kg, average, 2 significant digits)

(Fine lines indicate standard deviation. No measurement for Mitsuishi konara oak forest in 2011 and for Otama cedar forest in 2017 and 2019. Concentrations by

section of trees are those of the dominant species. Measurement results in the current fiscal year are shown in blue.)

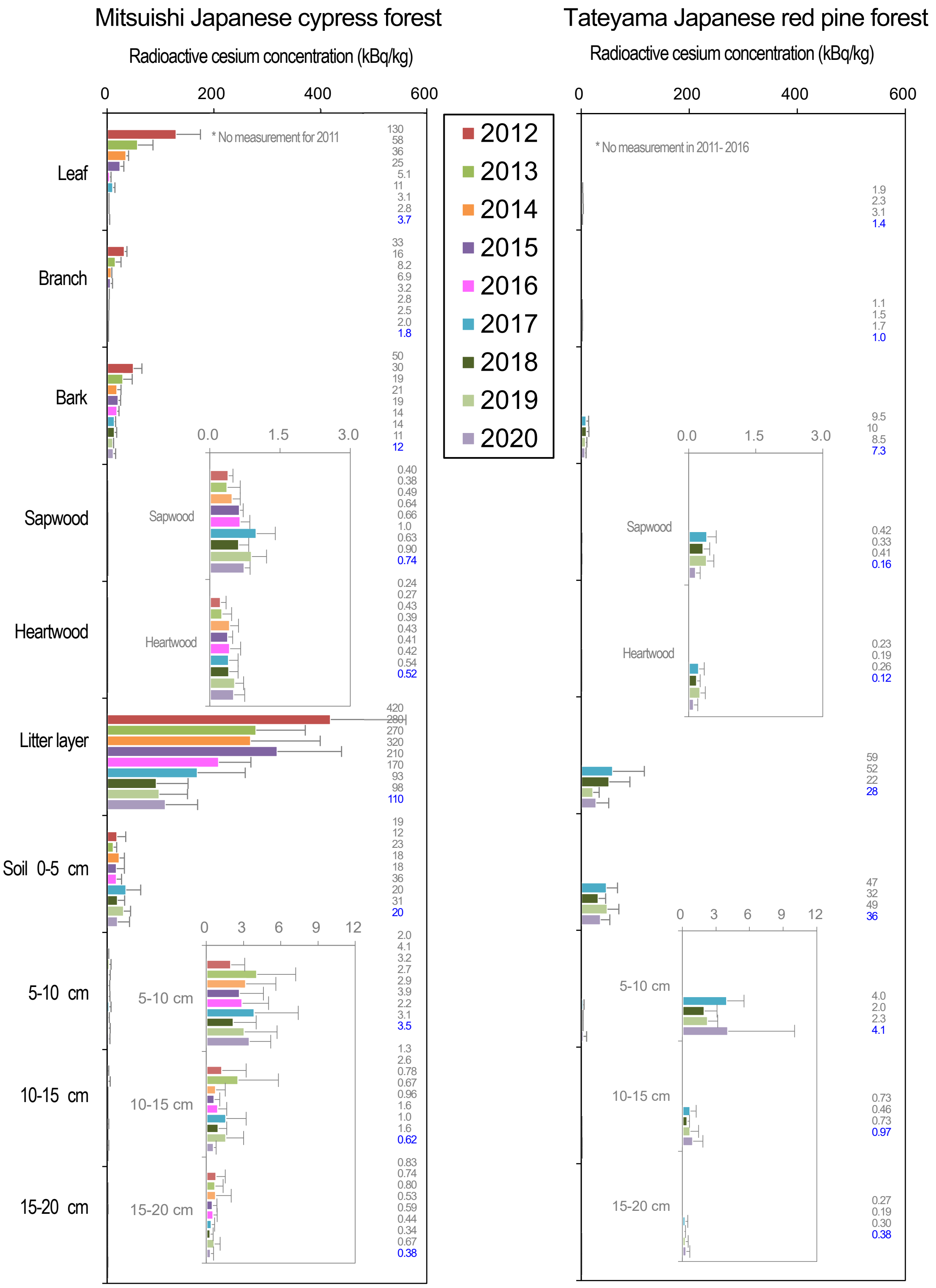


Figure 3 Changes in Radioactive Cesium Concentrations by Section at Each Monitoring Site (kBq/kg, average, 2 significant digits)

（Fine lines indicate standard deviation. No measurement for Mitsuishi Japanese cypress forest in

2011 and for Tateyama Japanese red pine forest in 2011-2016. Concentrations by section of trees are those of the dominant species. Measurement results in the current fiscal year are shown in blue.)

(3) Changes in the accumulated quantities and distributions of radioactive cesium for the entire forest

The accumulated quantities of radioactive cesium for the entire forest did not exhibit any clear trends at any of the monitoring sites (Figure 4).

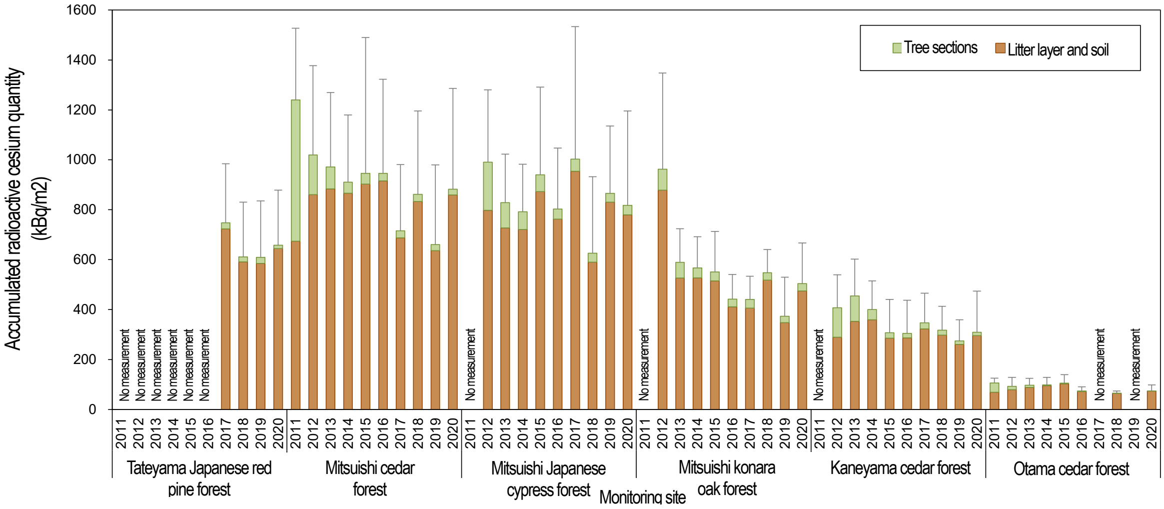


Figure 4 Changes in the Accumulated Quantities (Averages) of Radioactive Cesium for the Entire Forest from 2011 to 2020 (Fine lines indicate standard deviation)

Looking at the percentages of accumulated radioactive cesium quantity by section in trees and soil, the results for Mitsuishi cedar forest and Otama cedar forest for which the survey started in 2011 showed significant changes from 2011 over to 2012, a sudden increase in the percentage of soil and a resultant decrease in other sections. However, the percentages do not show many changes from 2012 to 2020 (Figure 5, Table 3).

At all monitoring sites, the percentage of radioactive cesium distributed in soil has been increasing each year or showing almost the same values over the years, and accounts for 53-96% of the entire amount in 2020. The distribution ratio of radioactive cesium in the litter layer is in a trend of gradual decrease, but the rate of decrease varies site to site. The distribution ratio in the litter layer suddenly decreased at the Mitsuishi cedar forest and Otama cedar forest to 3% or less by 2020, but 43% still remains in the litter layer of the Mitsuishi Japanese cypress forest even in 2020. The accumulated quantities of radioactive cesium in trees such as leaves and branches exhibited a trend of continuous decrease until 2015, but no significant change has been observed since 2016.

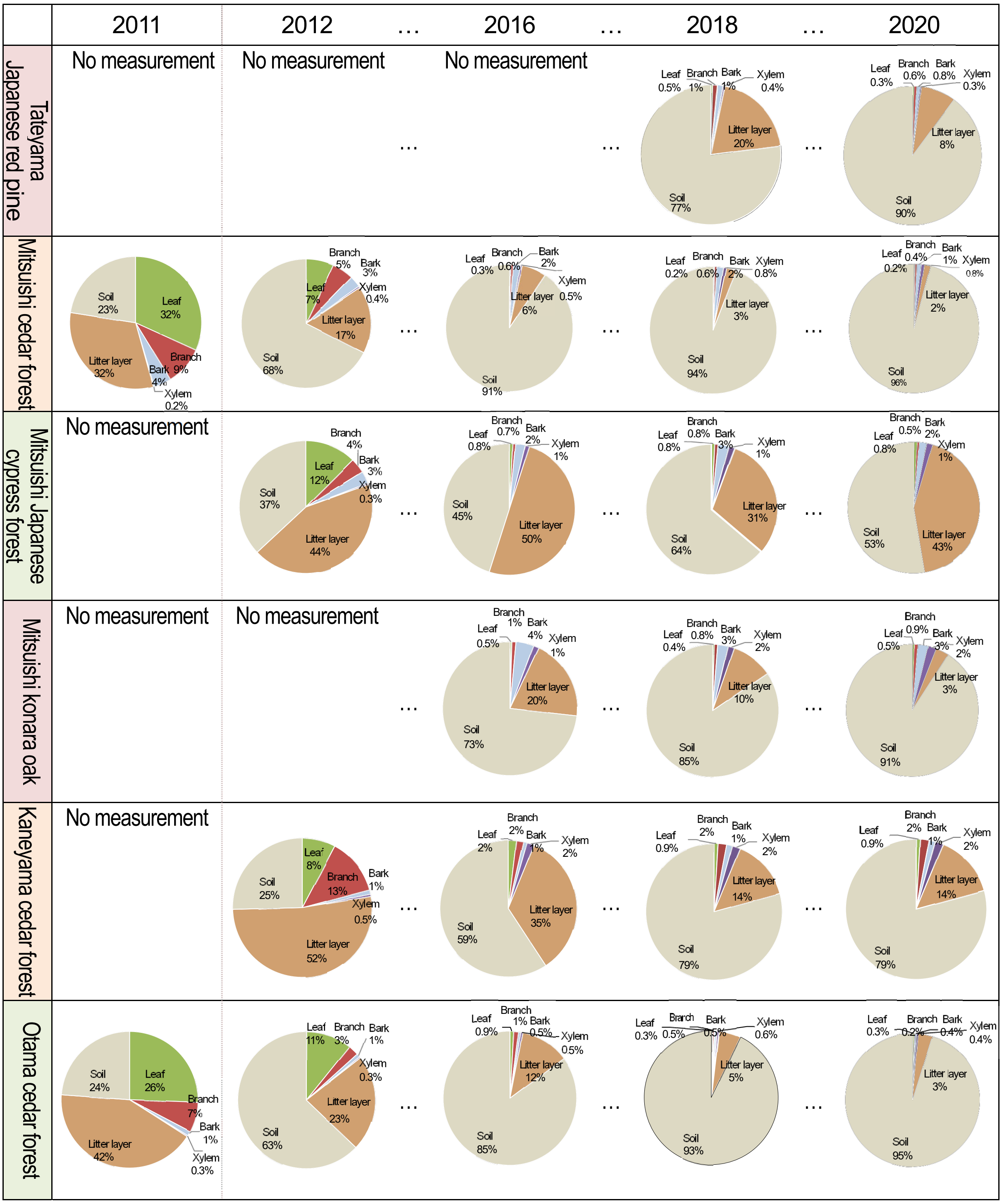


Figure 5 Percentage of Accumulated Radioactive Cesium Quantity by Section at Monitoring Sites from 2011 to 2020

(Note) Data are omitted for 2013, 2014, 2015, 2017 and 2019.

Table 3 Percentage of Accumulated Radioactive Cesium Quantity by Section at Monitoring Sites and Total Accumulated Quantities (TAQs) of Radioactive Cesium Per Unit Area (± Standard Deviation) from 2011 to 2020

		2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Tateyama Japanese red	Leaf, branch	-	-	-	-	-	-	0.5%, 1%	0.5%, 1%	0.7%, 2%	0.3%,
	Bark	-	-	-	-	-	-	1%	1%	1%	0.8%
	Xylem	-	-	-	-	-	-	0.5%	0.4%	0.6%	0.3%
	Litter layer	-	-	-	-	-	-	15%	20%	5%	8%
	Soil	-	-	-	-	-	-	82%	77%	91%	90%
	TAQs*	-	-	-	-	-	-	747±237	611±219	609±225	658±221
Mitsuishi cedar forest	Leaf, branch	32%, 9%	7%, 5%	2%, 3%	0.9%, 1%	0.9%, 1%	0.3%,	0.4%,	0.2%,	0.3%,	0.2%,
	Bark	4%	3%	3%	2%	2%	2%	2%	2%	2%	1%
	Xylem	0.2%	0.4%	0.5%	0.5%	0.5%	0.5%	1%	0.8%	1%	0.8%
	Litter layer	32%	17%	19%	19%	9%	6%	6%	3%	5%	2%
	Soil	23%	68%	72%	77%	87%	91%	90%	94%	92%	96%
	TAQs*	1240±287	1019±358	972±297	910±269	946±544	946±376	716±265	862±334	660±319	882±404
Mitsuishi Japanese cypress forest	Leaf, branch	-	12%, 4%	7%, 2%	5%, 1%	3%, 1%	0.8%,	2%, 0.5%	0.8%,	0.5%,	0.8%,
	Bark	-	3%	2%	2%	2%	2%	2%	3%	2%	2%
	Xylem	-	0.3%	0.4%	0.7%	0.8%	1%	1%	1%	1%	1%
	Litter layer	-	44%	49%	37%	50%	50%	35%	31%	20%	43%
	Soil	-	37%	39%	54%	43%	45%	60%	64%	76%	53%
	TAQs*	-	991±290	829±194	792±190	940±352	802±244	1002±531	626±306	866±270	818±378
Mitsuishi konara oak forest	Leaf, branch	-	-	-	-	0.4%, 1%	0.5%, 1%	0.6%, 1%	0.4%,	0.6%, 1%	0.5%,
	Bark	-	-	-	-	4%	4%	3%	3%	3%	3%
	Xylem	-	-	-	-	0.8%	1%	2%	2%	2%	2%
	Litter layer	-	-	-	-	37%	20%	20%	10%	13%	3%
	Soil	-	-	-	-	57%	73%	72%	85%	80%	91%
	TAQs*	-	-	-	-	551±162	443±98	441±93	548±93	373±157	504±163
Kaneyama cedar forest	Leaf, branch	-	12%, 16%	8%, 13%	4%, 4%	2%, 3%	2%, 2%	3%, 2%	0.9%, 2%	1%, 1%	1%, 1%
	Bark	-	0.9%	1%	1%	1%	1%	1%	1%	1%	0.9%
	Xylem	-	0.5%	0.5%	0.7%	0.8%	2%	1%	2%	2%	1%
	Litter layer	-	49%	52%	46%	31%	35%	16%	14%	24%	18%
	Soil	-	22%	25%	44%	61%	59%	77%	79%	71%	77%
	TAQs*	-	407±132	455±148	400±115	308±132	305±131	347±119	317±96	275±84	309±164
Otama cedar forest	Leaf, branch	26%, 7%	11%, 3%	5%, 3%	1%, 1%	0.6%,	0.9%, 1%	-	0.3%,	-	0.3%,
	Bark	1%	0.8%	0.9%	0.3%	0.6%	0.5%	-	0.5%	-	0.4%
	Xylem	0.3%	0.3%	0.3%	0.3%	0.5%	0.5%	-	0.6%	-	0.4%
	Litter layer	42%	23%	26%	15%	11%	12%	-	5%	-	3%
	Soil	24%	63%	65%	82%	86%	85%	-	93%	-	95%
	TAQs*	106±19	93±36	97±27	98±31	105±34	74±17	-	65±9	-	74±24

*Unit: kBq/m2

5. Discussions

(1) Changes in air dose rate

The decrease in air dose rates from 2011 to 2012 was smaller than the physical decay of radioactive cesium, which was likely caused by the distribution of radioactive cesium in forests having moved from the forest canopy to the litter layer and soil surface at the forest floor. The air dose rates then reduced each year in a manner reflecting the physical decay. In some areas, the air dose rate in FY2020 showed almost no decrease compared to the previous year. Now that more than nine years have passed since the nuclear accident, factors other than the physical decay (e.g., climate conditions) may have an effect on the air dose rate.

(2) Changes in concentration and distribution by section

The radioactive cesium concentrations in leaves, branches and bark substantially decreased from 2011 over to 2012. The drop in the concentrations was likely caused by radioactive cesium having been washed out by rain, in addition to the physical decay of radioactive cesium. The relatively small changes in the concentrations from 2012 was probably due to the movement of such highly mobile radioactive cesium having settled down.

The decrease in the concentrations in the leaves of evergreen trees such as cedar and Japanese cypress may have been affected by falling of old leaves and continuous replacement by elongating new leaves, in addition to washout by rain. Meanwhile, the concentrations in the leaves of konara oak trees that repeat leafing and falling each year fluctuated in the range of 5,600-10,500 Bq/kg at Mitsuishi, without showing any clear trend in changes.

The radioactive cesium concentrations in branches are in a decreasing trend, but the decrease in the concentrations from 2014 is slower than that from 2011 to 2014 and no longer shows any clear trend in changes. The concentrations in bark also is in a decreasing trend, but the rate of decrease is smaller than that in the branches.

The radioactive cesium concentrations in xylem haven't changed much since 2011, indicating that radioactive cesium taken in immediately after the accident remains inside trees. The concentrations in sapwood are in a slight increasing trend for konara oak and Japanese cypress. It is possible that radioactive cesium is absorbed from tree roots. However, no apparent increase in the radioactive cesium concentrations has been observed in sections other than xylem, and therefore the amount of absorption is considered not large enough to significantly change the rate of radioactive cesium accumulation by site in the forest. As various studies have indicated that cesium migrates from sapwood to heartwood in cedar, the radioactive cesium concentrations in cedar heartwood were slightly higher than those in sapwood, in this year's survey also. The Forestry Agency intends to continue the survey to monitor absorption of radioactive cesium into trees and changes in the distribution inside trees.

At the Mitsuishi cedar forest, the radioactive cesium concentrations in the litter layer fell to less than half from 2011 over to 2012. In contrast, the radioactive cesium concentrations in the surface soil (0-5 cm) increased in 2012 as a result of the soil surface having retained radioactive cesium that was washed out and leached from trees and the litter layer. Since 2012, the concentrations in the litter layer had shown a decreasing trend at all monitoring sites, but the value in 2020 was higher than the previous year's value at some monitoring sites, exhibiting stagnation in the decreasing trend. No apparent trend in the change in the concentrations is observed for the surface soil (0-5 cm) from 2013. The radioactive cesium concentrations in soil layers deeper than 5 cm continue to be substantially lower than those in surface soil, and didn't show any clear changes although some minor increase or decrease was observed. From the above, it is considered that radioactive cesium mostly remains in the soil surface and penetration into deeper soil layers is not progressing significantly.

(3) Assessment of radioactive cesium distribution ratio and accumulated quantities for entire forest

The distribution ratio of radioactive cesium accumulated in forests by section reflected the changes in radioactive cesium concentrations. From 2011 to 2012, the distribution ratio in trees decreased while that in the litter layer and soil increased greatly. The distribution ratio in the litter layer is in a decreasing trend every year, but the distribution ratio in the litter layer varies forest to forest. In 2020, the ratio was low at 2% at the Mitsuishi cedar forest, while it was high at 43% at the Mitsuishi Japanese cypress forest. Further monitoring and studies are required to find why such a difference has occurred.

The accumulated quantities of radioactive cesium for the entire forest did not show any clear changes. Considering that the accumulated quantities in trees are only 6% or less, unevenness in the cesium distribution arising from variations in the concentrations and accumulated quantities of radioactive cesium in the litter layer and soil may have increased the errors in the estimation of the accumulated quantities for the entire forest. Although the estimation errors are large, because the accumulated quantities of radioactive cesium for the entire forest are not showing any apparent changes, it is likely that radioactive cesium settled into a forest remains in the forest while shifting its primary residence to the soil surface.

(4) Circulation of radioactive cesium in forest ecosystems

Studies related to the Chernobyl accident and other studies suggest that radioactive cesium remains in a forest ecosystem and some of it circulates within the ecosystem. Meanwhile, it is known that circulation of cesium is greatly affected by the type of trees and soil. From the surveys conducted to this year, back in 2011, radioactive cesium that fell from the sky after the Fukushima Dai-ichi NPS accident showed a difference in its concentrations by section, reflecting the differences in the type of trees, such as evergreen trees and deciduous trees. However, radioactive cesium is relatively easy to migrate, and the majority of radioactive cesium adhered to bark moved to the soil or the litter layer by 2012. After that, the ratio of radioactive cesium that was distributed in trees gradually fell, and the distribution ratio in the litter layer was also decreasing. Meanwhile, the distribution ratio in soil increased, albeit small in changes. Trees absorb radioactive cesium from soil via their roots. However, the changes in the radioactive cesium concentrations in xylem were small, and accurate absorption amount of cesium could not be estimated from the results of surveys conducted to this year, along with the changes in cesium distribution within trees. Still, the results of the surveys conducted to this year indicate that, in forests with an age of 40-50 years, the amount of radioactive cesium absorption and accumulation by trees into sapwood and heartwood used as timber is small.

Additionally, it is considered that fallout radioactive cesium remains in a forest and the amount of it released to outside areas is small, since little change is observed in the accumulated quantities of radioactive cesium for the entire forest and the large majority of radioactive cesium remains in the soil surface. This is supported by other relevant studies conducted concurrently, such as the study on radioactive cesium concentrations in mountain stream water.

Continuous monitoring surveys are warranted to understand the dynamics of radioactive cesium in forest ecosystems and apply the findings to measures for regeneration of forests and forestry.