Radiation Monitoring in the Residential Environment: Time Dependencies of Air Dose Rate and $^{137}$Cs Inventory

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Background: Residential areas have some factors on the external exposure of residents, who usually spend a long time in these areas. Although various survey has been carried out by the government or the research institutions after the Fukushima Daiichi Nuclear Power Plant accident, the mechanism of radiocesium inventory in the terrestrial zone has not been cleared. To better evaluate the radiation environment, this study investigated the temporal changes in air dose rate and $^{137}$Cs inventories (Bq/m$^2$) in residential areas and agricultural fields.

Materials and Methods: Air dose rate and $^{137}$Cs inventories were investigated in residential areas located in an evacuation zone at 5–8 km from the Fukushima Daiichi Nuclear Power Plant. From December 2014 to September 2018, the air dose rate distribution was investigated through a walking survey (backpack survey), which was conducted by operators carrying a $\gamma$-ray detector on their backs. Additionally, from December 2014 to January 2021, the $^{137}$Cs inventories on paved and permeable grounds were also measured using a portable $\gamma$-ray detector.

Results and Discussion: In the areas where decontamination was not performed, the air dose rate decreased faster in residential areas than in agricultural fields. Moreover, the $^{137}$Cs inventory on paved surfaces decreased with time owing to the horizontal wash-off, while the $^{137}$Cs inventory on permeable surfaces decreased dramatically owing to the decontamination activities.

Conclusion: These findings suggest that the horizontal wash-off of $^{137}$Cs on paved surfaces facilitated the air dose rate decrease in residential areas to a greater extent compared with agricultural fields, in which the air dose rate decreased because of the vertical migration of $^{137}$Cs.

Results of this study can explain the faster environmental restoration in a residential environment reported by previous studies.

Keywords: Fukushima Daiichi Nuclear Power Plant Accident, Residential Area, Temporal Change, Air Dose Rate, $^{137}$Cs Inventory, Ground Characteristic

Introduction

The Japanese national project conducting the large-scale monitoring of air dose rate and radionuclide activity in extensive areas, particularly focused in areas within 80 km-radius of the Fukushima Daiichi Nuclear Power Plant (FDNPP), has been executed since the nuclear accident in 2011 [1–3]. This project has provided important information regarding the distribution and temporal changes in air dose rate and radionuclide activity. Conversely, the factors determining these distributions and temporal changes cannot be completely clarified using only large-scale monitoring results, because these
factors are affected by local characteristics such as topography and land use [3–5]. Therefore, a more detailed investigation considering the effects of field characteristics is required.

Even though most of the areas affected by the FDNPP accident are covered by forest, residential environments, which significantly affect public exposure compared to the forest owing to long spent-time by residents [6], were also affected owing to the deposition of radionuclides [4, 5]. Radiocesium, especially $^{137}$Cs, is a major source of radiation contributing to long-term exposure compared with other radionuclides released during the FDNPP accident [6, 7]. Therefore, current and future air dose rate distributions and $^{137}$Cs activity in the residential environment are serious concerns for the government and population.

Several studies after the FDNPP accident have reported that air dose rates decrease faster with time in residential environments than in environments with other land uses [3, 7, 8]. The residential environment consists of multimedia, such as pavements and buildings, in addition to permeable areas like agricultural and grass fields. Studies after the Chernobyl Nuclear Power Plant accident showed decreases in air dose rate and $^{137}$Cs inventory depending on the surface types; a faster decrease in air dose rate and $^{137}$Cs inventory was observed on paved surfaces compared with that in permeable grounds [9–11]. A faster decrease in $^{137}$Cs inventory on paved surfaces was also reported in areas near the FDNPP [12]. This difference in $^{137}$Cs behavior between the residential environment and environments with other land uses could result in differences in the time dependency of the air dose rate. However, this mechanism has not been elucidated yet. Therefore, detailed monitoring of $^{137}$Cs in relation to air dose rate in residential environments is required to better understand this mechanism and to obtain effective and practical information that can be applied to ensure radiation protection.

In this study, temporal changes in air dose rate and $^{137}$Cs inventory (Bq/m²) in a residential environment were evaluated to provide a better understanding of the factors affecting these changes. This investigation was based on monitoring the data corresponding to the areas affected by the FDNPP accident obtained from December 2014 to January 2021.

**Materials and Methods**

1. **Study Area**

This study was conducted in test sites (1–2 km²) of Okuma town and Tomioka town, located at distances of 5–8 km from the FDNPP (Fig. 1). Because the test sites are located in an evacuation zone, human activities including traffic are limited. The land uses in the test sites comprises residential areas

![Fig. 1](https://doi.org/10.14407/jrpr.2021.00199)
(61%), agricultural fields (31%), and others (8%) obtained from the land use data disclosed by National Land Numerical Information [14] using the geographic information system (GIS) (ArcMap. 10.6; ESRI Inc., Seoul, Korea).

2. Air Dose Rate

The air dose rate distribution at the height of 1 m above the ground level was measured using a second version of the Kyoto University Radiation Mapping (KURAMA-II) system equipped with a CsI(Tl) scintillation detector (C12137; Hamamatsu Photonics, Hamamatsu, Japan) and the GPS [15]. The air dose rate was estimated from the pulse height distribution obtained by the detector using a spectrum-dose conversion operator, G(E) function [16]. The operators carried the system on their backs during the survey and walked around the area. The data of air dose rate, time, and coordinates collected by the system at 3-second intervals were automatically stored in a server.

The surveys were conducted eight times from December 2014 to September 2018 (Table 1). To analyze the air dose rates corresponding to the different surveys, the data were averaged in each mesh area (100 m²), which was created according to the land use data [14] using the GIS.

3. Inventory of $^{137}$Cs

This study measured the $^{137}$Cs inventory on paved and permeable surfaces using a portable Ge $\gamma$-ray spectrometer (Falcon-5000; CANBERRA, Montigny-Le-Bretonneux, France) equipped with a cylindrical collimator (30-mm-thick Pb with a height and a diameter of 60 and 170 mm, respectively) [12]. The $\gamma$-rays emitted from the ground were measured at the height of 1 m above the ground for 30 minutes. Under the measurement conditions, more than 90% of the detected $\gamma$-rays were derived from a circular surface with a diameter of 4 m below the detector. An In-Situ Object Calibration Software (ISOCS, CANBERRA) was used for efficiency calibration of the $\gamma$-ray spectra. The relaxation mass depth ($\beta$, g/cm$^2$), representing the mass depth at which the radiocesium concentration is exponentially reduced to $1/e$ (Napier’s constant) of the concentration at ground level, is an essential parameter of the efficiency calibration. This study applied the $\beta$ of 0.1 g/cm$^2$ for paved surfaces. Conversely, the $\beta$ on permeable surfaces increases with time. Therefore, the $\beta$ on each investigation date was estimated from their time dependency reported by Nuclear Regulation Authority (NRA) [2]. The

| Investigation | Investigation date | Periods of investigation | Site numbers to measure the $^{137}$Cs inventory | $\beta$ |
|---------------|-------------------|--------------------------|-----------------------------------------------|--------|
| 1st           | December 16–18, 2014 | 3 | Decontaminated | 2.37 |
| 2nd           | September 29–October 8, 2015 | 6 | No decontamination | 2.66 |
| 3rd           | February 4–16, 2016 | 6 | Decontaminated | 2.79 |
| 4th           | October 11–19, 2016 | 8 | No decontamination | 3.04 |
| 5th           | January 30–February 2, 2017 | 8 | Decontaminated | 3.15 |
| 6th           | October 2–5, 2017 | 8 | No decontamination | 3.40 |
| 7th           | February 7–19, 2018 | 10 | Paved surfaces | 3.53 |
| 8th           | October 16–18, 2018 | 10 | Permeable surfaces | 3.78 |
| 9th           | January 21–24, 2019 | 10 | Paved surfaces | 3.88 |
| 10th          | September 9–10, 2020 | 11 | No decontamination | - |
| 11th          | January 19–24, 2021 | 11 | Permeable surfaces | - |

The site numbers on paved surfaces are shown for decontaminated site and no decontamination site, respectively. All of the investigated permeable surfaces were not affected by decontamination. The $\beta$ values applied to the spectral analysis for permeable surfaces are also shown. “Decontaminated” means paved surfaces decontaminated by high-pressure water washing and shot blasting, while the decontamination was not carried out on the paved surface of “No decontamination.” “Permeable surfaces” include abandoned agricultural fields and grasslands.
investigations were performed eleven times for paved surfaces and nine times for permeable surfaces from December 2014 to January 2021. The β applied to the spectral analysis for the permeable surfaces in each investigation was summarized in Table 2 with the investigation periods and site numbers of the measurement. The site numbers to measure the 137Cs inventory varied among the investigation because of the addition of measurement sites to increase the data number and discontinuance of the measurement on the sites under construction.

To analyze the data across measured surfaces with different deposition levels, the inventory was normalized by the initial deposition amount at each site. The initial deposition amount on November 5, 2011, was obtained from the result of the Fourth Airborne Monitoring Survey by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) [13] because the survey result is the earliest map data of 137Cs inventory covering the test site in this study.

**Results and Discussion**

1. **Decrease in the Air Dose Rate**

As an example of the time series of air dose rate distribution, the distribution map obtained in Okuma town is shown in Fig. 2. The air dose rate in most of the area was over 2.0 μSv/h in December 2014, and generally, decreased with time. Hous-

![Fig. 2. Time series of air dose rate distribution from December 2014 to September 2018 obtained by the backpack survey in Okuma town. The zones surrounded by broken lines indicate the areas that were decontaminated before each investigation (i.e., the lower-left area was decontaminated during December 2015 and December 2016, and the lower-right was decontaminated during December 2016 and September 2017). All of the area was included in the difficult-to-return zone. Land use obtained from National Land Numerical Information provided by the Ministry of Land, Infrastructure, Transport and Tourism [13] is also shown.

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es, roads, trees, and other permeable grounds in parts of the test sites were decontaminated four times before the surveys in December 2014, July 2016, December 2016, and September 2017. Overall, impermeable surfaces (such as building surfaces and asphalt roads) were decontaminated by manual removal of the surface sediments, wiping, brushing, high-pressure water washing, shot blasting, and scraping, depending on the decontamination efficiency [17, 18]. Decontamination of trees was performed by litter and surface soil removals, branch trimming, and trunk washing. Decontamination on permeable grounds was performed by topsoil stripping. The air dose rate in the decontaminated areas, including both residential areas and agricultural fields, clearly decreased compared with those observed in other areas, and most of the air dose rates reached values below 1.0 μSv/h in 2018. The obvious decrease in air dose rate after the decontamination was similarly found in Tomioka town.

The average and the range of the air dose rate observed in the entire test area and the decontaminated area are summarized in Table 3. The air dose rate average in the entire test area decreased from 3.8 to 1.3 μSv/h during the investigation period from December 2014 to September 2018. The average air dose rate in the decontaminated area was nearly half of that in the entire area in 2018.

Fig. 3 shows the temporal decrease in the air dose rates, represented as relative values with respect to the air dose rate obtained during the first investigation (December 2014) in both Okuma town and Tomioka town. The decreasing rates were 0.23 and 0.20 per year in residential areas and agricultural fields, respectively. The faster-decreasing rate in residential areas compared with agricultural fields was consistent with the results obtained in previous related studies [3, 7, 8]. Nakama et al. [19] monitored air dose rates on different surfaces (paved surfaces and permeable grounds) at 163 points using a NaI surveymeter for 4 years, beginning in 2012. According to this study, the decrease in air dose rate was statistically faster on paved surfaces (asphalt) compared with that on permeable grounds (plane soil ground). This difference in the decreasing trends between paved surfaces and permeable grounds can be the reason for the faster-decreasing rate in residential areas.

Decontamination was performed in residential areas mainly in 2016, while intensive decontamination in agricultural fields was conducted in 2017 in the test area. The decontaminations in 2016 and 2017 clearly reduced the air dose rate in both areas (Fig. 3). The relative air dose rates in both the de-

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**Table 3. The Average and the Range of Air Dose Rates Observed in the Whole Test Area and the Decontaminated Area**

| Investigation date   | Air dose in the whole test area | Air dose in the decontaminated area |
|----------------------|---------------------------------|-------------------------------------|
|                      | Average | Minimum | Maximum | Average | Minimum | Maximum |
| December 10, 2014    | 3.8     | 1.6     | 8.0     | 3.2     | 1.6     | 6.5     |
| September 15, 2015   | 3.2     | 1.3     | 7.1     | 2.6     | 1.3     | 5.1     |
| December 14, 2015    | 3.0     | 1.2     | 6.6     | 2.4     | 1.2     | 5.2     |
| July 26, 2016        | 2.5     | 0.7     | 6.2     | 1.7     | 0.7     | 4.8     |
| December 6, 2016     | 2.2     | 0.5     | 5.6     | 1.4     | 0.5     | 5.1     |
| September 5, 2017    | 1.7     | 0.3     | 4.8     | 0.9     | 0.3     | 2.1     |
| January 15, 2018     | 1.6     | 0.3     | 4.6     | 0.8     | 0.3     | 2.0     |
| September 12, 2018   | 1.3     | 0.2     | 3.8     | 0.7     | 0.2     | 1.6     |
contaminated residential areas and agricultural fields accounted for 57% and 46% of the values in the areas without decontamination in September 2018 (7.5 years after the accident), respectively. The residential areas showed slightly less decontamination efficiency compared with the agricultural fields, consistent with the decontamination efficiency reported so far [17, 18]. This difference in the decontamination efficiency can be attributed to the difference in the decontamination methods used on the distinct surfaces [20], and also the components of residential areas and agricultural fields. Regarding agricultural fields, most of the radiocesium deposited on the ground was retained on the surface soil and was easily removed by topsoil stripping. In contrast, paved surfaces, which represent the dominant surface in the residential areas, are usually decontaminated through brush cleaning, high-pressure washing, and shot blasting in the test area. Shot blasting is the most effective decontamination method to reduce the surface count rate among the methods mentioned above. However, the shot blasting reduces the surface count rate to 60%–95% of the initial value [18], implying that a certain proportion of radiocesium remains on the paved surfaces after decontamination. Additionally, the air dose rate in residential areas reflects not only the γ rays emitted from paved surfaces but also objects around the roads such as bushes and trees, of which the decontamination efficiency is usually small. Therefore, the difference in the decontamination methods and the area components can be the reason for the differences in decontamination efficiency between residential areas and agricultural fields.

### 2. Temporal Changes in the $^{137}$Cs Inventory

To confirm the effect of $^{137}$Cs migration on the decrease in the air dose rate, the $^{137}$Cs inventory (Bq/m²) on permeable and paved surfaces was monitored within the 2014–2021 period. The relative $^{137}$Cs inventory, which is a relative value to the initial $^{137}$Cs deposition amount on November 5, 2011 [13], and the initial $^{137}$Cs deposition amount are summarized in Tables 4–6. The initial $^{137}$Cs deposition amount ranged from 1,082 to 5,084 kBq/m². Fig. 4 shows the time dependency of the relative $^{137}$Cs inventory on each surface obtained in both

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### Table 4. Location, Initial $^{137}$Cs Inventory and Relative Inventory on Permeable Surfaces

| Site no. | Latitude | Longitude | Initial $^{137}$Cs inventory (kBq/m²) | Relative inventory (kBq/m²) |
|----------|----------|-----------|--------------------------------------|-----------------------------|
|          |          |           | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th |
| 1        | 37.369346 | 140.994855 | 2,347 | 1,039 | 1,184 | 1,154 | 1,119 | 1,071 | 1,037 | 1,061 | 1,089 | 1,148 |
| 2        | 37.367400 | 140.992927 | 1,518 | 1,044 | 1,151 | 1,138 | 1,144 | 1,128 | 1,065 | 1,079 | 1,055 | 1,084 |
| 3        | 37.364228 | 140.998419 | 1,488 | 1,206 | 1,327 | 1,338 | 1,215 | 1,214 | 1,154 | 1,172 | 1,181 | 1,208 |
| 4        | 37.360425 | 141.001120 | 1,575 | 1,402 | 1,513 | 1,459 | 1,287 | 1,226 | 1,176 | 1,155 | 1,181 | 1,181 |
| 5        | 37.364018 | 141.005711 | 1,819 | 1,187 | 1,280 | 1,187 | 0,941 | 0,937 | 1,094 | 1,093 | 1,125 | 1,135 |

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### Table 5. Location, Initial $^{137}$Cs Inventory and Relative Inventory on Paved Surfaces (No Decontamination)

| Site no. | Latitude | Longitude | Initial $^{137}$Cs inventory (kBq/m²) | Relative inventory (kBq/m²) |
|----------|----------|-----------|--------------------------------------|-----------------------------|
|          |          |           | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th | 10th | 11th |
| 1        | 37.403750 | 140.981691 | 2,770 | 0,297 |          |      |      |      |      |      |      |      |
| 2        | 37.404784 | 140.977262 | 3,051 | 0,266 |          |      |      |      |      |      |      |      |
| 3        | 37.369031 | 140.994949 | 1,769 | 0,584 | 0,604 | 0,557 | 0,497 | 0,480 |          |      |      |      |
| 4        | 37.399840 | 140.979629 | 2,313 | 0,273 | 0,250 | 0,242 | 0,229 | 0,231 | 0,189 | 0,174 | 0,175 | 0,165 |
| 5        | 37.405130 | 140.977285 | 3,087 | 0,338 | 0,298 | 0,299 | 0,297 | 0,292 | 0,268 | 0,244 | 0,251 | 0,248 | 0,162 | 0,156 |
| 6        | 37.407666 | 140.986642 | 2,827 | 0,425 | 0,423 | 0,388 | 0,345 | 0,351 | 0,347 |          |      |      |      |
| 7        | 37.403931 | 140.992739 | 2,910 | 0,148 | 0,148 | 0,121 | 0,117 | 0,106 | 0,103 |          |      |      |      |
| 8        | 37.367507 | 140.992877 | 1,525 | 0,401 | 0,342 | 0,337 | 0,343 | 0,336 | 0,170 | 0,149 | 0,139 | 0,142 |      |      |
| 9        | 37.362452 | 140.988713 | 1,501 | 0,297 | 0,251 | 0,248 | 0,231 | 0,229 | 0,204 | 0,185 | 0,188 | 0,184 |      |      |
| 10       | 37.360620 | 141.001394 | 1,590 | 0,266 | 0,213 | 0,210 | 0,185 | 0,182 | 0,153 | 0,140 | 0,137 | 0,129 |      |      |
| 11       | 37.365567 | 141.000293 | 1,680 | 0,220 | 0,210 | 0,167 | 0,159 | 0,147 | 0,123 |          |      |      |      |
| 12       | 37.397001 | 140.999036 | 2,786 | 0,084 | 0,081 |      |      |      |      |      |      |      |
| 13       | 37.394306 | 141.001931 | 2,892 | 0,123 | 0,120 |      |      |      |      |      |      |      |
| 14       | 37.365266 | 141.032211 | 1,967 | 0,094 | 0,077 |      |      |      |      |      |      |      |
| 15       | 37.412287 | 140.990820 | 4,059 | 0,162 | 0,178 |      |      |      |      |      |      |      |
Table 6. Location, Initial $^{137}$Cs Inventory and Relative Inventory on Paved Surfaces (Decontaminated)

| Site no. | Latitude | Longitude | Initial $^{137}$Cs Inventory (kBq/m$^2$) | Relative inventory (kBq/m$^2$) |
|----------|----------|-----------|--------------------------------------|---------------------------------|
|          |          |           | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th | 10th | 11th |
| 1        | 37.403750| 140.981691| 2,770 | 0.086 | 0.080 | 0.066 | 0.060 | 0.048 | 0.046 | 0.043 | 0.044 | 0.030 | 0.029 |
| 2        | 37.404784| 140.977262| 3,051 | 0.136 | 0.130 | 0.096 | 0.085 | 0.051 | 0.049 | 0.044 | 0.044 | 0.030 | 0.030 |
| 3        | 37.369031| 140.994949| 1,769 | 0.049 | 0.042 | 0.040 | 0.039 | 0.037 | 0.035 | 0.036 | 0.036 | 0.032 | 0.028 |
| 4        | 37.404751| 140.982427| 2,778 | 0.043 | 0.046 | 0.044 | 0.040 | 0.039 | 0.037 | 0.035 | 0.036 | 0.036 | 0.032 |
| 5        | 37.404291| 140.982046| 2,782 | 0.045 | 0.040 | 0.037 | 0.038 | 0.042 | 0.033 | 0.036 | 0.033 | 0.031 | 0.025 |
| 6        | 37.404139| 140.983287| 2,739 | 0.015 | 0.015 | 0.011 | 0.012 | 0.012 | 0.009 | 0.008 | 0.007 | 0.007 | 0.006 |
| 7        | 37.403565| 140.982542| 2,739 | 0.082 | 0.074 | 0.066 | 0.061 | 0.052 | 0.053 | 0.045 | 0.043 | 0.027 | 0.025 |
| 8        | 37.405409| 140.974407| 3,238 | 0.045 | 0.044 | 0.037 | 0.038 | 0.033 | 0.031 | 0.019 | 0.019 | 0.019 | 0.019 |
| 9        | 37.403077| 140.973397| 2,874 | 0.031 | 0.029 | 0.024 | 0.022 | 0.021 | 0.022 | 0.028 | 0.020 | 0.020 | 0.020 |
| 10       | 37.365611| 140.995727| 1,487 | 0.015 | 0.014 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 |
| 11       | 37.371611| 141.007217| 2,265 | 0.019 | 0.015 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 | 0.019 |
| 12       | 37.370471| 140.966849| 1,082 | 0.023 | 0.016 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 | 0.023 |
| 13       | 37.412491| 140.990643| 5,084 | 0.004 | 0.003 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |

The sites of number 1–3 correspond to those in Table 5.

Fig. 4. Temporal changes in $^{137}$Cs inventory relative to the initial deposition amount (i.e., November 5, 2011) obtained from the results of the Fourth Airborne Monitoring Survey conducted by the Ministry of Education, Culture, Sports, Science and Technology [12]. The error bars represent standard deviation.

Okuma town and Tomioka town. The relative inventories on permeable surfaces were close to 1 and varied throughout the investigation period; no clear trend of the inventory was observed. The $^{137}$Cs inventory variation on the permeable surface was probably a result of the variation on the site conditions (i.e., the water content in soil and vegetation) and surface soil agitation by animals. The minor temporal changes in the inventory on the plane permeable surface corresponded to the results of the long-term/extensive monitoring of the $^{137}$Cs inventory [21]. The negligible loss of radiocesium on permeable surfaces indicated that the decrease in the air dose rate in agricultural fields was mainly facilitated by the downward migration of radiocesium.

Conversely, paved surfaces showed a small relative inventory of less than 0.35 in December 2014 even without decontamination, and the value decreased with time reaching 0.12 in January 2021. The relative inventory on decontaminated paved surfaces exhibited small values, accounting for 10%–20% of the values on paved surfaces with no decontamination. Even after the decontamination, the relative inventory further decreased with time. These results demonstrate that large amounts of radiocesium deposited on the paved surface were removed by initial run-off followed by wash-off as a result of the precipitation in addition to the decontamination [12]. Because the radiocesium on paved surfaces remains at the top surface and does not show vertical migration with time [22, 23], the horizontal wash-off of radiocesium was identified as a major factor facilitating the decrease in the air dose rate on paved surfaces. Because the paved surface can be a major radiation source in residential areas, our results probably explain the faster environmental restoration in a residential environment reported so far.

Conclusion

This study demonstrated the different temporal changes in air dose rate and the differences in the decontamination effect on residential areas and agricultural fields. The difference in time dependency of air dose rate resulted from dif-
ferences in $^{137}$Cs migration and retention in permeable and paved surfaces. Therefore, the surface condition is an important factor affecting the environmental restoration associated with the $^{137}$Cs transfer in the residential environment.

**Conflict of Interest**

No potential conflict of interest relevant to this article was reported.

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**Author Contribution**

Investigation and methodology: Nakama S, Fujiwara K, Yoshimura K. Formal Analysis, Writing of the original draft, review and editing: Yoshimura K.

**References**

1. Saito K, Onda Y. Outline of the national mapping projects implemented after the Fukushima accident. J Environ Radioact. 2015;139:240–249.
2. Nuclear Regulation Authority. Report on radioactive substance distribution mapping project in FY2019 [Internet]. Tokyo, Japan: Nuclear Regulation Authority; 2020 [cited 2022 Feb 11]. Available from: https://radioactivity.nsr.go.jp/ja/list/579/list-1.html.
3. Saito K, Mikami S, Andoh M, Matsuda N, Kinase S, Tsuda S, et al. Summary of temporal changes in air dose rates and radionuclide deposition densities in the 80 km zone over five years after the Fukushima Nuclear Power Plant accident. J Environ Radioact. 2019;210:105878.
4. Onda Y, Taniguchi K, Yoshimura K, Kato H, Takahashi J, Wakiyama Y, et al. Radionuclides from the Fukushima Daiichi nuclear power plant in terrestrial systems. Nat Rev Earth Eviron. 2020;1(12):644–660.
5. Taniguchi K, Onda Y, Smith HG, Blake W, Yoshimura K, Yamasaki Y, et al. Transport and redistribution of radionuclides in Fukushima fallout from the power plant. Environ Sci Technol. 2019;53(21):12339–12347.
6. United Nations Scientific Committee on the Effects of Atomic Radiation. Sources and effects of risks of ionizing radiation (Volume 1). New York, NY: United Nations Scientific Committee on the Effects of Atomic Radiation; 2013.
7. Yoshimura K, Saegusa J, Sanada Y. Initial decrease in the ambient dose equivalent rate after the Fukushima accident and its difference from Chernobyl. Sci Rep. 2020;10(1):3859.
8. Andoh M, Mikami S, Tsuda S, Yoshida T, Matsuda N, Saito K. Decreasing trend of ambient dose equivalent rates over a wide area in eastern Japan until 2016 evaluated by car-borne surveys using KURAMA systems. J Environ Radioact. 2018;192:385–398.
9. Jacob P, Meckbach R. Measurements after the Chernobyl accident in relation to the exposure of an urban population (No. IAEA-TECDOC-1131). Wien, Austria: International Atomic Energy Agency; 2000. P. 34–41.
10. Andersson KG, Roed J, Fogh CL. Weathering of radiocaesium contamination on urban streets, walls and roofs. J Environ Radioact. 2002;62(1):49–60.
11. Golikov VY, Balonov MI, Jacob P. External exposure of the population living in areas of Russia contaminated due to the Chernobyl accident. Radiat Environ Biophys. 2002;41(3):185–193.
12. Yoshimura K, Saito K, Fujiwara K. Distribution of $^{137}$Cs on components in urban area four years after the Fukushima Dai-ichi Nuclear Power Plant accident. J Environ Radioact. 2017;178–179:48–54.
13. Ministry of Education, Culture, Sports, Science and Technology. Results of the Fourth Airborne Monitoring Survey by MEXT [Internet]. Tokyo, Japan: Ministry of Education, Culture, Sports, Science and Technology; 2011 [cited 2022 Feb 11]. Available from: https://radioactivity.nsr.go.jp/en/contents/4000/3179/24/1270_1216.pdf.
14. Ministry of Land, Infrastructure, Transport and Tourism. National land numerical information [Internet]. Tokyo, Japan: Ministry of Land, Infrastructure, Transport and Tourism; 2020 [cited 2022 Feb 11]. Available from: https://nlftp.mlit.go.jp/ksj/.
15. Andoh M, Nakahara Y, Tsuda S, Yoshida T, Matsuda N, Takahashi F, et al. Measurement of air dose rates over a wide area around the Fukushima Dai-ichi Nuclear Power Plant through a series of car-borne surveys. J Environ Radioact. 2015;139:266–280.
16. Tsuda S, Yoshida T, Tsutsumi M, Saito K. Characteristics and verification of a car-borne survey system for dose rates in air: KURAMA-II. J Environ Radioact. 2015;139:260–265.
17. Ministry of the Environment. Decontamination projects for radioactive contamination discharged by Tokyo Electric Power Company Fukushima Daiichi Nuclear Power Station Accident [Internet]. Tokyo, Japan: Ministry of the Environment; 2018 [cited 2022 Feb 11]. Available from: http://josen.env.go.jp/en/policy_document/pdf/decontamination_report1807_01.pdf.
18. Nakayama S, Kawase K, Iijima K, Miyahara K, Hardie S, McKinley I, et al. Remediation of contaminated areas in the aftermath of the accident at the Fukushima Daiichi Nuclear Power Station: overview, analysis and lessons learned. Part 2: Recent developments, supporting R&D and international discussions (No. JAEA-REVIEW-2014-052). Tokaimura, Japan: Japan Atomic En-
19. Nakama S, Yoshimura K, Fujiwara K, Ishikawa H, Iijima K. Temporal decrease in air dose rate in the sub-urban area affected by the Fukushima Dai-ichi Nuclear Power Plant accident during four years after decontamination works. J Environ Radioact. 2019; 208–209:106013.

20. Ministry of the Environment. Decontamination Guidelines 2nd ed. [Internet]. Tokyo, Japan: Ministry of the Environment; 2013 [cited 2022 Feb 11]. Available from: http://josen.env.go.jp/en/framework/pdf/decontamination_guidelines_2nd.pdf.

21. Mikami S, Maeyama T, Hoshide Y, Sakamoto R, Sato S, Okuda N, et al. Spatial distributions of radionuclides deposited onto ground soil around the Fukushima Dai-ichi Nuclear Power Plant and their temporal change until December 2012. J Environ Radioact. 2015;139:320–343.

22. Yoshimura K, Watanabe T, Kurikami H. Vertical and horizontal distributions of $^{137}$Cs on paved surfaces affected by the Fukushima Dai-ichi Nuclear Power Plant accident. J Environ Radioact. 2020;217:106213.

23. Andersson KG. Airborne radioactive contamination in inhabited areas. Amsterdam, Netherlands: Elsevier; 2009. p. 107-146.