6. Comprehensive study on migration of radionuclides

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6.1 Purpose of study

Previous experiences such as Chernobyl Nuclear Power Plant accident have confirmed that fallout radionuclides on the ground surface migrate through natural environment including soils and rivers. Therefore, in order to estimate future changes in radionuclide deposition, migration process of radionuclides in forests, soils, ground water, rivers, and entrainment from trees and soils should be confirmed. However, such comprehensive studies on migration through forests, soils, ground water and rivers have not been conducted so far. Thus, following comprehensive investigation was conducted to confirm migration of radionuclides through natural environment including soils and rivers at present. (The overview of this study is shown in Figure 6-1.)

(1) Migration study of radionuclides in natural environment including forests and rivers
   1) Study on depth distribution of radiocaesium in soils within forests, fields, and grassland
   2) Confirmation of radionuclide distribution and investigation on migration in forests
   3) Study on radionuclide migration due to soil erosion under different land use
   4) Measurement of radionuclides entrained from natural environment including forests and soils

(2) Migration study of radionuclides through hydrological cycle such as soil water, rivers, lakes and ponds, ground water
   1) Investigation on radionuclide migration through soil water, ground water, stream water, spring water under different land use
   2) Study on paddy-to-river transfer of radionuclides through suspended sediments
   3) Study on river-to-ocean transfer of radionuclides via suspended sediments
   4) Confirmation of radionuclide deposition in ponds and reservoirs

(3) Dynamic analysis of radionuclides in natural environment including atmosphere, soils and rivers

1) Confirmation of relationship between radionuclide deposition on soils and precipitation
2) Confirmation of relationship between radionuclides transferring from the surface soils and forests to atmosphere and aerosol
3) Confirmation of attachment of radionuclide in rainfall passing through forest canopies onto organic materials
4) Confirmation of chemistry of radiocaesium in suspended sediment in soils and rivers

6.2 Content of study

6.2.1 Summary of study

Summary of our investigation is as follows;

(1) Migration study of radionuclides in natural environment including forests and rivers

1) Study on depth distribution of radiocaesium in soils within forests, fields, and grassland

In order to clarify the differences in radionuclides under different natural environment and depth distribution of soil, soil samples were collected from the following 8 sites: forests (young Japanese cedar forest, mature Japanese cedar forest, and broad-leaved mixed forest), fields (tobacco field, farmland), paddy field, grassland (meadow) and pasture. Nuclide analysis of the samples was conducted. In addition, the results of the depth distribution of radiocaesium in soil investigated right after the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident and those of this study were compared, which confirmed changes in downward distribution of radiocaesium in soil.

2) Confirmation of radionuclide distribution and investigation on migration in forest

In order to study deposition on and migration within the forest environment of radionuclides released from the FDNPP, trends in aerial dose rate at different heights and deposition of radiocaesium on forest floor were studied in and outside the young cedar forest, mature cedar forest, and broad-leaved mixed forest using a portable germanium gamma-ray detector. Moreover, concentrations of radiocaesium deposited on leaves, throughfall, stemflow, fallen leaves were measured at different heights to investigate distribution and migration of radiocaesium in the forests.

3) Study on radionuclide migration due to soil erosion under different land use

To investigate migration of radionuclide due to soil erosion under different land use, 5 hilly spots were randomly chosen at mild hillslope on tobacco field, steep hillslope on farmland, meadow, pasture and young cedar forest. Together with stainless steel boards for making borders, triangular weirs for flow measurement and a sediment trap for retaining sediments were placed to measure the amount of sediment and radiocaesium discharge.

4) Measurement of radionuclides entrained from natural environment including forests and soils

In order to confirm the differences in resuspention process of fallout radionuclides from ground surface and forests to the atmosphere under different land use, 8 sampling sites of bare land (elementary school playground), fields (tobacco field, farmland), paddy field, meadow, pasture, young cedar forest and broad-leaved mixed forest were investigated, measuring the amount of entrained radiocaesium using air collectors.

(2) Migration study of radionuclides through hydrological cycle such as soil water, rivers, ponds and reservoirs, ground water

1) Investigation on radionuclide migration through soil water, ground water, stream water, spring water under different land use

To confirm migration and circulation process of radionuclides deposited on the ground surface with the hydrological cycling process of soil water, ground water, stream water and spring water, investigation was conducted on 6 sampling sites of pasture, grassland, meadow, farmland, young cedar forest and mature cedar forest. Soil water, ground water, stream water and spring water was collected from each sampling site to obtain data on distribution and migration of radiocaesium.

2) Study on paddy-to-river transfer of radionuclides through suspended sediments

To study migration of radionuclides transferring from catchments to rivers via paddy field farming, suspended sediments from two paddy fields with different farming, and radiocaesium concentrations in those sediments were measured.

3) Study on river-to-ocean transfer of radionuclides via suspended sediments

In order to clarify the flux of radionuclides from catchments to oceans via rivers, 6 points chosen from the Kuchibuto River and the lower Abukuma Main River were observed for water level and discharge. Together with the observation of soil discharge using suspension collectors, water was collected at the same spot and radiocaesium concentrations in the suspended sediments was measured.

4) Confirmation of radionuclide deposition in ponds and reservoirs

To confirm how the radionuclides discharged from rivers migrate to downstream ponds and reservoirs, lake sediment was collected using soil core samplers in 4 agricultural reservoirs (hereafter called “reservoir”) and a dam lake to confirm depth distribution of radiocaesium concentrations in the lake sediment.

(3) Dynamic analysis of radionuclides in natural environment including atmosphere, soils and rivers

1) Confirmation of relationship between radionuclide deposition on soils and precipitation

In order to confirm relationship between radionuclide deposition on soils and precipitation, radar AMeDAS data, rain gauge data (Japan Meteorological Agency, telemeter rainfall gauge at Ministry of Land, Infrastructure, Transport and Tourism, Fukushima University) and rain radar data at Fukushima University (x-band) were analyzed and compared with the precipitation time series and the rainfall pattern of Yamakiya district.

2) Confirmation of relationship between radionuclides transferring from the surface soils and forests to atmosphere and aerosol

To investigate what particle diameter of aerosol particles the radiocaesium dispersed from surface soils and forests to atmosphere attach to and resuspend from, entrained dust released from soils and forests were collected using air samplers. Radiocaesium concentration was measured and the attachment process of radiocaesium to aerosol was confirmed.

3) Confirmation of attachment of radionuclide in rainfall passing through forest canopies onto organic materials

To study how the radionuclides deposited on forests migrate through precipitation, rainfall passing through forest canopies (hereafter called "throughfall") was collected using throughfall samplers and stemflow samplers. By measuring plant-derived organic acids (formic, acetic, oxalic acids) and various kinds of inorganic ions, on what forest-plantation-derived organic materials the radiocaesium in throughfall and stemflow is deposited has been confirmed.

4) Confirmation of chemistry of radiocaesium in suspended sediments in soils and rivers

To reveal the chemistry of radiocaesium in the suspended sediments in soils and rivers, water solubility of radiocaesium in soils was probed, local structure of cesium in clay minerals was analyzed using x-ray absorption fine structure, and the distribution of radiocaesium in the soils and suspended sediments was confirmed.

6.2.2 Period of this study

In association with several laboratories including universities, studies were conducted to clarify migration process of radionuclides from forests to soils, to confirm soil distribution of radionuclides and their downward migration, to investigate migration process of radionuclides through hydrological cycles such as soil water, ground water and stream water, to reveal entrainment of radilnuclides from forests and soils under different land use, to confirm radionuclide discharge due to soil erosion, and to clarify radionuclide deposition in ponds, reservoirs and catchments. These studies were initiated on June 6 with the earliest placement of measuring devices and efforts were made to clarify the early migration process after the fallout of radionuclides. Every investigation continued until August 31.

6.2.3 Study sites

Considering that the results of this study will become important in understanding the effects of radionuclides on the environment and in offering basic data for residents in the planned evacuation zone to return to their hometown, study sites were chosen from Yamakiya district of Kawamata town, Date county in the catchment of the upstream Kuchibuto River supplied from the Abukuma River The sites are within the planned evacuation zone with relatively high amount of radionuclide deposition. Yamakiya district, as shown in Figure 6-2, is the place where more than 300 kBq/m^2 of Cs-137 inventory has been reported in the third airborne monitoring conducted by the Ministry of Education, Culture, Sports, Sciences and Technology (MEXT) and in the radionuclide analyses of 2,200 soil sampling points within 100km of the NPP and the surrounding areas within Fukushima prefecture. The Cs-137 deposition tended to show higher values when approaching to the northeast, marking approximately 1,000 kBq/m^2 near the Mizusakai area located in the east of Yamakiya district.

In this study, various investigations were conducted at the following places, with main sites in Yamakiya district.

(1) Migration study of radionuclides in natural environment including forests and rivers

1) Depth distribution of radiocaesium in soils within forests, fields, and grassland

Eight sampling sites were chosen from Kawamata town, Date county, Fukushima prefecture (farmland as in Figure 6-3(a)⑧, tobacco field Figure 6-3(a)⑩, meadow Figure 6-3(a)④, paddy field Figure 6-3(a)③, pasture Figure 6-3(a)⑥, mature Japanese cedar forest Figure 6-3(a)⑦, young Japanese cedar forest Figure 6-3(a)⑦, and broad-leaved mixed forest Figure 6-3 (a)②). In addition, soils in the site where preliminary survey was conducted on April 28, 2011 (Kotsunagi in Kawamata town as shown in Figure 6-3(b)⑫) was collected again to confirm difference among depth distribution of radiocaesium with time.

2) Confirmation of radionuclide distribution and investigation on migration in forest

One mature Japanese cedar forest of 40 - 50 years old (Figure 6-3(a)⑦) and one young Japanese cedar forest of 18 years old (Figure 6-3(a)⑦) representing coniferous forests, and one broad-leaved mixed forest with *Quercus Aliena* (Figure 6-3 (a)②) representing broad-leaved forest were chosen within Yamakiya district of Kawamata town. Towers (one tower of 8m, two towers of 12m) were built in each forest to study vertical distribution of radionuclides with heights.

3) Study on radionuclide migration by soil erosion under different land use

Within Yamakiya district of Kawamata town, mild slope on tobacco field (Figure 6-3(a)⑩), steep slope on farmland (Figure 6-3(a)⑧, grassland (Iboishi mountain Figure 6-3(a)⑪), pasture (Figure 6-3(a)⑥), and young cedar forest (Figure 6-3(a)⑦) were chosen as our sampling sites. At each site, stainless steel boards were placed within the USLE-standard plot (width: 5m, length 22.1m) established for confirming effects of soil erosion. Triangular weirs for flow measurement and tanks for retaining sediments were also set up at the end of downstream to measure sediment and radiocaesium discharge from the sites.

4) Measurement of radionuclides entrained from natural environment including forests and soils

Our sampling sites were chosen within Yamakiya district of Kawamata town: bare land (playground of Yamakiya elementary school, Figure 6-3(a)①), fields (Figure 6-3(a)⑧&⑩), paddy field (Figure 6-3(a)③), meadow (Iboishi Mountain, Figure 6-3(a)⑪) pasture (Figure 6-3(a)⑥), young cedar forest (Figure 6-3(a)⑦), and broad-leaved mixed forest (Figure 6-3(a)②). Total of 9 air samplers were placed at each site to measure resuspended amount of radionuclides deposited on soils. The Hi and Low signals in the figure show high and low volume samplers, respectively. (High volume samplers were used where power supply was available).

Furthermore, in order to conduct detailed observation of how the radiocaesim is entrained, resuspenended amount from the ground surface was measured by placing a set of meteorological instruments at Yamakiya elementary school (Figure 6-3(a)①), field (Figure 6-3(a)⑧) and young cedar forest (Figure 6-3(a)⑦).

(2) Migration study of radionuclides through hydrological cycle such as soil water, rivers, ponds and reservoirs, well water

1) Investigation on radionuclide migration through soil water, ground water, stream water, spring water under different land use

Pasture (Figure 6-3(a)⑥), meadow (Figure 6-3(a)④&⑪), mature cedar forest (Figure 6-3(a)⑦) and young cedar forest (Figure 6-3(a)⑦) within Yamakiya district of Kawamata town were selected as our study site. In Pasture and grassland, soil water, ground water(Figure 6-3(a)⑥&⑪), spring water (Figure 6-3(a)⑪alone) and stream water was collected, while soil water was collected in young and mature cedar forests to measure readiocaesium concentration.

2) Study on paddy-to-river transfer of radionuclides through suspended sediments

Two paddy fields (one of normal cultivation and one with surface soil scraped off: hereafter called "surface - scraped off paddy field) in Yamakiya district of Kawamata town were investigated (Figure 6-3(a)⑥). Partial flume flowmeters, turbidimeters and suspended sediment collectors were placed for a continuous measurement of suspended sediments running off from each field and radiocaesium concentration in those sediments.

3) Study on river-to-ocean transfer of radionuclides via suspended sediments

Kuchibuto River and its downstream Abukuma River were chosen as the study site. Since Kuchibuto River, which flows into Abukuma River, is an outlet of water and sediments from Yamakiya district, investigating its effect on environment is considered critical.

Therefore, total of 4 sites in the Kuchibuto River catchment (Figure 6-3(b) ㉑:Mizusakai River, ㉒Upstream Kuchibuto River, ㉓Midstream Kuchibuto River, ㉔Downstream Kuchibuto River) and 2 sites in Abukuma River (Figure 6-3(b)㉕: Abukuma River Fushiguro, ㉖Abukuma River Iwanuma) were selected. Flow was observed and water was collected using suspension collectors to investigate migration of radionuclides in rivers.

4) Confirmation of radionuclide deposition in ponds and reservoirs

In addition to the reservoir of Abukuma River, a reservoir in Nihonmatsu City was included in the study sites as the deposition of radionuclides was confirmed relatively large.

As a result, study sites were chosen from Horai dam lake in Abukuma River (Figure 6-3(b)㉛), 3 reservoirs in the catchment of Kuchibuto River (Figure 6-3(b): ㉝Nebbami pond, ㉞Oyado ㉟Takayashiki) and a reservoir in the catchment of Hirose River, Nihonmatsu City (Figure 6-3(b)㉜ Matsuzawa pond).

The contents of the investigation in each site are exhibited in Table 6-1.

6.3.1.2. Investigating distribution and migration of radionuclides in forests

(1) Purpose of this investigation

In order to confirm how the radionuclides released from the Fukushima Daiichi Nuclear Power Plant (FDNPP) was deposited on and migrated in forests, a study was conducted in Yamakiya district of Kawamata town, which is located in the northern part of Fukushima Prefecture. Young and mature cedar forests, broad-leaved mixed forests, and outside the forests were investigated to confirm a trend in aerial dose rate under different heights, and to measure radiocaesium deposition on the forest floor. In addition, radiocaesium concentrations in leaves, throughfall, stemflow, fallen leaves at different heights were measured to determine distribution and migration of radiocaesium in the forests.

(2) Description of the study

A portable germanium gamma-ray detector was used to confirm a trend of aerial dose rate under different heights in and out of the forests and to measure inventory of radiocaesium on the forest floor. Towers were also built to collect leaves of trees at different heights. Such leaves, together with the collected throughfall, stemflow, and fallen leaves, were studied to estimate distribution of radionuclides within the forests and migration of those with time. The details of the study were as follows:

① Study site
Our study site is located in Yamakiya district of Kawamata town in Fukushma Prefecture. Two coniferous forests including cedar, young and mature each, and one forest including *Quercus aliena* were chosen (Figure 6-11). According to the results of the third airborne monitoring survey conducted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the deposition of Cs-137 at the study area was 300 – 600 kBq/m^{2}.

② Distribution of radiocaesium on canopies
In order to confirm radiocaesium distribution in different forest types and heights of canopies, aerial dose rate and were measured on three different days (July 25, Sept. 9, Oct. 21, 2011), using a germanium gamma-ray detector at the towers placed for each study site. Measurements were conducted at 6

different heights from the ground surface to the height of 10.6 m (1.6 m, 4.2 m, 5.9 m, 7.7 m, 10.6 m) for the young cedar forest, at 9 heights from the ground surface to the height of 14.2 m (0.9m, 3.7m, 5.5m, 7.2m, 9.0m, 10.6m, 12.4 m, 14.2 m) for the mature cedar forest, and at 9 heights from the ground surface to the height of 13.9 m (0.6 m, 3.3 m, 5.1 m, 6.7 m, 8.5 m, 10.3 m, 12.0 m, 13.9 m) for the broad-leaved mixed forest. In addition, samples of both dead and fresh leaves on the trees were collected at the heights corresponding to those where aerial dose rate was measured by a portable germanium gamma-ray detector. Samples of those leaves were brought back to the laboratory, dried, fragmented to measure concentration of radiocaesium on dry weight basis using a germanium gamma-ray detector.

③ Distribution of radiocaesium on forest floor

In order to clarify the spatial distribution and the change in radiocaecium on the ground surface (forest floor) with time, a plot of approximately 10 m x 10m was selected in each forest, 49 spots within which were measured using a portable germanium gamma-ray detector to assess the inventory of radiocaesium on the ground surface. Those 49 spots were arranged in a grid of 7 x 7, with each spot marked with a plastic peg. The measurement of the radiocaesium inventories on the ground surface was conducted on three different days of July 25, Sept. 9, and Oct, 21, 2011. The germanium crystal of a portable gamma-ray detector and the ground surface are placed to have 5 cm distance with the measurement time of 1 minute for each spot.

④ Concentration of radiocaesium in rainwater

To collect throughfall in the forests, water collectors of 3 each were placed on open fields in the neighbor of the young cedar forest, the mature forest and the broad-leaved mixed forest. Seven throughfall collectors were arranged in each young and mature cedar forests, and 5 were placed in the broad-leaved mixed forest (Figure 6-12). As for the regularly planted cedar plantations, collectors of stemflow and throughfall were evenly placed to attain spatial balance.

With regard to stemflow, collectors of 3 each were installed to forest stands and the collected stemflow was guided into a 90-liter bucket (stemflow tank) as shown in Figure 6-12. Water captured in the water collectors and stemflow tank was measured and transferred to a 2-liter container. Then, those samples were brought back to the laboratory, sieved through a 100 μm stainless sieve to remove coarse particles mixed during the collecting process, and the concentration of radiocaesium was determined.

(3) Results

① Results on aerial dose rate and (gamma rays) of Cs-134 and Cs-137 at different heights in the forests

Figure 6-13 and 6-14 show the vertical distribution of the aerial dose rate and the Cs-134 and Cs-137 count rate in the forests and their changes in 3 different days. The young cypress forest showed the highest figures of aerial dose rate and Cs-134 andCs-137 count rate (cps) in the middle of the canopy, while the mature forest exhibited the highest in the upper canopy, with a decreasing trend as moving down towards the lower canopy and again showed an increasing trend near the ground surface. The broad-leaved mixed forest demonstrated an almost uniform value of both rates in the canopy, increasing the rates as moving down towards the ground surface.

The aerial dose rate and the count rate of Cs-134 andCs-137 were also measured at upslope and downslope for comparison. The result showed higher values in both rates at upslope even at the same height.

In addition, a comparison was made among three different days of measurement for each forest. In both young and mature cedar forests, the upper canopy showed decrease in the aerial dose rate and the count rate of Cs-134 and Cs-137 in September and October, while ground surface area exhibited no change or only a slight increase. As for broad-leaved mixed forest, it was confirmed that both aerial dose rate and count rate of Cs-134 and Cs-137 decreased with time in the canopy, while they increased near the ground surface area.

② Radiocaesium concentrations in leaves at different heights

Radiocaesium concentrations in fresh leaves on forest trees were studied using a germanium gamma-ray detector. (Figure 6-15)

- In the broad-leaved mixed forest, the mean radioactive concentration of Cs-134 in fresh leaves was 14.3 kBq/kg, while that of Cs-137 was confirmed 15.4 kBq/kg.

- In the young cedar forest, the average radioactive concentration of Cs-134 in fresh leaves was 42.8 kBq/kg, while that of Cs-137 was 50.9 kBq/kg. In the mature forest, the mean radioactive concentration of Cs-134 in fresh leaves was 39.6 kBq/kg, while that of Cs-137 was 46.3 kBq/kg.
- The result confirmed that the radiocaesium concentration in the fresh leaves of the cedar forests was approximately three times higher than that in the broad-leaved mixed forest.

Dead leaves in the cedar forests were also studied to measure radiocaesium concentrations.

- In the young cedar forest, the mean radioactive concentration of Cs-134 was 39.3 kBq/kg, while that of Cs-137 was 44.9 kBq/kg. In the mature forest, the average radioactive concentration of Cs-134 was 103.9 kBq/kg, while that of Cs-137 was 119.1 kBq/kg.
- As for the young cedar forest, not much difference in the radiocaesium concentration was observed between fresh and dead leaves. In the mature forest, however, the concentration in dead leaves was nearly twice the amount in fresh leaves at all measured heights.
- In both young and mature cedar forests, the radiocaesium concentration in the litter layer was nearly the same, approximately below 100 kBq/kg. On the other hand, the radiocaesium concentration in fresh leaves in the broad-leaved mixed forest was approximately below 40 kBq/kg at each height, while that in litter layer exhibited particularly high value of approximately 350 kBq/kg.

③ Results on studies of aerial dose rate at different heights outside the forest

Aerial dose rate at different heights was measured using a portable germanium gamma-ray detector placed in an aerial truck to determine the relationship between the aerial dose rate and the distance from the ground surface. Flat cultivated land with no forests in its 200 m neighborhood was chosen as a study site. As Figure 6-16 shows, the aerial dose rate decreased as the height increased until it reached 5 m from the ground surface, and remained almost constant at the height of 5 m and above.

④ Spatial distribution of radiocaesium on forest floor and its change with time

Figure 6-17 demonstrates the spatial distribution of radiocaesium on the floor of each forest. Outlined circles show the location of trunks and unfixed drawings express the contour lines of canopies.

It was confirmed that the count rate of radiocaesium measured under the canopies was lower than that at canopy openings (hereafter called "gap") in the young cedar forest. The count rate of radiocaesium in the gaps exhibited a decreasing trend, while that under the canopies showed an increasing trend when 3 different measurement days were compared.

The result for the mature cedar forest also confirmed that the count rate of radiocaesium measured under the canopy was lower than that in the gap. When three different days were compared, the overall count rate of radiocaesium showed an increasing trend, which was strongly observed under the canopy.

In the broad-leaved forest, the count rate of radiocaesium under the canopy was lower than that in the gap. Comparison among three days confirmed that the overall count rate of radiocaesium was in a decreasing trend.

⑤ Redistribution of radiocaesium in the forest

1) Results of the measurement of radiocaesium concentrations in the throughfall

Table 6-2 shows the radiocaesium concentrations calculated by averaging the weight of throughfall collected at 7 spots in each forest (only 5 in the broad-leaved mixed forest).

In the mature cedar forest, the radiocaesium concentrations in the throughfall collected by rainfall collectors during the period from July 3 to August 23 were 34.5 – 243.2 Bq/L for Cs-134 and 47.5 – 327.3 Bq/L for Cs-137.

In the young cedar forest, the radiocaesium concentrations in the throughfall ranged 14.8 – 145.4 Bq/L for Cs-134 and 17.0 – 183.8 Bq/L for Cs-137 as shown in Table 6-2.

For the broad-leaved mixed forest, the radiocaesium concentrations in the troughfall were found 8.1 – 67.0 Bq/L for Cs-134 and 12.2 – 86.2 Bq/L for Cs-137.

2) Results of measurement of radiocaesium concentrations in the throughfall and rainfall

Table 6-3 shows the weighted average of radiocaesium concentrations in the stemflow collected from three trees in each forest.

In the mature cedar forest, the radiocaesium concentrations in the stemflow collectors individually placed during the periods from July 3 to 23 and July 23 to August 19 were 27.4 Bq/L and 33.8 Bq/L for Cs-134 and 63.9 Bq/L and 83.2 Bq/L for Cs-137, respectively. In the young forest, the radiocaesium concentrations in the stemflow were 27.5 Bq/L and 29.7 Bq/L for Cs-134 and 42.1 Bq/L and 45.6 Bq/L for Cs-137, respectively. For the broad-leaved mixed forest, the radiocaesium concentrations in the stemflow were 10.5 Bq/L and 15.0 Bq/L for Cs-134 and 40.2 Bq/L and 44.4 Bq/L for Cs-137, respectively.

Moreover, Table 6-2 shows the weighted average of radiocaesium concentrations in the open rainfall collected at 3 spots in each forest. The Cs-137 concentrations in the rainfall collected with each collector were 0.34 – 0.76 Bq/L in the neighborhood of the cedar forests, and ranged 0.08 – 0.31 Bq/L near the broad-leaved mixed forest. Thus, it was confirmed that the radiocaesium concentrations in the open rainfall were approximately below 1 Bq/L, which was much lower than those in the throughfall.

In order to confirm a change in radiocaesium concentrations in throughfall due to intensive rainfall, the relationship between weekly throughfall and radiocaesium concentrations was studied. The result confirmed that the concentrations of radiocaesium in throughfall decreased with increased rainfall during a certain period as shown in Figure 6-18 (a). On the other hand, a clear correlation between rainfall and the total amount of radiocaesium in the throughfall was not found from the graph in Figure 6-18 (b).

3) Results of the measurement of radiocaesium concentrations in the litter

A nuclide analysis was conducted for the litters collected during the period from July 3 to 31 and from July 31 to August 19. In the mature cedar forest, the Cs-134 concentrations increased from 98 kBq/kg to 331 kBq/kg, while Cs-137 concentrations rose from 114 kBq/kg to 398 kBq/kg.

In the young forest, Cs-134 concentrations increased from 95 kBq/kg to 135 kBq/kg, while Cs-137 concentrations were 101 kBq/kg and 155 kBq/kg. As for the broad-leaved mixed forest, Cs-134 concentrations increased from 62 kBq/kg to 107 kBq/kg, while Cs-137 concentrations enlarged from 76 kBq/kg to 126 kBq/kg.

(4) Discussion

The results of this study demonstrate a certain process of radiocaesium migration within the forests in our model sites, though further study is required to confirm whether similar process exists or not in forests with different vegetation. This study is expected to be employed for decontaminating radionuclides in forests with similar vegetation cover.

The following shows the discussions on each result obtained by this study;

① Distribution of radiocaesium in forests with time

- As shown in Figure 6-15, fresh leaves that absorb radiocaesium together with nutrients and water through their roots and leaves exhibit similar or less radioactive concentration, compared to dead leaves without such absorption. At this moment, absorbed amount of radiocaesium through roots and leaves is considered to be extremely small in comparison with the deposited amount of radiocaesium on leaves.
- When ground surface is the only source of radiation, aerial dose rate normally decreases with height as demonstrated in Figure 6-13. In the cedar forests, however, aerial dose rate tends to increase as it goes closer to the canopy, due to a significant deposition of radiocaesium on the canopy as exhibited in Figure 6-15. For the broad-leaved mixed forest, the aerial dose rate increases as it goes closer to the ground surface. This is because the fallout radiocaesium released from the NPP right after the accident was not accumulated on the leaves, which were then in a growing period, but was directly deposited on the litter layer of the ground surface including fallen leaves, leading to a greater deposition of radiocaesium on the litter layer compared to those amount in the cedar forests.
- As indicated in Figure 6-17, it was clear that the inventory of radiocaesium in forest soils increases with time. The count rate of radiocaesium on the forest floor in both young and mature cedar forests increased with time, while that in the broad-leaved mixed forest decreased with time. The reason for this is that in the ever green cedar forests, most of the radiocaesium fallen in the forest is trapped in the canopy and then with the

precipitation afterwards, they are considered to migrate intermittently from the canopy to the forest floor. In the broad-leaved mixed forest, decreasing trend in the count rate of radiocaesium indicates that radiocaesium deposited on the litter layer has started to migrate deeper into the soil due to rainfall infirtration.

② Migration of radiocaesium within forests

- Given that the throughfall and stemflow contain a certain amount of radiocaesium, as visible in Table 6-2 and 6-3, the radiocaesium attached to the leaves and trunks, together with the trapped radiocaesium in the canopy was rinsed off by rain and is considered to be transferred to the forest floor. The higher radiocaesium concentration in throughfall compared to stemflow indicates that the accumulation of radiocaesium on the ground surface within the forests has increased mainly because the radiocaesium attached to the leaves has transferred to the forest floor through rainfall.
- As given in Figure 6-18, it was confirmed that total amount of radiocaesium in throughfall does not change significantly by the amount of rainfall in a certain period. Thus, it is considered that the transfer of radiocaesium may not be enhanced even though rainfall is heavy.

Based on these results, it is considered that the amount of radiocaesium accumulation in the cedar forest soils has been increasing with the deposition of fallen leaves and the transfer of deposited radiocaesium on leaves to the ground surface through rainfall.

In the broad-leaved mixed forest, it is indicated that the radiocaesium deposited on the uppermost layer (especially on the litter layer) has started to infiltrate downward due to an infiltration of rainwater and decay of organic matter. In order to quantify the radiocaesium distribution and migration process, it is suggested that throughfall and stemflow should be continuously monitored.

In addition, given that radiocaesium is greatly accumulated on litter layer in the broad-leaved mixed forest, removal of the litter layer was confirmed effective in reducing aerial dose rate in forests, taking an effect on ecosystem into consideration.

On the other hand, removing fresh and dead leaves was found effective in the cedar forests because the fresh and dead leaves near the canopy showed a high concentrations of radiocaesium. For the mature cedar forest, removal of litter layer is also effective as the accumulation of radiocaesium on the ground surface is higher compared to the young cedar forest and broad-leaved mixed forest.

6.3 Details of study

Methodology, results and discussion are as follows.

6.3.1.3. Migration study of radionuclides due to soil erosion under different land use

(1) Purpose of study

In order to confirm migration of radionuclides due to soil erosion under different land use, 5 hill hillslopes were randomly chosen on mild hillslope on tobacco field, steep hillslope on field, meadow, pasture and young cedar forest. The areas were bordered by stainless steel boards (herein after called "plot") with a triangular weir (flowmeter) and tank (sediment trap) placed in the downstream of the plot to measure sediment and radionuclide discharge.

(2) Details of study

① Content of study

The following investigation was conducted between June 5 to September 4 to confirm migration of radiocaesium due to sediment transfer in mild hillslope tobacco field, steep hillslope field, meadow, pasture and young cedar forest.

A) Study on radiocaesium migration

A triangular weir and water gauge was set at the outlet of each plot. Sediments accumulated in the triangular weir and the pool are collected once a week, brought back to our laboratory and dried. Then, radiocaesium concentrations in those sediments were measured using a gamma-ray germanium detector. (Shown in Figure 6-19)

B) Types of radiocaesium migration at each plot

Relationship between vegetation and sediment discharge, and radionuclide discharge was investigated and how differently radiocaesium migrate with sediments due to rainfall under different land use was examined.

② Study sites

Within Yamakiya district of Kawamata town, Date county, Fukushima prefecture, 5 places were selected as study sites: fields with different hill hillslopes (mild hillslope tobacco field and steep hillslope field), meadow, pasture and young cedar forest. Concentrations of radiocaesium in the discharged sediments at those sites were measured. The 5 sites where plots were placed are characterized as follows. (Figure 6-20)

- Mild hillslope tobacco field (herein after called "Field A") (Photo 6.8.1)

  The land, being uncultivated at the time of study, had been used to grow tobacco before the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident. The hillslope is mild and the soil is soft compared to other cultivated lands due to cultivation history. Since vegetation was abundant, the place had to be mowed every week to enhance sediment flow. (Vegetation is considerably little).

- Steep hillslope field (herein after called "Field B) (Photo 6.8.2)

  The land had been used as a field before the FDNPP accident, but the cultivated crops were unidentified. Now the land is uncultivated. The soil is clay and the foundation is highly stable. As the plot was relatively rich in vegetation, mowing was done once in two weeks. (Vegetation is little.)

- Meadow (herein after called "Pasture A") (Photo 6.8.3)

  Prior to the accident, grasses used for stock feed were cultivated in the land. Since grasses in the area are not allowed to be fed anymore, the land is now covered by weeds. With no entry of cattle or cars, soils are mildly undisturbed with thick root density. (Vegetation is rich.)

- Pasture (herein after called "Pasture B") (Photo 6.8.4)

  Having been pasture before the accident, opportunities of soil disturbance are abundant with scarce root density. Although vegetation was rich, the plot was mowed once a week to recreate pasture. (Vegetation is considerably rich.)

- Young cedar forest (Photo 6.8.5)

  Due to dense plantation of cedar, solar radiation is low with scarce vegetation on the forest floor. Litter supplied from the cedar leaves, however, is plenty. (Litter is abundant.)

(3) Result of study

The result of our study is shown in Table 6-5. In either plot of land under different use, radiocaesium discharge due to soil erosion during the study period of one and half month accounted for 0.008% (Pasture B) – 0.26% (Field A) of the radiocaesium inventory. Although the precipitation during the same period was approximately 260 mm within the normal range, radionuclide migration due to soil erosion was confirmed gentle.

In addition, when the accumulation of discharge water during the study period was compared as shown in Figure 6-21(a), the largest amount was observed in

Pasture A with the accumulation of 717 m^3/ha, followed by Field A (mild hillslope tobacco field) with 604 m^3/ha, Field B (steep hillslope field) with 372 m^3/ha, young cedar forest with 10m^3/ha and Pasture B with 5 m^3/ha.

Moreover, a comparison of runoff sediments tells us, as exhibited in Figure 6-21(b), that Field A (mild hillslope tobacco field) marked the highest figure of approximately 920 kg/ha, followed by Field B (steep hillslope field) with 265 kg/ha, Pasture A with 95 kg/ha and young cedar forest with 64kg/ha.

As demonstrated in Figure 6-22, when the radiocaesium discharged from each plot (herein after called "radionuclide discharge") was compared, Field A (mild hillslope tobacco field) came on top of the list with approximately 1.0 kBq/m^2 (10 MBq/ha) of Cs-134 and 1.2 kBq/m^2 (12 MBq/ha) of Cs-137. Field B (steep hillslope field) was second (Cs-134: 0.24 kBq/m^2 (2.4 MBq/ha), Cs-137: 0.28 kBq/m^2 (2.8 MBq/ha)), followed by young cedar forest (Cs-134: 0.13 kBq/m^2 (1.3 MBq/ha), Cs-137: 0.15 kBq/m^2 (1.5 MBq/ha)), Pasture A (Cs-134: 0.11 kBq/m^2 (1.1 MBq/ha), Cs-137: 0.13 kBq/m^2 (1.3 MBq/ha)), Pasture B (Cs-134: 0.07 kBq/m^2 (0.7 MBq/ha), Cs-137: 0.09 kBq/m^2 (0.9 MBq/ha)), and lastly paddy field of normal cultivation to be described later in 6.3.2.2 (Cs-134: 0.083 kBq/m^2 (0.83 MBq/ha), Cs-137: 0.087 kBq/m^2 (0.87 MBq/ha)). Except for the soil puddling period, the radionuclides discharged from the paddy fields was confirmed less than those from the fields.

Now, the discharge rate is calculated as follows: discharge amount was divided by the product of precipitation and the plot area (110.65 m^2:5 m x 22.13 m).

(4) Discussion

Table 6-6 shows the results of the studies mentioned above. According to the results, a clear difference was observed in discharged sediments and the radionuclide discharge among 5 study sites with different vegetation: fields with different hillslopes (mild hillslope tobacco field and steep hillslope field), meadow, pasture and young cedar forest. Radionuclide discharge was confirmed little in the sites with rich vegetation (Pasture A, Pasture B), which can be explained that grasses covering the soil surfaces is hindering the migration of radiocaesium. It was confirmed that vegetation has greater influence on radiocaesium discharge than gradient of slope.

On the other hand, in the young cedar forest, while vegetation of forest floor is scarce, litter is covering the soil surface, which is considered to be preventing discharge of sediments.

Migrated amount of radionuclides with sediment discharge during the study period remained approximately below 0.3% of the radiocaesium inventory of each study sight at the highest. Lal (1984) has reported that gully erosion occurs with intensive flow of water when slopes are long. Therefore, in order to confirm details of radionuclide migration due to soil erosion, continuous research and analysis of long slopes and migration of radionuclides including gully erosion is required.

【reference material】

Lal, R. (1984), Effects of slope length on runoff from alfisols in western Nigeria, Geoderma, 33, 181– 189.

6.4 Conclusion and suggestions for the future

In this study, migration of radionuclides in different natural environments including soils, ground water and river water was investigated together with monitoring entraiment process from trees and soils mainly in Yamakiya district of Kawamata town in Date county, Fukushima prefecture in a short period after the FDNPP accident.

Although comprehensive migration process is yet to be fully confirmed, we have come to a certain level of understanding regarding the initial migration of radionuclides in each environment. (Shown in Figure 6-47)

Among the results, migration of radionuclides to soil water, stream water and ground water was confirmed low at present. On the other hand, concentration of radiocaesium was found approximately 50 kBq/kg in the suspended sediments flowing down the river. As for these suspended sediments, it is essential to quantify absorption by organic materials which are easily transferrable in environment and by environmentally-stable clay minerals in grasping detailed migration process.

In addition, small particles of earth and sand which form suspended sediments are considered to originate from a downflow of diminutive soil particles to rivers by soil erosion. In this study, amount of sediments deposited in the tank placed at the end of downstream within the plot was confirmed together with the concentrations of radiocaesium. Extremely small soil particles, however, overflows the tank and those particles have not been quantified in this study. In addition, the scope of the study was limited. Therefore, while obtaining data on particles, it is essential in predicting migrated amount of radionuclides in wide area to investigate land use and landform, and to conduct quantitative analysis of radionuclide migration by applying soil erosion models. It is also of great importance to estimate future migration based upon those results.

In forests, on the other hand, distribution of radiocaesium was able to be confirmed to a certain extent by placing towers in the Japanese cedar forest and broad-leaved forest. To date, since a large amount of radiocaesium is considered to be found in coniferous tree canopies, these data are expected to be applied to future decontamination. Moreover, further investigation is necessary on the chemical state of radiocaesium which falls down to the forest floor as throughfall and on the actual condition of downward migration from forest floor to deeper soil layers.

As for the resuspension from soils and forests, the result showed that the amount was not so large as it was relatively humid during the study period. On the other hand, still many issues remain to be resolved including the change in the amount of resuspension during the dry season, the resuspension process of readionuclides through pollens, and the resuspension ratio of radionuclides into the atmosphere via entrainment of soils. Continuous monitoring on these issues is vital in the future.

Furthermore, resolving the chemical state of radionuclides is a crucial issue in elucidating the actual conditions of migration process on land and its future change. Studies on this issue should be continued to analyze migration process of radionuclides in the environment.