HIROSAKI UNIVERSITY

Radiation Environment and Medicine 2023 Vol.12, No.1 37–52

REM
Radiat Environ Med

Review

Regional Case Studies: Environmental Radioactivity Levels and Estimated Radiation Exposure Doses of Residents and Workers in Areas Affected by the Fukushima Daiichi Nuclear Power Plant Accident

Yasuyuki Taira[1, 2]*, Masahiko Matsuo[1], Makiko Orita[1], Hitomi Matsunaga[1], Yuya Kashiwazaki[1], Xu Xiao[1], Shigekazu Hirao[3] and Noboru Takamura[1, 3]

[1]*Department of Global Health, Medicine and Welfare, Atomic Bomb Disease Institute, Nagasaki University, Nagasaki City, Nagasaki Prefecture, Japan*
[2]*Fukushima Global Medical Science Center and Radiation Medical Science Center for the Fukushima Health Management Survey Fukushima Medical University, Fukushima City, Fukushima Prefecture, Japan*
[3]*Institute of Environmental Radioactivity, Fukushima University, Fukushima City, Fukushima Prefecture, Japan*

Received 3 September 2022; revised 25 November 2022; accepted 6 December 2022

Nagasaki University established four satellite offices within a 30-km radius of the Fukushima Daiichi Nuclear Power Plant (FDNPP) in Japan's Fukushima Prefecture: in Kawauchi Village, Tomioka Town, Okuma Town, and Futaba Town. To evaluate the external and internal exposures attributable to the FDNPP accident, environmental radioactivity levels continue to be investigated at these sites. Our previous studies examined specific and regional case studies based on in-situ environmental radioactivity monitoring activities. Their findings suggested that current external and internal exposure doses of radiocesium have been controlled at the lower limit of the current "exposure situation" (1–20 mSv/y, International Commission on Radiological Protection) in the evacuation order-lifted areas of Kawauchi Village and Tomioka Town. However, conducting long-term follow-up studies, such as environmental radioactivity monitoring, developing countermeasures for further decontamination in the difficult-to-return zone, and implementing restrictions on the consumption of local foods, are all needed to reduce unnecessary radiation exposure to residents and workers, particularly since radiocesium derived from the FDNPP accident remains in some areas around the site. These case studies have clarified scientifically the temporal dose levels and aided in the development of environmental remediation measures that consider radiation exposure in the recovery and reconstruction process following the accident.

Key words: difficult-to-return zone, evacuation order-lifted areas, external exposure, Fukushima Daiichi Nuclear Power Plant accident, internal exposure, radiocesium

1. Introduction

More than 11 years have passed since the 9.0 magnitude Great East Japan Earthquake and subsequent tsunami and disaster at the Fukushima Daiichi Nuclear Power Plant (FDNPP), on March 11, 2011. As a result of the disaster, a variety of radionuclides were released into the atmosphere and deposited in the surrounding terrestrial

*Yasuyuki Taira: Department of Global Health, Medicine and Welfare, Atomic Bomb Disease Institute, Nagasaki University Graduate School of Biomedical Sciences 1-12-4 Sakamoto, Nagasaki City, Nagasaki Prefecture 852-8523, Japan
E-mail: y-taira@nagasaki-u.ac.jp
https://doi.org/10.51083/radiatenvironmed.12.1_37
Copyright © 2023 by Hirosaki University. All rights reserved.

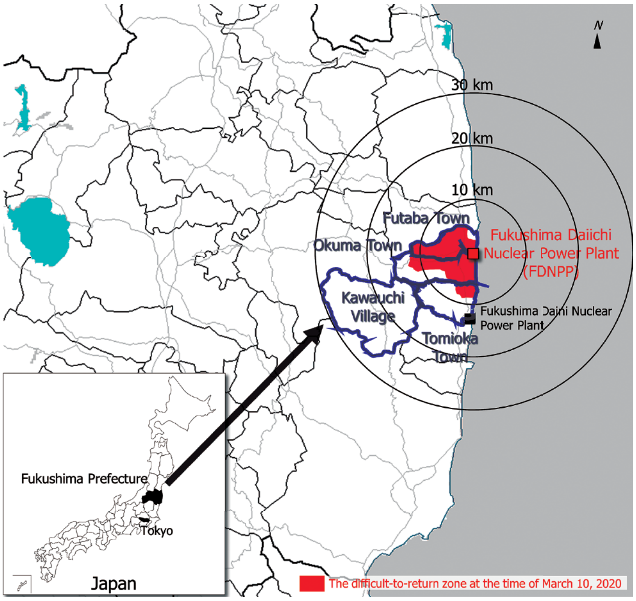

Fig. 1. Location of Nagasaki University satellite offices. The map was produced by the first author (YT) using Green Map III software (Tokyo Shoseki Co., Ltd., Tokyo, Japan; http://www.tokyo-shoseki.co.jp/company_english/philosophy.html) and reprinted under a CC BY license with permission from Tokyo Shoseki Co., Ltd.; original copyright 2003.

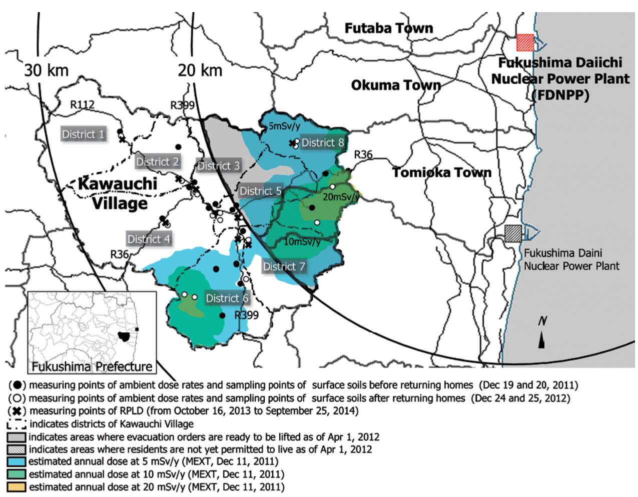

Fig. 2. Location of survey points in Kawauchi Village, Fukushima Prefecture. Closed circles (●) indicate measuring points for ambient dose rates and sampling points for surface soils (December 19–20, 2011). Open circles (○) indicate measuring points for ambient dose rates and sampling points for surface soils (December 24–25, 2012). Crosses (×) indicate measuring points for RPLD (from October 16, 2013 through September 25, 2014). Dashed lines indicate the districts of Kawauchi Village (Districts 1–8). Dark gray shading indicates areas where evacuation orders were lifted as of April 1, 2012. Light gray shading indicates areas where residents were not yet permitted to return, as of April 1, 2012 through March 31, 2013 (available: http://www.meti.go.jp/english/earthquake/nuclear/roadmap/; accessed January 24, 2014). Blue areas have an estimated annual dose of 5 mSv/y, green areas have an estimated annual dose of 10 mSv/y, and yellow areas have an estimated annual dose of 20 mSv/y, based on measuring data (MEXT, Dec 11, 2011). The map was produced by the first author (YT) using Green Map III software (Tokyo Shoseki Co., Ltd., Tokyo, Japan; http://www.tokyo-shoseki.co.jp/company_english/philosophy.html) and reprinted under a CC BY license with permission from Tokyo Shoseki Co., Ltd.; original copyright 2003.

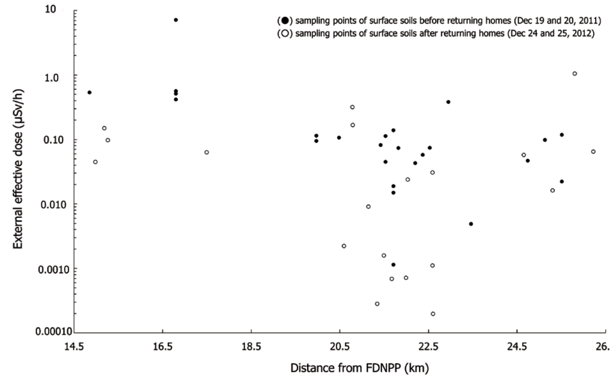

Fig. 3. Relationships among distances from the FDNPP and external dose rates at different sampling points. Open circles (○) indicate sampling points for surface soils after residents returned home (December 24 and 25, 2012). Closed circles (●) indicate sampling points for surface soils before residents returned home (December 19–20, 2011). The external effective doses from the soil samples were estimated from the radioactive fission product concentrations using the formula $H_{ext} = C \cdot D_{ext} \cdot f \cdot s$ where C is the activity concentration of the radiocesium [kBq/m^2, estimated from the radiocesium concentration in Bq/kg-dry including soil particles (<2 mm) and collected areas of surface soil (0.00182 m^2)]; and D_{ext} is the dose conversion coeffcient reported as the kerma-rate in the air 1 m above the ground, per unit activity per unit area [(μGy/h)/(kBq/m^2)], with the assumption that the kerma-rate in the air and the absorbed dose rate in the air are the same value for radiocesium, with the relaxation mass per unit area (β: g/cm^2) set to 3.0 due to the passage of less than two years since the FDNPP accident [3.3×10^{-3} (μGy/h)/(kBq/m^2) for ^{134}Cs and 1.3×10^{-3} (μGy/h)/(kBq/m^2) for ^{137}Cs, the International Commission on Radiation Units and Measurements (ICRU) 1994]; f is the unit conversion coeffcient (0.7 Sv/Gy for the effective dose rate in the body per unit of the absorbed dose rate in air); and s is the occupancy-shielding factor (0.36 for the public; 0.2 fractional time outdoors + 0.8 fractional time indoors × 0.2 building shielding).

and marine environments[1]. Subsequently, international institutes and academic institutions, as well as national and municipal governments, have published numerous reports and developed databases and websites related to the disaster. Nagasaki University, which has investigated specific and local cases regarding the environmental contamination and radiation exposure doses, currently administers four satellite offices in areas located within a 30-km radius of the FDNPP: Kawauchi Village (opened in April 2013), Tomioka Town (September 2016), Okuma Town (July 2020), and Futaba Town (December 2021) (Fig. 1)[2]. Based on agreements with the four municipalities, Nagasaki University has conducted environmental radioactivity surveys to investigate issues related to external radiation exposure, including residents' radiation doses; internal radiation exposure, such as exposure through the consumption of local foods and/or the inhalation of airborne dust; and educating the public about protection measures against ionizing radiation[3]. Our previous studies evaluated the status of environmental contamination in Kawauchi Village and Tomioka Town, which are within 30 km and 20 km of the FDNPP, respectively, and estimated the radiation exposure doses due to artificial radionuclides, such as radiocesium, among residents immediately before and after returning to their homes.

2. Environmental radioactivity monitoring in Kawauchi Village

2.1. Immediately before and after returning home, 2011–2013

Six months after the FDNPP accident, designated emergency evacuation preparation zones within a 20–30-km radius of the FDNPP were lifted, as levels of environmental radioactivity had decreased due to the decay of short-lived radionuclides, such as iodine-131 (^{131}I, half-life: 8.0 d) and efforts by the national government to remediate contaminated soils[4-5]. In addition, by December 2011, the Japanese government announced that the FDNPP's reactors had been stabilized and successfully brought to a condition equivalent to a "cold shutdown[6]." Kawauchi Village, which is located within 30 km of the plant, was the site of several restricted areas at that time. In January 2012, the mayor declared that residents could safely return home, because radiation doses were lower than those in other areas around the plant. Although residents hoped that their return at that time would be permanent, the environmental contamination and estimated exposure doses during the initial phase of the accident, including radiation health risks due to returning, had not been sufficiently reported.

First, the concentration of artificial radionuclides in environmental samples, such as those taken from soils, tree needles, and local foods (e.g., wild mushrooms), were analyzed using gamma spectrometry with a high purity germanium detector coupled to a multi-channel analyzer for 7,200–72,000 s. The purpose of these analyses was to evaluate the extent of environmental contamination and radiation exposure dose rates from the artificial radionuclides in Kawauchi Village (Fig. 2)[7]. In this case, the prevalent dose-forming artificial radionuclides from all samples were determined to be radiocesium ($^{134+137}Cs$). An investigation conducted nine months after the accident, but before residents were allowed to return, revealed that the estimated external effective doses from surface soils in December 2011 were 0.42–7.2 μSv/h (equivalent to 3.7–63.0 mSv/y, in the case of staying outdoors all day long (24 h×365 d) at 1 m above the ground under typical land conditions; the same applies to the rest of this paragraph), and that ambient dose rates were >2.3 μSv/h in areas within a 20-km radius of the FDNPP. In addition, the estimated external effective doses from surface soils in December 2011 were 0.0011–0.38 μSv/h (0.010–3.3 mSv/y), while the ambient dose rates were 0.18–1.8 μSv/h in areas within 20–30 km of the plant (Fig. 3)[7]. Investigations conducted to find the external effective doses from soils collected in December 2012 found 0.045–0.15 μSv/h (0.39–1.3 mSv/y) and ambient dose rates of 0.41–1.5 μSv/h within a 20-km radius of the FDNPP, and 0.00020–1.1 μSv/h (0.0017–9.2 mSv/y) and 0.12–2.9 μSv/h within a 20–30-km radius of the plant (Fig. 3)[8]. Thus, compared to the radiocesium levels just prior to the residents' return in December 2011 (median: 0.85 (0.40–1.4) mSv/y), radiocesium levels appeared to be decreasing, irrespective of the distance from the plant (median: 0.21 (0.012–0.56) mSv/y) (Fig. 3)[7-8].

The activity concentrations of artificial radionuclides ($^{134+137}Cs$) were also analyzed in 2,654 samples of common local food items (i.e., vegetables, edible wild plants and mushrooms, and fruits) produced and/or collected in Kawauchi Village between May 2012 and March 2013. Radionuclide concentrations were measured using an NaI detector coupled with a multichannel analyzer for 1,800 s[8]. Samples exceeding the radiocesium regulatory limit (100 Bq/kg for general foods) included 5 of 1,358 (0.4%) vegetables; 307 of 737 (41.7%) wild plant and mushroom samples (mainly mushrooms); and 4 of 256 (1.6%) fruit samples. The radiocesium levels in the vegetables, edible wild plants, mushrooms, and fruits in Kawauchi Village showed a wide range in all seasons, especially in edible wild mushrooms, which ranged from <20–3,472 Bq/kg for ^{134}Cs and <23–5,833 Bq/kg for ^{137}Cs in autumn[8]. The committed effective doses from the local food samples were sufficiently low, ranging from 18–48 μSv for children and 25–43 μSv for adults (18–44 μSv for males and 20–48 μSv for females), compared to the public dose limit (1 mSv/y) (International Commission on Radiological Protection (ICRP), 1991), although the potential for radiation exposure still exists (Fig. 4)[8].

These findings suggested that residents could safely return to their homes, provided they engaged with long-term follow-up via environmental monitoring and countermeasures to reduce unnecessary radiation exposure[7-8]. Although the case of Kawauchi Village was the first model for residents returning to their homes after the accident, the external and internal exposure doses due to residents' daily activities remains a matter of considerable public interest, and the timely dissemination of scientific findings to the public is considered extremely important.

2.2. After returning home in 2013–2015

Despite the decontamination of areas around the FDNPP and the homes of returning residents, radiocesium with a long half-life was still present in environmental samples, such as soils, plants, and local foods (e.g., agricultural products). In particular, residents were most concerned about the internal radiation exposure doses associated

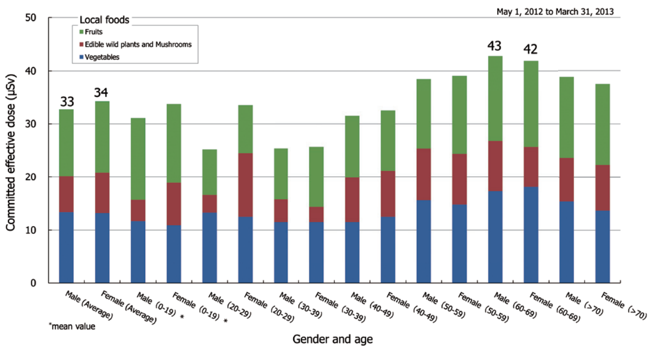

Fig. 4. Committed effective doses due to radiocesium in Kawauchi Village, Fukushima Prefecture, May 1, 2012 through March 31, 2013. The internal effective doses (committed effective doses) from vegetables, edible wild plants and mushrooms, and fruit samples were estimated from the radioactive fission product concentrations using the formula $H_{int} = C{\cdot}D_{int}{\cdot}e$ where C is the median radiocesium concentration (Bq/kg-fresh); D_{int} is the dose conversion coefficient for child intake (age: 0–19, 1.3×10^{-5} to 3.0×10^{-5} mSv/Bq for ^{134}Cs and 9.6×10^{-6} to 2.2×10^{-5} mSv/Bq for ^{137}Cs) and for adult intake (age: >20, 1.9×10^{-5} mSv/Bq for ^{134}Cs and 1.4×10^{-5} mSv/Bq for ^{137}Cs), based on the ICRP Publication 67; and e is quoted from the average daily intake data (g/d) for age, sex, and season in areas around the FDNPP issued by the Environmental Radioactivity Monitoring Center of Fukushima, Fukushima Prefecture, Japan in 2009–2010. To calculate the committed effective doses, the undetected data (N.D.) of the radiocesium was defined as follows:
1) In the case of "N.D. >80%", the value corresponding to N.D. is 5 Bq/kg (2.5 Bq/kg for ^{134}Cs and 2.5 Bq/kg for ^{137}Cs), one-fourth of the detection limit (20 Bq/kg).
2) In the case of "80% ≥ N.D. >60%", the value corresponding to N.D. is 10 Bq/kg (5 Bq/kg for ^{134}Cs and 5 Bq/kg for ^{137}Cs), half of the detection limit (20 Bq/kg).
3) In case of "N.D. ≤60%", the value corresponding to N.D. is 20 Bq/kg (10 Bq/kg for ^{134}Cs and 10 Bq/kg for ^{137}Cs), the detection limit (20 Bq/kg).
Values were based on the Global Environment Monitoring System-Food Contamination Monitoring and Assessment Programme (GEMS/Food) administered by the World Health Organization (WHO) and the new standard limits for radionuclides in food established by the Ministry of Health, Labour, and Welfare in Japan (MHLW). In this study, vegetables, edible wild plants and mushrooms, and fruit samples (main agricultural products) have been selected to calculate the committed effective doses because these samples are frequently consumed and are assumed to be well suited for estimating potential internal exposure. The asterisk indicates the mean value of committed internal doses for child intake.

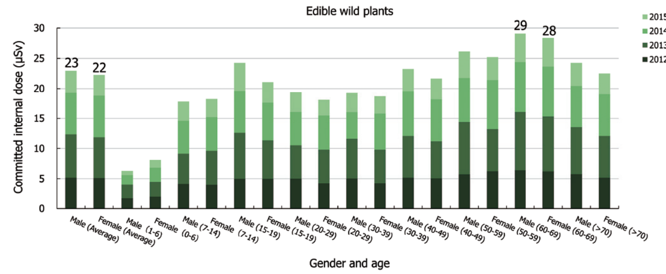

Fig. 5. Committed internal doses attributable to the intake of edible wild plants collected in Kawauchi Village, Fukushima Prefecture between 2012 and 2015. The internal effective doses (estimated effective doses) from edible wild plants were estimated from the radioactive fission product concentrations using the formula $H_{int} = C{\cdot}D_{int}{\cdot}e$ where C is the radiocesium concentration (the median value of 12 varieties of edible wild plants) (Bq/kg-fresh); D_{int} is the dose conversion coefficient for child intake (age: 0–18 years, 1.3×10^{-5} to 2.6×10^{-5} mSv/Bq for ^{134}Cs and 9.6×10^{-6} to 2.1×10^{-5} mSv/Bq for ^{137}Cs) and for adult intake (age: >19 years, 1.9×10^{-5} mSv/Bq for ^{134}Cs and 1.3×10^{-5} mSv/Bq for ^{137}Cs), based on ICRP Publication 72; and e is quoted from the median value of daily intake data (g/man/d) for age and sex, as issued by the MHLW, Japan in 2015. To calculate the committed effective doses, the undetected data (N.D.) of the radiocesium were defined based on GEMS/Food published by the WHO and the new standard limits for radionuclides in food by the MHLW (Fig. 4).

with ingesting local foods during their activities of daily living. A follow-up study was conducted to measure the radiocesium concentrations in 7,668 local foods, including vegetables, edible wild plants, mushrooms, and fruits produced and/or collected in Kawauchi Village between April 2013 and December 2014[9]. The number of samples exceeding the regulatory limit for radiocesium (100 Bq/kg for general foods) was 5 of 4,080 (0.1%) vegetables; 652 of 1,986 (32.8%) edible wild plants and mushrooms; and 8 of 647 (1.2%) fruits. The radiocesium concentrations of all samples varied markedly among seasons. For example, in the autumn, the concentrations of radiocesium in edible wild plants and mushrooms ranged from <20–2,754 Bq/kg for ^{134}Cs and <23–8,487 Bq/kg for ^{137}Cs. The committed effective doses from the local food samples were generally low, ranging from 2.5–12 μSv for male children and 3.0–15 μSv for female children (24–43 μSv for all males and 22–43 μSv for all females). This suggested that the internal radiation doses associated with ingesting these foods were acceptably low, compared to the public dose limit (1 mSv/y). In other words, the internal exposure doses for radiocesium were changing at low levels, even after residents returned home to Kawauchi Village.

The customs of residents, especially the *satoyama* (countryside) culture of harvesting *sansai* (edible wild plants) and mushrooms, also need to be considered in the reconstruction of areas affected by the disaster, such as Kawauchi Village. The range of mushrooms collected in Kawauchi Village is relatively broad; for example, 154 mushrooms belonging to 22 species were collected between September and November 2013, 81 mushrooms of only one species (*Sarcodon aspratus*) were collected between September and November 2014, and 159 mushrooms belonging to 23 species were collected between September and November 2015. Radiocesium concentrations >100 Bq/kg were detected in 125 of 154 mushrooms (81.2%) collected in 2013 and in 123 of 159 mushrooms (77.4%) collected in 2015. However, the committed effective doses were relatively limited, ranging from 0.11–1.6 mSv in 2013 and <0.001–0.6 mSv in 2015, with no differences observed in the concentrations of ^{137}Cs between 2014 and 2015 ($p = 0.45$)[10-11]. Based on surveys of local food consumption in Kawauchi Village (screening

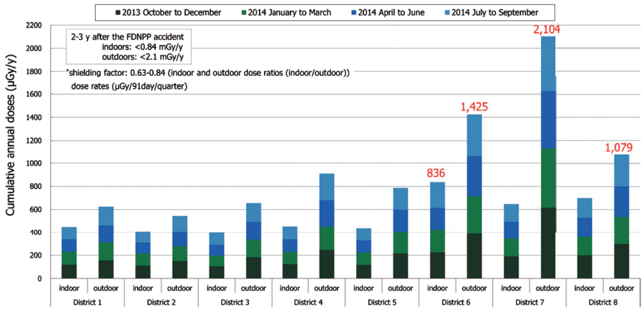

Fig. 6. Accumulated radiation dose rates in assembly halls in Kawauchi Village, Fukushima Prefecture, October 2013 through September 2014. Values are the cumulative annual doses of the 91-day conversion for each quarter (μGy/91 d/quarter).

against the standard limit of 100 Bq/kg radiocesium for general foods), the radiocesium concentrations of several edible wild plant species, such as *Eleutherococcus sciadophylloides* (koshiabura), *Aralia elata* (taranome), and *Osmunda japonica* (zenmai), also exceeded standard limits; consequently, the consumption of these plant and mushroom species should be avoided[12]. Moreover, it was clear that the internal exposure doses depended on the dietary habits of the consumers and the species of plants consumed, with some age groups (≥50 years) ingesting larger doses than others (<40 years)[10]. Nevertheless, it was estimated that total internal doses were significantly lower than the recommended public dose limit (1 mSv/y) (Fig. 5)[12]. In short, radiocesium concentrations remained at extremely low levels between 2012 and 2015[12]. The monitoring system used for local foods has worked effectively in this area, and the internal exposure risk could be strictly controlled.

In contrast to the above, when evaluating external exposure in areas frequented by residents, such in living spaces (e.g., assembly halls), over the long term, passive dosimeters, including thermoluminescent dosimeters, optically stimulated luminescent dosimeters, and radiophotoluminescence dosimeters (RPLD), were used to estimate the dose rates in the environment and/or for a variety of wildlife under field conditions, as these dosimeters could simply be placed in the environment. RPLDs have also been used in field studies to determine the exposure dose rates of soil biota in the Chernobyl Exclusion Zone and to estimate external absorbed dose rates in rodents and amphibians in contaminated areas around the FDNPP[13-14]. The external radiation doses in living spaces (e.g., assembly halls in Districts 1–8 of Kawauchi Village) were measured using RPLDs between October 2013 and September 2014 to evaluate a long-term radiation dose rates during the village's reconstruction (Fig. 2)[15]. Although radiation doses decreased temporarily during the winter (December 2013 through March 2014) and the shielding coefficient varied by 0.63–0.84, other than the shielding effect of snow accumulation and one-story wooden houses, it was unclear what contributed to the seasonal fluctuations (Fig. 6)[15]. Actually, in Districts 1–5, the cumulative annual radiation dose rates were stable, at <1 mGy/y (Fig. 6)[15]. Conversely, in Districts 6–8, the cumulative annual radiation dose rates were >1 mGy/y outdoors (Fig. 6)[15]. These findings suggested that radiocesium remains present in residential areas' vicinities, such as forests (Fig. 6). Following the FDNPP accident, the residential areas, farmlands, and forests close to residential areas (<20 m) and roads within the evacuation order areas around the plant were extensively decontaminated using appropriate methods. However, the decontamination of boundary areas, including those 20 m away from living spaces and back yards with overgrown plants, may have been limited (Fig. 2). Nevertheless, the median individual dose was 1.4 (0.71–3.3) mSv/y, even in Kawauchi Village's evacuation order area (i.e., within a 20-km radius of the FDNPP), and the cumulative individual doses were lower than those estimated based on ambient doses (data not shown)[16]. These findings suggest that the discrepancy between the cumulative individual doses and those estimated from ambient doses was mainly due to variations in residents' daily lives; the differing shield-rates of houses; and dosimeter characteristics, such as the directional dependency of the irradiation angle[16]. Furthermore, external effective dose levels were continually decreasing due to the decay of artificial radionuclides and the decontamination of contaminated soil[16-17]. Finally, current estimates indicated that the external and internal exposure doses in Kawauchi Village due to artificial radionuclides (radiocesium) derived from the FDNPP accident were equivalent to the public dose limit and/or were sufficiently lower than the upper value of the reference level for existing exposure situations (20 mSv/y), as determined by the ICRP.

3. Environmental radioactivity monitoring in Tomioka Town

3.1. Before returning home, 2013–2016

In preparation for residents' return to Tomioka Town, temporary visits and residential stays were permitted from September 17, 2016 through March 31, 2017; however, some residents remained anxious about radiation exposure due to the FDNPP accident. Indeed, the size of the "difficult-to-return" zone, where the integrated dose rates exceeded 50 mSv/y as of March 2012, accounted for approximately 12% (8.5 km^2) of the town's total area (Fig. 7). As previously mentioned, Nagasaki University established four satellite offices in areas around the FDNPP to support the recovery efforts in cooperation with residents and municipal

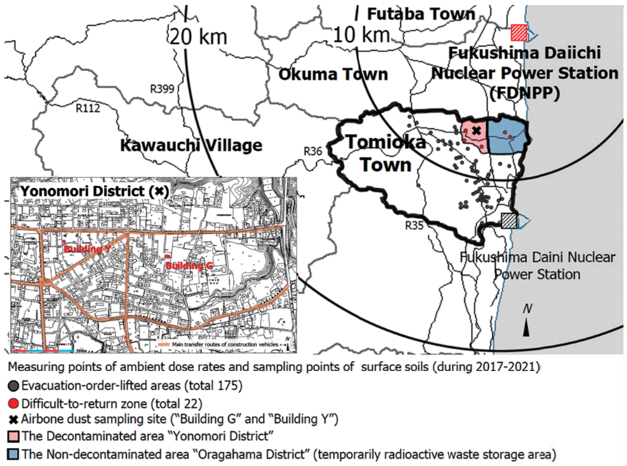

Fig. 7. Location of survey points in Tomioka Town, Fukushima Prefecture. Black and red dots show the measuring points of ambient dose rates and sampling points of surface soils in the evacuation order-lifted area and difficult-to-return zone, respectively. The cross shows the sampling site for airborne dust (i.e., Buildings G and Y) in the Yonomori district of Tomioka Town. The map was produced by the first author (YT) using Green Map III software (Tokyo Shoseki Co., Ltd., Tokyo, Japan; http://www.tokyo-shoseki.co.jp/company_english/philosophy.html) and reprinted under a CC BY license with permission from Tokyo Shoseki Co., Ltd.; original copyright 2003.

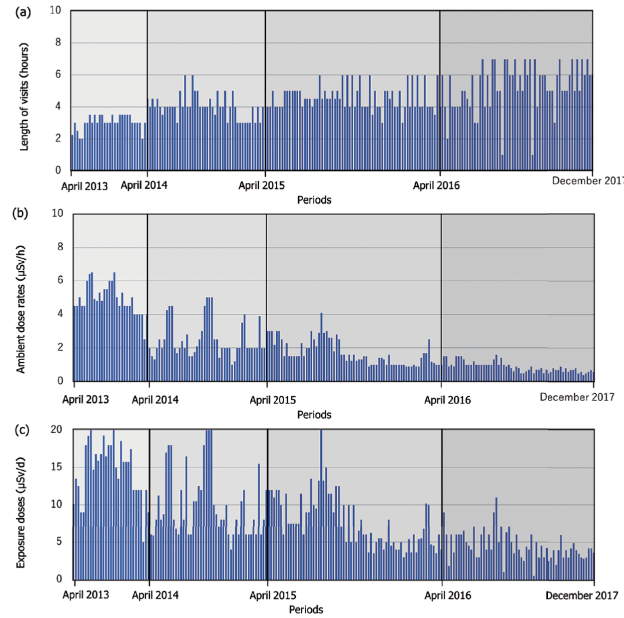

Fig. 8. Personal records of a case study (a 70-year-old man). (a) Length of visits, (b) ambient dose rates, and (c) exposure doses in a resident of Tomioka Town measured between April 2013 and March 2015, April 2015 and March 2016, and April 2016 and December 2017.

authorities. At these offices, analyses of individual doses using dosimeters has also been conducted. During the temporary visits, the individual doses (median) of some residents (n=58) was 1.5 (0.59–3.6) mSv/y in Tomioka Town (data not shown).

In one case, a 70-year-old man recorded the lengths of his visits and the ambient dose rates within his home using an ambient dosimeter and individual dose rates using a personal dosimeter during his visits to the town[18]. The average length of his visits to prepare his home for his return increased significantly in April–December 2016 (5.1 ± 1.4 h), compared to his visits in April 2013–March 2015 (3.7 ± 0.8 h) and April 2015–March 2016 (4.4 ± 0.8 h) (Fig. 8)[18]. His average daily exposure doses decreased significantly in April–December 2016 (4.7 ± 1.9 μSv/d), compared with those in April 2013–March 2015 (12.5 ± 5.0 μSv/d) and April 2015–March 2016 (8.8 ± 3.7 μSv/d). These fluctuations were closely reflective of changes in ambient dose rates (Fig. 8)[18]. His individual dose was estimated at 1.7 mSv/y in 2016[18], which suggested that his long-term external exposure doses decreased dramatically in his everyday Tomioka Town environment, due to the national government's decontamination efforts and the natural decrease in artificial radionuclides. In addition, personal doses could be measured under various conditions, which is extremely important for individual risk assessments, because radiation dose rates measured by the national and municipal governments were merely representative environmental values.

3.2. After returning home, 2017–2021

Tomioka Town is located within 20 km of the FDNPP. On April 1, 2017, after the promulgation of the Act on Special Measures Concerning Nuclear Emergency Preparedness, the Japanese government declared that residents in approximately 88% of Tomioka Town could return home, because the air dose rates were sufficiently low (i.e., <20 mSv/y) (Fig. 7). However, the external and internal exposure risks in living spaces, such as those in and around individual houses, was not evaluated; this was unlike the data collected by the national and municipal governments that were reported in the literature, collated in databases, and published online. Therefore, the amount of environmental contamination and the external radiation exposure doses of residents who had already returned, or who planned to return, were evaluated by measuring the ambient dose rates of artificial radionuclides in surface soils collected in Tomioka Town's residential areas and measured via gamma spectrometry after the restrictions in town were lifted. In addition, internal exposure due to the intake of local foods, such as edible wild plants, mushrooms, vegetables, and fruits that had been produced and/or collected in Tomioka Town was analyzed in returning residents.

Immediately after returning home in 2017, residents' ambient dose rates were 0.20 ± 0.058 μSv/h indoors, 0.29 ± 0.12 μSv/h outdoors, and 0.40 ± 0.19 μSv/h in back yards, and the additional radiation exposure dose rate in the evacuation order-lifted areas was estimated at

Table 1. Ambient dose rates around residential areas and assembly halls in Tomioka Town, Fukushima Prefecture during 2017–2021

Measurement point		Year	*n*	Ambient dose rate			Additional radiation dose rate in mSv/y	Shielding factor
				Mean in μSv/h	Range in μSv/h	Median in μSv/h		
Evacuation-order-lifted area	Indoors[a]	2017	43	0.20 ± 0.058[b]	0.0086-0.37[c]	0.20 (0.28)[d]	1.5[e]	0.77[f]
	Outdoors		61	0.29 ± 0.12	0.0088-0.68	0.26 (0.43)		
	Backyard		61	0.40 ± 0.19	0.14-1.34	0.34 (0.63)		
	Indoors	2018	35	0.18 ± 0.052	0.098-0.30	0.16 (0.26)	1.3	0.68
	Outdoors		59	0.26 ± 0.084	0.088-0.48	0.25 (0.37)		
	Backyard		59	0.34 ± 0.17	0.12-1.2	0.29 (0.51)		
	Indoors	2019	10	0.16 ± 0.055	0.11-0.27	0.14 (0.26)	1.1	0.73
	Outdoors		25	0.23 ± 0.076	0.084-0.44	0.22 (0.32)		
	Backyard		25	0.29 ± 0.14	0.13-0.68	0.24 (0.53)		
	Indoors	2020	15[g]	0.16 ± 0.047	0.064-0.25	0.15 (0.21)	0.96	0.84
	Outdoors		15	0.19 ± 0.057	0.080-0.30	0.17 (0.26)		
	Backyard		15	0.23 ± 0.081	0.10-0.49	0.21 (0.28)		
	Indoors	2021	15	0.14 ± 0.036	0.064-0.20	0.14 (0.18)	0.88	0.81
	Outdoors		15	0.17 ± 0.050	0.062-0.26	0.16 (0.23)		
	Backyard		15	0.21 ± 0.060	0.076-0.36	0.20 (0.26)		
Difficult-to-return zone	Outdoor	2017	4	2.2 ± 0.65	1.1-2.9	2.3 (2.7)		
	Backyard		4	2.1 ± 0.23	1.8-2.4	2.1 (2.4)		
	Outdoor	2018	5	1.0 ± 0.89	0.24-2.4	0.37 (2.1)		
	Backyard		5	1.2 ± 1.1	0.21-2.8	0.53 (2.5)		
	Outdoor	2019	5	1.6 ± 0.65	0.32-2.2	1.8 (2.1)		
	Backyard		5	1.5 ± 0.62	0.27-2.0	1.6 (1.9)		
	Outdoor	2020	4	0.65 ± 0.27	0.24-0.94	0.70 (0.90)		
	Backyard		4	1.0 ± 0.61	0.23-1.9	0.93 (1.7)		
	Outdoor	2021	4	0.61 ± 0.27	0.22-0.94	0.63 (0.88)		
	Backyard		4	1.0 ± 0.57	0.20-1.6	1.2 (1.6)		

[a]indoors mean the inside of the entrance (entrance hall) and outdoors mean the outside of the entrance (yard)
[b]mean ± S.D.
[c]minimum-maximum
[d]parentheses show 90th percentile
[e]calculated using equation; A_{ext} (mSv/y) = $\{(C_{int} - 0.05\ \mu Sv/h) \times 16\ h + (C_{ext} - 0.04\ \mu Sv/h) \times 8\ h\} \times 365\ d \times 0.001$
where C_{int} is the mean ambient dose rate indoors (entrance hall) (μSv/h) and C_{ext} is the mean ambient dose rate outdoors (yard) (μSv/h). The fixed values (0.05 μSv/h indoors and 0.04 μSv/h outdoors) in the equation are defined as the natural radiation dose rates (external terrestrial radiation and cosmic radiation), and 16 and 8 h (24 h/d) are considered as representing the indoor and outdoor activities of daily living based on the guideline of the Ministry of the Environment, Japan, respectively
[f]ambient dose ratio (indoors/outdoors) calculated from mean values
[g]only assembly halls to avoid the infection of covid-19 between 2020 and 2021

1.5 mSv/y[19]. However, the ambient dose rate was 2.2 ± 0.65 μSv/h outdoors and 2.1 ± 0.23 μSv/h in back yards of the difficult-to-return zone (Table 1)[19]. The dose-forming artificial radionuclide (radiocesium) levels in surface soils were 0.30 mSv/y in the evacuation order-lifted areas, and 4.5 mSv/y in the difficult-to-return zone (Table 2)[19]. Although $^{134}Cs/^{137}Cs$ values had been decreasing because of the natural decay of ^{134}Cs (half-life: 2.1 years), the contamination levels due to radiocesium were markedly different in the two areas; they were low in the evacuation order-lifted areas and relatively high in the difficult-to-return zone (Table 2). In 2021, the ambient dose rates were 0.14 ± 0.036 μSv/h indoors, 0.17 ± 0.050 μSv/h outdoors, and 0.21 ± 0.060 μSv/h in back yards, and the additional radiation exposure dose rate was estimated to be 0.88 mSv/y in the evacuation order-lifted areas (Table 1). However, the ambient dose rate was 0.61 ± 0.27 μSv/h outdoors and 1.0 ± 0.57 μSv/h in back yards in the difficult-to-return zone (Table 1). The radiocesium levels in the surface soil were 0.97 mSv/y in the evacuation order-lifted areas and 6.5 mSv/y in the difficult-to-return zone (Table 2). These findings suggest that the estimated external exposure doses in the evacuation order-lifted areas have been decreasing due to the effective decontamination measures of surface soils (0–5 cm) and the natural decay of artificial radionuclides (Tables 1 and 2, Fig. 9). Based on these findings regarding radiocesium concentrations and effective dose rates, decreases in external exposure doses indicated that evacuees could safely return to Tomioka Town.

Despite the above, further environmental remediation efforts in the difficult-to-return zone are still required. Following the FDNPP accident, residential areas, farmlands, forests close to residential areas, and roads within the evacuation order areas were decontaminated extensively by March 19, 2018;[4] however, such efforts

Table 2. Radiocesium distribution in surface soil (0–5cm) in Tomioka Town, Fukushima Prefecture during 2017–2021

Sampling site[a]	Year	n	Radiocesium concentration in kBq/m^2						External effective dose rate in mSv/y	Concentration ratio in Bq/kg ^{134}Cs/^{137}Cs
			Mean		Range		Median			
			^{134}Cs (2.1 y)	^{137}Cs (30 y)	^{134}Cs (2.1 y)	^{137}Cs (30 y)	^{134}Cs (2.1 y)	^{137}Cs (30 y)		
Evacuation-order-lifted area	2017	61	13 ± 20[b]	93 ± 146	0.18-101[c]	0.74-756	5.8 (37.7)[d]	40.2 (274)	0.30[e]	0.13 (0.14)[f]
	2018	59	15 ± 22	135 ± 218	0.25-146	0.26-1498	8.2 (34)	72 (363)	0.66	0.092 (0.10)
	2019	25	8.8 ± 13	114 ± 167	0.17-55	0.99-726	2.7 (23)	37 (316)	0.54	0.071 (0.077)
	2020	15[g]	8.1 ± 18	129 ± 320	0.32-66	0.67-1314	2.6 (7.0)	40 (140)	0.60	0.052 (0.060)
	2021	15	8.2 ± 14	234 ± 388	0.77-59	5.2-1629	3.6 (9.4)	72 (298)	0.97	0.036 (0.039)
Difficult-to-return zone	2017	4	182 ± 76.9	1400 ± 585	66.8-282	515-2144	190 (258)	1471 (1975)	4.5	0.13 (0.13)
	2018	5	58 ± 42	615 ± 443	1.0-121	13-1301	62 (105)	650 (1109)	3.1	0.094 (0.096)
	2019	5	58 ± 62	820 ± 879	0.86-165	9.7-2328	21 (135)	307 (1917)	3.9	0.070 (0.082)
	2020	4	79 ± 57	1569 ± 1121	0.88-140	22-2791	88 (136)	1732 (2694)	7.0	0.051 (0.051)
	2021	4	54 ± 29	1492 ± 799	13-93	335-2559	55 (83)	1538 (2309)	6.5	0.036 (0.038)

[a]residences and assembly halls (same site as Table 1) (See Fig. 7)
[b]mean ± S.D.
[c]minimum-maximum
[d]parentheses show 90th percentile
[e]calculated using equation; $H_{ext} = CD_{ext}S$
where C is the radiocesium (^{134}Cs and ^{137}Cs) concentration (mean: radiocesium inventory in kBq/m^2 calculated from the radiocesium concentration in Bq/kg, including fine particles (< 2 mm) of surface soils (0–5 cm) collected with a size of 0.00182 m^2) based on the in-situ gamma-ray spectrometry, D_{ext} is the dose conversion coefficient reported as the ambient dose equivalent rate at 1-m above the ground per unit activity per unit area {(μSv/h)/(kBq/m^2)}, supposing the air-kerma rate and the absorbed dose rate in air were equivalent, for radiocesium with the relaxation mass per unit area (β: g/cm^2) adopted as 5.0 based on the measurement data in Fukushima Prefecture after the FDNPP accident (3.41×10^{-3} (μSv/h)/(kBq/m^2) for ^{134}Cs and 1.25×10^{-3} (μSv/h)/(kBq/m^2) for ^{137}Cs), and S is the occupancy-shielding factor (0.2 fractional time outdoors + 0.8 fractional time indoors × 0.2 building shielding = 0.36)
[f]median (90th percentile)
[g]only assembly halls to avoid the infection of covid-19 between 2020 and 2021

were not conducted in the difficult-to-return area, where entry and lodging are essentially still prohibited. Based on the Act on Special Measures for the Reconstruction and Revitalization of Fukushima in 2017, six municipalities, including Tomioka Town, are now making plans to construct a Specified Reconstruction and Revitalization Base (SRRB) in the difficult-to-return zone. The aim of the plan is to lift evacuation orders and allow residents to return home[4]. The external exposure levels and the decontamination effects on the landscape in the difficult-to-return zone have not been evaluated thoroughly, although data from the literature, databases, and websites have been published by the national and local governments. Therefore, a detailed and high-frequency radiation monitoring program using a car-borne survey system to provide relatively high-density data was implemented to evaluate the effects of decontamination efforts on reductions in ambient and radiocesium dose rates in the areas (i.e., the "decontaminated area" and the "non-decontaminated area" (contaminated area: temporary storage area for radioactive waste), with markedly different characteristics noted in the difficult-to-return zone in Tomioka Town[20]. In the Yonomori district, in the decontaminated area, the proportion of locations with ambient dose rates > 0.95 μSv/h decreased markedly, from 59.2% in July 2018 to 0% in—and since—October 2020 (Fig. 10)[18]. In response to the ambient dose rates, the detection rates of radiocesium also decreased rapidly, from 92.7% (^{134}Cs: 35.3% and ^{137}Cs: 57.4%) to 0% (Fig. 10)[20]. By contrast, the dose rates in the Oragahama district, in the non-decontaminated area, were mainly concentrated in the range 0.38–0.95 μSv/h (from 82.2%–45.2%) until March 2021 (Fig. 10)[20]. During this period, the radiocesium detection rates decreased gradually, from 92.7% (^{134}Cs: 41.1% and ^{137}Cs: 51.6%) to 15.5% (^{134}Cs: 6.9% and ^{137}Cs: 8.6%) (Fig 10)[20]. Moreover, the physical decay of radiocesium released in areas around the FDNPP between July 2018 and November 2021 was estimated to be 19.9%, using dose conversion coefficients under the assumption that the depth profile of radiocesium did not change over time and that the initial radioactivity of ^{134}Cs and ^{137}Cs were 9.0 and 8.8 PBq, respectively[21-22]. This suggested that the reduction rates of radiocesium in the Yonomori district were clearly faster than the rate of natural physical decay. Finally, the ambient dose rates and detection rates of radiocesium in the decontaminated area decreased faster than those in the non-decontaminated area between July 2018 and November 2021.

Significant differences in ambient dose rates were observed in the survey results from the decontaminated and non-decontaminated areas ($p < 0.001$) (Fig. 10)[20]. A relatively stable downward trend in the radiocesium frequency was observed in the decontaminated area between 2018 and 2020 (Fig. 10). The main reason for the

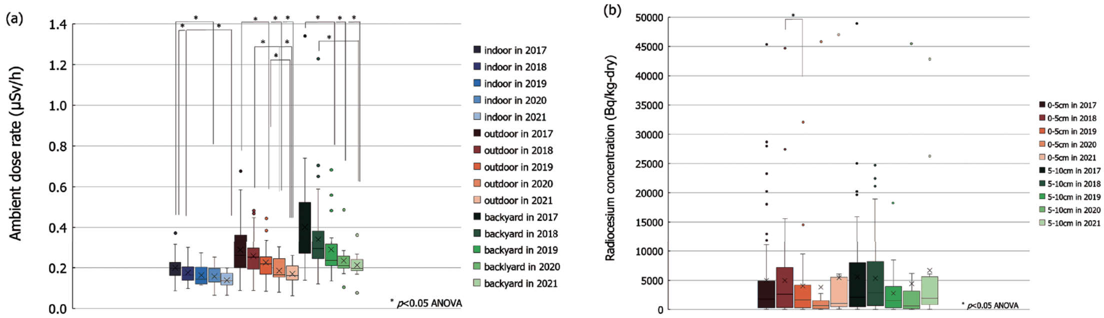

Fig. 9. Temporal changes in (a) ambient dose rates and (b) radiocesium concentrations in the evacuation order-lifted areas of Tomioka Town in 2017 and 2021.

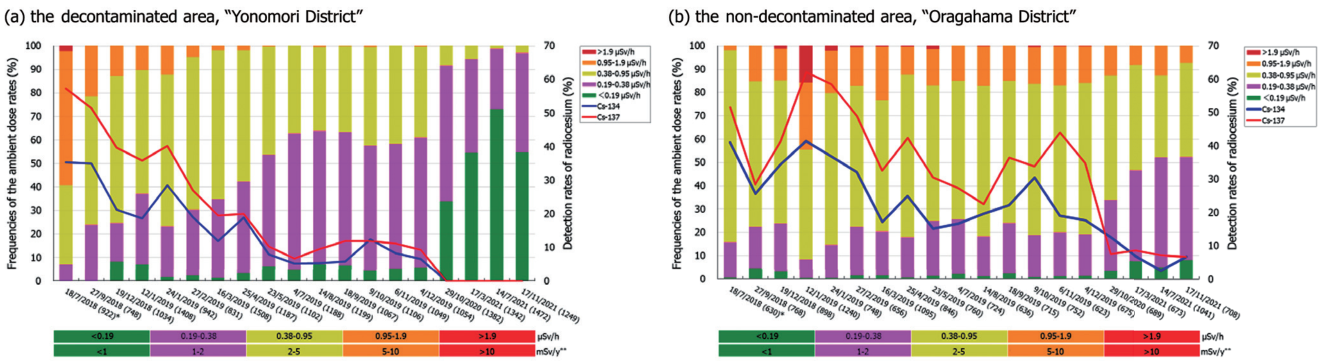

Fig. 10. Relative frequencies of the ambient dose and detection rates of radiocesium in the (a) decontaminated area Yonomori District and the (b) non-decontaminated area Oragahama district in the difficult-to-return zone of Tomioka Town, Fukushima Prefecture, July 2018 through November 2021. The single asterisk shows the measuring point. The double asterisk shows the dose rates for indoor (16 h) and outdoor (8 h) activities (24 h/d), based on guidelines set by the Japanese Ministry of the Environment. The data were not normally distributed. The Mann-Whitney U and Kruskal-Wallis H tests were used to compare differences between these areas in the same period and the time trends within the same district. Regression lines were used to calculate the reduction rate in the average ambient dose rates.

observed decreases in the ambient dose rates and in the detection rate of radiocesium in the decontaminated area since July 2018 was due to decontamination efforts, such as removing sediment and subjecting buildings to high-pressure washing[4]. Furthermore, the estimated external exposure doses of workers in the first year (July 2018 through July 2019) were extremely low, at 0.66 mSv/y in the decontaminated area, and 0.55 mSv/y in the non-decontaminated area[20]. The case of Tomioka Town, including its difficult-to-return zone, is expected to be the first reconstruction model for evaluating environmental contamination and radiation exposure dose rates for artificial radionuclides.

More than a decade after the FDNPP accident, intensive decontamination and demolition efforts have been conducted in the SRRB of the difficult-to-return zone around the FDNPP. To evaluate the working environment and internal exposure risk due to inhalation in the Yonomori district of Tomioka Town's SRRB, ^{137}Cs radioactivity levels in the airborne dust at building demolition sites were measured by gamma spectrometry using a high-volume air sampler with a single-stage impactor (Fig. 7). The ^{137}Cs radioactivity levels did not increase significantly, despite demolition operations that used heavy machinery (Table 3)[23]. Moreover, the limited resuspension factor (L-RF) values varied by one order of magnitude, depending on the location and whether a sampling site was inside or outside the difficult-to-return zone; the large-scale remediation efforts may reflect a reduction rate in L-RFs as atmospheric aerosols that were derived from a wide area (Table 3). In this case, no substantial increases in accident-derived ^{137}Cs levels due to decontamination and demolition were observed in the airborne dust samples in Tomioka Town's SRRB, suggesting that the ^{137}Cs radioactivity in the airborne dust was primarily associated with particles that are resuspended by localized winds accompanied by the transfer of construction vehicles, as opposed to decontamination and demolition operations (Table 3 and Fig. 7)[23]. The internal exposure doses in decontamination workers aspirating airborne dust containing ^{137}Cs were extremely low, compared to the estimated annual effective doses or the limits recommended by the Japanese government (Table 3)[23-24]. In addition, suitable countermeasures, such as wearing protective masks, could have helped to decrease the on-

Table 3. ^{137}Cs radioactivity in airborne dust at building sites in Tomioka Town, Fukushima Prefecture during 2019–2021

Measurement point	Period	n	^{137}Cs (mBq/m^3)	Internal exposure dose rate (μSv/d)[a] Inhaled particulates (activity median aerodynamic diameter of 1 μm)	Internal exposure dose rate (μSv/d)[a] Inhaled particulates (activity median aerodynamic diameter of 5 μm)	L-RFs × 10^{-8} (m^{-1})[b]	Remark
Building G (SRRB)	From September 2019 to February 2020[c]	4 (3)[d]	<0.11–0.73 (0.085–0.098)[e]	<6.8 × 10^{-6} to 4.7 × 10^{-5}[f]	<9.5 × 10^{-6} to 6.6 × 10^{-5}	1.1–7.5	Before demolition
	From May to August 2020[g]	20 (16)	<0.10–0.62 (0.091–0.11)	<6.7 × 10^{-6} to 4.0 × 10^{-5}	<9.3 × 10^{-6} to 5.6 × 10^{-5}	0.47–2.8	During demolition
Building Y (SRRB)	February 2–3[h]	2 (2)	0.35–0.36 (0.091–0.098)	2.2 × 110^{-5} to 2.3 × 110^{-5}	3.1 × 110^{-5} to 3.2 × 110^{-5}	1.6	Before demolition
	March 3–24[i]	13 (9)	<0.13–2.3 (0.089–0.15)	<8.2 × 10^{-6} to 1.5 × 10^{-4}	<1.1 × 10^{-5} to 2.0 × 10^{-4}	0.58–10	During demolition
Tomioka town office (evacuation order-lifted area)	From August 2019 to April 2021[j]	5 (2)	<0.034–0.15 (0.023–0.097)	<1.6 × 10^{-6} to 7.1 × 10^{-6}	<2.2 × 10^{-6} to 1.0 × 10^{-5}	0.056-0.25	Control building

[a]calculated using equation; $H_{int} = C \cdot D_{int} \cdot e$
where C is the average detected ^{137}Cs radioactivity (Bq/m^3) (^{137}Cs concentration in filter dust sample), D_{int} is the effective dose coefficients for inhaled particulates (activity median aerodynamic diameters of 1 and 5 μm) for workers based on International Commission on Radiological Protection (ICRP) Publications 68 and 119 (1 μm: 4.8 × 10^{-6} mSv/Bq and 5 μm: 6.7 × 10^{-6} mSv/Bq for ^{137}Cs) (ICRP, 1994 and ICRP, 2012), and e is quoted from the reference values of daily ventilation rates for dosimetric modeling for adult workers based on ICRP Publication 89 (13.5 m^3/8h/d for the decontamination/demolition workers and 9.6 m^3/8h/d for office workers) (ICRP, 2002). In this methodology, average daily inhalation was estimated based on internal exposure doses due to inhalation during occupational activities among heavy manual workers
[b]calculated using equation; $K = {}^{137}Cs_{invent} / {}^{137}Cs_{cont}$
where $^{137}Cs_{invent}$ is defined as the ^{137}Cs radioactivity of airborne dust (Bq/m^3) and $^{137}Cs_{cont}$ is defined as the ^{137}Cs contamination of the surface soil layer (0–0.5 cm) (Bq/m^2) collected in the present study, respectively. Because decontamination in the Yonomori district of the SRRB proceeded by the same schedule and technical methods, the surface soil contamination levels closest to airborne dust sampling points (time) were adopted as the reference values. $^{137}Cs_{cont}$ (surface soil samples) were 9.7 × 10^3 Bq/m^2 before demolition of Building G, 21.9 × 10^3 Bq/m^2 during demolition of Building G, and before and during demolition of Building Y, and 60.6 × 10^3 Bq/m^2 for the control building
[c]airborne dust was collected four times (September 5, 2019, November 21, 2019, December 5, 2019, and February 27, 2020)
[d]sample number (^{137}Cs detection number)
[e]detection limit at the time of ^{137}Cs detection
[f]minimum–maximum (values less than those indicated were not detected)
[g]airborne dust was collected 20 times (from May 27 to August 6, 2020)
[h]airborne dust was collected two times (February 2-3, 2021)
[i]airborne dust was collected 13 times (March 3-24, 2021)
[j]airborne dust was collected five times (August 13-14, 2019, February 26, 2020, May 22, 2020, April 9, 2021 and April 12, 2021)

site inhalation of soil-derived radionuclides. The case of Tomioka Town's SRRB might be the first working model for evaluating the environmental contamination and internal exposure dose rates due to artificial radionuclides derived from the FDNPP accident.

In addition to the above, the activity concentrations of radiocesium ($^{134+137}$Cs) were analyzed in 2,491 local food samples (i.e., vegetables, edible wild plants, mushrooms, and fruits) produced and/or collected in Tomioka Town between January 2018 and December 2021 using an NaI detector coupled to a multichannel analyzer for 600 s[25]. A summary of the radioactive contaminants in local foods produced and/or collected in Tomioka Town is shown in Fig. 11. The radiocesium distribution in local foods showed a wide range throughout the year, and the detected rates in all local foods that exceeded the standard limit of radiocesium (100 Bq/kg for general foods) were 15.4–17.5% between 2018 and 2021. The detected rates exceeding the standard limit were 35.8–50.9% for edible wild plants and 72.7–88.2% for mushrooms, while the radiocesium concentration of edible wild plants and mushrooms ranged widely, from <23,994 Bq/kg in edible wild plants to <99,653 Bq/kg in mushrooms between 2018 and 2021[25]. At the same time, the radiocesium concentration in fruits and vegetables did not show a wide range, measuring <233 Bq/kg in vegetables and <1,990 Bq/kg in fruits from 2018–2021[25]. In these screening experiments, foodstuffs brought by residents to the Tomioka Town Food Inspection Department of the Tomioka Town Office were analyzed. These included vegetables, fruits, and tubers that had been grown in decontaminated private gardens at residents' homes and edible wild plants and mushrooms that had been collected from non-decontaminated areas, such as boundary sites, contaminated forests, or roadsides[25]. The radiocesium in wild edible plants and mushrooms mainly contributed to the committed effective doses, because the excess rate against the standard limits for wild edible plants and mushrooms was relatively higher than those for fruits and vegetables (Fig. 11)[25]. Moreover, the committed effective

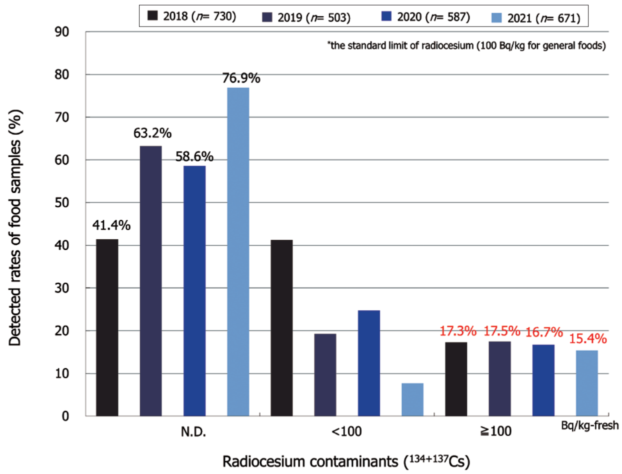

Fig. 11. Detected rates of radiocesium contaminants in local foods in Tomioka Town, Fukushima Prefecture, 2018–2021. The committed effective doses in the main agricultural products (vegetables, edible wild plants, mushrooms, and fruits) in all local food samples were estimated from the radiocesium concentration using the formula $H_{int} = C \cdot D_{int} \cdot e$ where C is the median radiocesium concentration (Bq/kg-fresh); D_{int} is the dose conversion coefficient for child intake (age: 0–18 y, 1.3×10^{-5} to 2.6×10^{-5} mSv/Bq for ^{134}Cs and 9.6×10^{-6} to 2.1×10^{-5} mSv/Bq for ^{137}Cs) and for adult intake (age: >19 y, 1.9×10^{-5} mSv/Bq for ^{134}Cs and 1.3×10^{-5} mSv/Bq for ^{137}Cs), based on ICRP Publication 72; and e is quoted from the average daily intake survey (g/person/d) for age and sex, as issued by Japan's MHLW in 2018 and 2019. To calculate the committed effective doses, the undetected data (N.D.) of the radiocesium were defined based on GEMS/Food published by the WHO and the new standard limits for radionuclides in food by the MHLW (Fig. 4 and 5).

doses from local foods due to the intake of agricultural products (i.e., main food items such as vegetables, fruits, edible wild plants, and mushrooms) in Tomioka Town were 26–120 μSv/y for children and 40–152 μSv/y for adults (19–152 μSv/y for males and 19–150 μSv/y for females) between 2018 and 2021[25]. Despite the risk of severe radiation exposure, the daily consumption of edible wild plants and mushrooms contributed only slightly to residents' committed effective doses, with the level of radiocesium contamination in foodstuffs considerably lower than the standard (>100 Bq/kg for radiocesium) or public dose limits (1 mSv/y) (Fig. 11).

Finally, current estimates indicated that the external and internal exposure doses in Tomioka Town due to artificial radionuclides (radiocesium) derived from the FDNPP accident were equivalent to the public dose limit and/or were sufficiently lower than the upper value of the reference level for existing exposure situations (20 mSv/y), as determined by the ICRP.

3.3. Non-decontaminated forests, 2018–2019

Since 68% of the Fukushima Prefecture is covered by forests, and forest areas in the prefecture accumulated 72% of the total atmospheric input of ^{137}Cs, forest ecosystems contaminated with ^{137}Cs may increase the local population's exposure to radiation by elevating ambient dose rates (external exposure) and through the consumption of contaminated forest products (internal exposure) over the coming decades[26-28]. However, since Japan is susceptible to natural disasters, such as earthquakes and heavy rains due to tropical storms (typhoons) and localized downpours, we decided to analyze the environmental radiation levels in forest areas along the Mt. Okura hiking trail (3.9 km) in Tomioka Town near the FDNPP. Specifically, the spectra of artificial radionuclides (mainly radiocesium) were measured using a portable survey system and personal dosimeters. The results were used to examine the temporal changes in the attenuation of external exposure doses and environmental radiation contamination due to the rainfall associated with typhoons and heavy rains between October and December 2019 (Fig. 12)[29]. We confirmed: (1) the ambient dose rates of 0.38–0.95 μSv/h in most forest areas were 79.9–84.7% higher than in residential areas, (2) the number of sites along the hiking trail where ^{137}Cs was detected was limited (1.1–4.7%), and (3) individual dose rates of 0.21–0.34 μSv/h were lower than ambient dose rates (Fig. 13 and 14). These findings suggested that radiocesium has remained stable in natural forests that have not been decontaminated and that current levels are low, despite the occurrence of heavy rainfall associated with Typhoon Hagibis in 2019 and localized downpours[29].

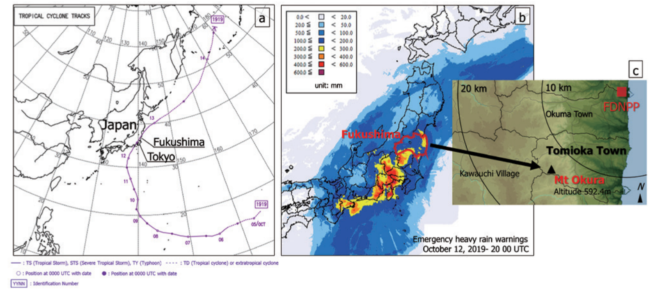

Fig. 12. (a) Path of Typhoon Hagibis in 2019, (b) precipitation after 48 h, and (c) location of Mt. Okura in Tomioka Town, Fukushima Prefecture, Japan. (a) and (b) are reprinted and modified from the Regional Specialized Meteorological Centre's Best Track Data (Graphics), published in 2019 (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/bstve_2019_m.html) and a JMA Report on Typhoon 19 (http://www.data.jma.go.jp/obd/stats/data/bosai/report/2019/20191012/jyun_sokuji20191010-1013.pdf) under a CC BY license, with permission; (c) map produced by the first author (YT) using Green Map III software (Tokyo Shoseki Co., Ltd., Tokyo, Japan; http://www.tokyo-shoseki.co.jp/company_english/philosophy.html) and reprinted under a CC BY license with permission from Tokyo Shoseki Co., Ltd.; original copyright 2003.

Is forest decontamination still necessary? The forested area that needs to be decontaminated is vast and will require a sizeable budget; thus, further discussions related to forest decontamination policies are needed from the perspectives of cost-effectiveness and

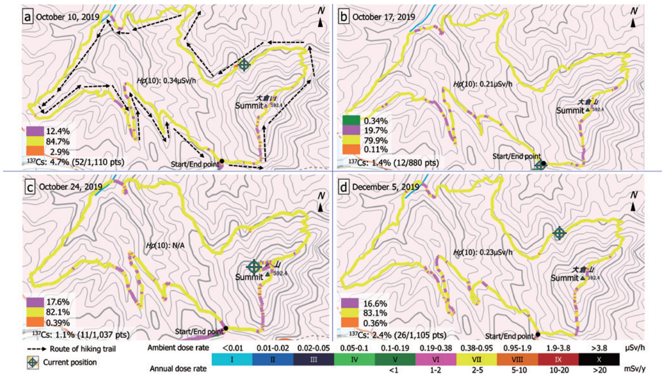

Fig. 13. Real-time map of color-scaled ambient dose rates along the Mt. Okura hiking trail. The map data were collected using a walking survey system, Radi-probe, in October and December 2019. This radiation map was modified by the first author (YT) using GIS and PowerPoint software, based on the mapping data obtained by Radi-probe (GIS software: Shobunsha Publications, Inc., Tokyo, Japan. https://www.mapple.co.jp/en/; the Radi-probe system: Chiyoda Technology Corp., Tokyo, Japan. http://www.c-technol.co.jp/eng). Reprinted from the map software (Mapple, ver. 18) for the Radi-probe system under a CC BY license with permission (No. 4-063) from Shobunsha Publications, Inc., Tokyo, Japan; original copyright 2017 and Chiyoda Technology Corp., Tokyo, Japan.

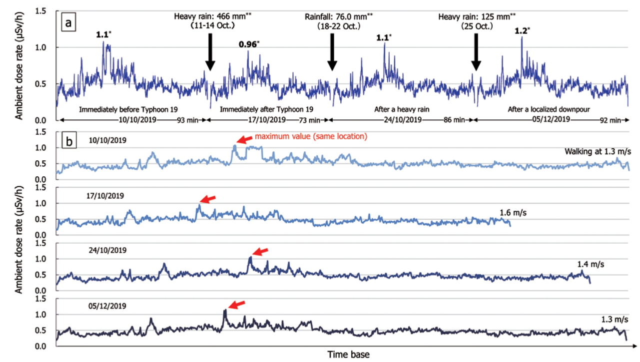

Fig. 14. Temporal changes in ambient dose rates along the Mt. Okura hiking trail (3.9 km). (a) All variations in ambient dose rates. The data were obtained by a walking survey conducted between October and December 2019 using a Radi-probe system. The asterisk shows the maximum μSv/h values. Maximum values were consistently measured at the same locations. The double asterisk shows heavy rainfall events such as typhoons or downpours and precipitation measured at a weather station in Kawauchi Village near Mt. Okura. The 466 mm of precipitation due to Typhoon 19, October 11–14, 2019, was equivalent to three times the monthly average (JMA, Tokyo, Japan. Available from: http://www.data.jma.go.jp/obd/stats/etrn/view/daily_a1.php?prec_no=36&block_no=1129&yeye=2019&month=10&day=&view=); (b) Separate variations in ambient dose rates. Red arrows show the same location on the hiking trail (maximum value shown). Walking speed except for breaks was in the range 1.3–1.6 m/s.

prioritization. Identifying decontamination areas (zoning) while managing external exposure and environmental contamination may help to recover Fukushima's original landscape[30]. Moreover, hiking while managing exposure to environmental contamination using a personal dosimeter may be a model for those wishing to spend time outdoors[29].

4. Monitoring environmental radioactivity in Okuma Town and Futaba Town

The FDNPP disaster area encompasses two towns (Okuma Town and Futaba Town). These towns are located within a 20-km radius of the FDNPP, and both towns have an interim storage facility close to the FDNPP. In the Fukushima Prefecture, large quantities of soil and waste were collected for off-site decontamination.[4] Interim storage facilities managed and stored this soil and waste, and specific waste (>100,000 Bq/kg), until its final disposal[4]. The soil storage facilities in the difficult-to-return zone have been in operation since October 2017 in Okuma Town and since December 2017 in Futaba Town[4]. The soil and waste were transferred by truck from temporary radioactive waste storage areas elsewhere in the Fukushima Prefecture to these interim facilities[4].

As a next step, following the temporary visits and stays by residents that began on December 3, 2021 in preparation for their return to Okuma Town, evacuation orders in Okuma Town's SRRB were lifted on June 30, 2022. Temporary visits and stays for residents preparing to return to Futaba Town began on January 20, 2022, and the lifting of the evacuation order in the SRRB there was scheduled for August 30, 2022. Under these circumstances, the continued monitoring of environmental radiation in the restricted zone close to residential areas is extremely important, so a detailed, high-frequency radiation monitoring program using car-borne surveys was developed to provide generally high-density data. These surveys have been conducted at the interim storage facilities since October 2021. Below, the results of this monitoring are briefly described.

At the interim storage facility in Okuma Town, the proportion of locations with ambient dose rates exceeding 1.9 μSv/h was 4.8%; most dose rate measurements ranged between 0.38 and 1.9 μSv/h (81.4%) on October 18, 2021 (Fig. 15). The detection rates for radiocesium were 20.5% for ^{134}Cs and 29.5% for ^{137}Cs, respectively. At the interim storage facility in Futaba Town, the proportion of locations with ambient dose rates >1.9 μSv/h was 0%, and most dose rates were <0.38 μSv/h (80.6%) on October 19, 2021 (Fig. 15). The detection rate of radiocesium was only 2.4% for ^{137}Cs. This suggests that the distribution of ambient dose and detection rates of radiocesium differed markedly and were affected by factors such as trucks transporting soil and waste to the interim storage facilities and the decontamination and demolition activities in the difficult-to-return zone, which are countermeasures against radioactive contamination after the FDNPP

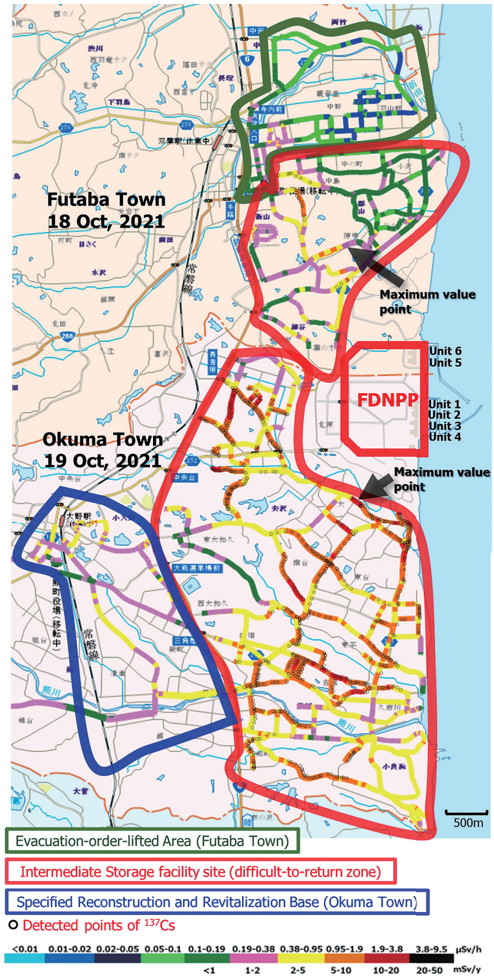

Fig. 15. Real-time map of color-scaled ambient dose rates and detected points of 137Cs among sampling locations in the interim storage facility sites in the difficult-to-return zone in Okuma and Futaba Towns Fukushima Prefecture. The data were collected using a Radi-probe car-borne survey system on October 18–19, 2021. The radiation map was modified by the first author (YT) using GIS and PowerPoint software, based on the Radi-probe mapping data (GIS software: Shobunsha Publications, Inc., Tokyo, Japan. https://www.mapple.co.jp/en/; the Radi-probe system: Chiyoda Technology Corp., Tokyo, Japan. http://www.c-technol.co.jp/eng). Map reprinted from the map software (Mapple, ver. 20) for the Radi-probe system under a CC BY license, with permission (No. 4-063) from Shobunsha Publications, Inc., Tokyo, Japan; original copyright 2019 and Chiyoda Technology Corp., Tokyo, Japan.

accident. Although the detection rates of radiocesium are shown qualitatively on the gamma-ray energy spectra and a low range of less than 0.38 μSv/h may be detected on a limited basis, long-term monitoring, in combination with various analytical methods and systems, such as car-borne surveys and nuclide analyses of environmental samples, can be used to accurately evaluate the decontamination and environmental remediation efforts in the future[19]. These cases of the interim storage facility sites in Okuma and Futaba Towns may be the first reports evaluating environmental contamination and external exposure dose rates due to radiocesium derived from the FDNPP accident.

5. Conclusion

In our previous studies, we mainly examined environmental contamination and the external and internal exposure doses attributed to the FDNPP accident in Kawauchi Village and Tomioka Town, in Japan's Fukushima Prefecture. The findings suggested that external doses have decreased steadily, compared to levels detected immediately after the FDNPP accident, and the internal doses were low compared to the public dose limit (1 mSv/y). In particular, the current external and internal exposure doses due to radiocesium have been maintained at low levels in evacuation order-lifted areas, but long-term follow-up measures, such as monitoring the radioactivity in the environment; further decontamination of areas in the difficult-to-return zone, including SRRBs and forested areas; and imposing restrictions on the intake of local foods, are needed to reduce residents' radiation exposure, since radiocesium derived from the FDNPP accident persists even in the decontaminated areas around the FDNPP. The monitoring efforts and evaluation of radiation exposure doses have been extremely effective in Kawauchi Village and Tomioka Town; thus, long-term follow-up and detailed evaluations of the external and internal exposure doses and clarification of the temporal dose levels in the recovery and reconstruction phases of the affected areas around the plant are important for ensuring the safety and future prosperity of residents and communities.

Appendix: List of equipment

(1) Ambient dose rates were measured in the air at a height of 1 m above the ground using a NaI(Tl) scintillation survey meter (thallium-doped sodium iodide, ϕ1×1 inch), which can measure gamma rays (energy range: 50 keV–3 MeV, ambient dose equivalent rate ($H^*(10)$): 0–30.0 μSv/h at 1-cm depth; TCS-172B, Hitachi-Aloka Medical, Ltd., Tokyo, Japan; Fig. 1)[7-8, 19, 25].

(2) Radiocesium levels of the environmental samples (surface soils and airborne dust) were analyzed using a high-purity germanium detector (ORTEC GMX series, Ortec International Inc., Ltd., Oak Ridge, TN, USA) coupled to a multi-channel analyzer (MCA7600, Seiko, EG&G Co., Ltd., Chiba, Japan) for 3,600–80,000 s. The measuring time was set to the level at which the target radionuclide (radiocesium) was detectable at low levels. The gamma-ray peaks adopted for the measurements were 604.66 keV for ^{134}Cs (2.1 y) and 661.64 keV for ^{137}Cs (30 y). Decay corrections were set to the sampling date. Detector efficiency calibration for different measurement

geometries, including the density and thickness of samples, was performed using mixed activity standard volume sources (Japan Radioisotope Association, Tokyo, Japan). The relative detection efficiencies of this apparatus were 32.9–37.7%, with 1332.47 keV for cobalt-60 (5.3 y). All environmental samples were processed and analyzed at Nagasaki University, Nagasaki, Japan[7-8, 19, 25].

(3) Radiocesium levels in local foods produced and/or collected in Kawauchi Village were analyzed using a NaI(Tl) (thallium-doped sodium iodide, ϕ2 × 2 inch) detector (Canberra, CAN-OSP-NAI, AREVA NC Inc., Meriden, CT, USA) coupled to a multi-channel analyzer (Genie 2000, Canberra Japan KK., Tokyo, Japan) covering 1,024 channels (2,000 keV) for 1,800 s. The gamma-ray peaks used for the measurements were 604.7 keV for ^{134}Cs (2.1 y) and 661.6 keV for ^{137}Cs (30 y). The resolution of the instrument was <7.5% at 661.64 keV for ^{137}Cs. The sum peak of ^{134}Cs (1,401 keV) was separated from the gamma-ray peak of potassium-40, which is typically dominant in natural radionuclides. To assess the geometric and detector efficiency, the LabSOCS mathematical efficiency calibration software package (Laboratory Sourceless Calibration Software, Canberra Japan KK., Tokyo, Japan) was used to calibrate without the need for conventional calibration methods typically used, such as different measurement geometries, including the density and thickness of samples performed by mixed activity standard volume sources. Local food sampling was performed by residents of Kawauchi Village, the processing and measurements of radionuclides were performed by the Kawauchi Village Office, and the analyses of radionuclides were performed at Nagasaki University, Nagasaki, Japan[8-9, 12].

(4) Radiocesium activities in local foods produced and/or collected in Tomioka Town were analyzed using the NaI(Tl) detector (thallium-doped sodium iodide, ϕ5 × 5 inches) coupled to a multi-channel analyzer (AFT-NDA2, Advanced Fusion Technology, Co., Ltd., Tokyo, Japan) for 600 s. This detector covers a wide range of energy peaks (100 keV to 3,000 keV) and can be used to analyze a variety of radionuclides in food samples. The gamma-ray peaks adopted for measurements were 605 keV for ^{134}Cs (2.1 y) and 662 keV for ^{137}Cs (30 y). The resolution of this apparatus was <7.5% at 661.64 keV for ^{137}Cs. Calibration of the energy and efficiency of this detector were performed using a standard source of ^{134}Cs and ^{137}Cs. Local food sampling was performed by residents of Tomioka Town, the processing and measurements of radionuclides were performed by the Tomioka Town Office, and the analyses of radionuclides were performed at Nagasaki University, Nagasaki, Japan[25].

(5) Long-term radiation dose rates were measured using RPLD (FGD-201; Chiyoda Technology Corp., Tokyo, Japan) with silver-activated phosphate glass (SC-1; AGC Techno Glass Co., Ltd., Kawashiri, Shizuoka, Japan). RPLDs are insensitive to ambient influences such as temperature and have low temporal and light fading. The RPLDs measured approximately 30×40 mm, including a holder to protect the glass elements from damage. Regeneration treatment was performed at 400 °C for 1 h, and annealing was performed at 70 °C for 1 h before each measurment[15].

(6) Surveys of the ambient dose rates and radionuclides in Tomioka Town's difficult-to-return zone were carried out using a car-borne survey system, Radi-probe (Chiyoda Technology Corp.) and a handheld radiation detector (HDS-101GN, Mirion Technologies, Inc., Tokyo, Japan). The Radi-probe system was installed in a vehicle and the detector was set on the front passenger seat at approximately 1 m above the ground. The ambient dose rates were measured and geographic coordinates and a photograph were captured automatically every 5 s, in addition to spectrum segments every 0.2 s. Gamma detection was performed using a large thallium-doped cesium iodide scintillator with high sensitivity (typical 1400 cps per μSv/h for ^{137}Cs source). The measurable energy range of gamma-ray energy was 30 keV to 6 MeV. Measurements were performed using a multichannel analyzer with 512 channels. Real-time maps with color-scaled ambient dose rates and gamma-ray energy spectra can be output using the system. The detected energy peaks of radiocesium (^{134}Cs and ^{137}Cs) registered in the nuclear library (i.e., detected net count values), and their associated confidence intervals, were obtained for the region of interest (with levels 1–10 used as reference values). Generally, the car chassis and doors acted as shields for radiation from the outside. The shielding factors were estimated by taking measurements inside and outside the car in flat, open areas at a height of 1 m above the ground. Since many factors can influence the shielding factors (e.g., the type of car and number of passengers), the shielding effects were calculated before each vehicle survey. The shielding factors ranged from 1.1–1.6[20].

(7) Surveys of ambient dose rates and radionuclides on Mt. Okura in Tomioka Town were carried out using a walking survey system, Radi-probe (Chiyoda Technology Corp.). The handheld radiation detector (HDS-101GN, Mirion Technologies, Inc.) was the same as that used in (6). For the walking survey, the shielding factor was taken as 1.0[20, 29].

(8) In the case study of Kawauchi Village, individual doses of the entire time spent conducting daily and leisure activities were measured using a personal dosimeter (MYDOSE G2, PDM-501, Hitachi-Aloka Medical, Tokyo, Japan) capable of measuring total dose ranges of 0.01 μSv to 1 Sv. In the case studies of Tomioka Town, a personal cumulative dosimeter (DOSEe;. Fuji Electric Co., Ltd.,

Tokyo, Japan) capable of measuring total cumulative dose ranges from 0.000 mSv to 99.99 mSv (0.00 μSv/h to 999.9 μSv/h) was used to measure gamma radiation, and a personal cumulative dosimeter (D-SHUTTLE; Chiyoda Technology Corp., Hp(10)) capable of measuring total cumulative dose ranges of 0.1 μSv to 99.9999 mSv was used to measure gamma radiation, with doses recorded every hour; the dosimeter incorporated a semiconductor equipped with an error-detection prevention function and a shock sensor[16-18, 29].

(9) Airborne dust samples were collected on 203×254-mm quartz-fiber filters (GB100R-810A; SIBATA Scientific Technology Ltd., Saitama, Japan) at a flow rate of 1000 L/min using a high-volume air sampler with a single-stage impactor (HV-1000R; SIBATA Scientific Technology Ltd.). Cumulative flows were in the range of 349.8–403.9 m^3 (5 h 50 min to 6 h 45 min) for Building G and 250.5–429.9 m^3 (4 h 10 min to 7 h 10 min) for Building Y[23].

(10) Sampling, processing, and analyses were carried out using standard methods for radioactivity measurement, as certified by the Ministry of Education, Culture, Sports, Science and Technology and the Nuclear Regulation Authority in Japan[31-32].

Ethics statement

The investigations in Kawauchi Village and Tomioka Town were approved by the ethics committee of Nagasaki University's Graduate School of Biomedical Sciences (No. 14011079 and 17030212). Permission to measure individual doses and ambient doses, and to collect soil samples in the village and towns, was obtained from the relevant municipal authorities. In addition, written informed consent was obtained from the homeowners where individual and ambient doses were measured and where samples were collected.

Acknowledgements

We sincerely thank the members of the Kawauchi Village Office and the Tomioka Town Office, as well as Noriyuki Takizawa, Shinichi Hoshi, Hideki Saito, and Hidefumi Sanpei, for their assistance with the environmental samples' collection and analyses.

Funding

These works were supported by a research project on the health effects of radiation organized by Ministry of the Environment, Japan and the Environmental Radioactivity Research Network Center (F-19-22, F-20-17, and F-21-30).

Conflicts of interest

The authors have no conflicts of interest to declare.

Author contributions

Yasuyuki Taira, Shigekazu Hirao, and Noboru Takamura contributed to the research concepts and design; Yasuyuki Taira, Masahiko Matsuo, Makiko Orita, Hitomi Matsunaga, Yuya Kashiwazaki, and Xiao Xu contributed to the data acquisition, analysis, and interpretation; Yasuyuki Taira and Shigekazu Hirao contributed to writing a draft of the manuscript and revising it for intellectual content. All authors approved the final version of the manuscript.

References

1. IAEA. The Fukushima Daiichi Accident. In Technical Volume 1. Description and Context of the Accident. Vienna: International Atomic Energy Agency; 2015 [cited 2022 Sep 3]. Available from: https://www-pub.iaea.org/MTCD/Publications/PDF/AdditionalVolumes/P1710/Pub1710-TV1-Web.pdf.
2. JAEA. Fukushima Nuclear Accident Archive. Ibaraki: Japan Atomic Energy Agency; 2016 [cited 2022 Sep 3]. Available from: https://f-archive.jaea.go.jp/collection.php?locale=eng.
3. Nagasaki University. Bases of Research and Education of Atomic Bomb Disease Institute, Nagasaki University. Nagasaki: Atomic Bomb Disease Institute [cited 2022 Sep 3]. Available from: https://www.genken.nagasaki-u.ac.jp/abdi/bases/index_e.html.
4. MOE. Off-site Environmental Remediation in Affected Areas in Japan. Tokyo: Ministry of the Environment, Japan; 2020 [cited 2022 Sep 3]. Available from: http://josen.env.go.jp/en/pdf/environmental_remediation_2008.pdf.
5. Fukushima Prefectural Government. Fukushima Revitalization Station. The Official Website for Fukushima's Restoration. Fukushima: Fukushima Prefectural Government; 2014 [cited 2022 Sep 3]. Available from: http://www.pref.fukushima.lg.jp/site/portal-english/list385.html.
6. Prime Minster of Japan and His Cabinet. Press Conference by Prime Minister Yoshihiko Noda. Tokyo: Prime Minster of Japan and His Cabinet [cited 2022 Sep 3]. Available from: https://japan.kantei.go.jp/noda/statement/201112/16kaiken_e.html.
7. Taira Y, Hayashida N, Yamaguchi H, Yamashita S, Endo Y, Takamura N. Evaluation of environmental contamination and estimated radiation doses for the return to residents' homes in Kawauchi Village, Fukushima Prefecture. PLoS One. 2012;7(9): e45816.
8. Taira Y, Hayashida N, Orita M, Yamaguchi H, Ide J, Endo Y, *et al*. Evaluation of environmental contamination and estimated radiation doses after the return to residents' homes in Kawauchi Village, Fukushima Prefecture. Environ Sci Technol. 2014;48(8): 4556–63.
9. Orita M, Nakashima K, Hayashida N, Endo Y, Yamashita S, Takamura N. Concentrations of radiocesium in local foods collected in Kawauchi Village after the accident at the Fukushima Dai-ichi Nuclear Power Station. Sci Rep. 2016;6:28470.
10. Nakashima K, Orita M, Fukuda N, Taira Y, Hayashida N, Matsuda N, *et al*. Radiocesium concentrations in wild mushrooms collected in Kawauchi Village after the accident at the Fukushima Daiichi Nuclear Power Plant. PeerJ. 2015;3:e1427.

11. Orita M, Nakashima K, Taira Y, Fukuda T, Fukushima Y, Kudo T, *et al*. Radiocesium concentrations in wild mushrooms after the accident at the Fukushima Daiichi Nuclear Power Station: follow-up study in Kawauchi village. Sci Rep. 2017;7(1):6744.

12. Tsuchiya R, Taira Y, Orita M, Fukushima Y, Endo Y, Yamashita S, *et al*. Radiocesium contamination and estimated internal exposure doses in edible wild plants in Kawauchi Village following the Fukushima nuclear disaster. PLoS ONE. 2017;12(12):e0189398.

13. Bonzom JM, Hättenschwiler S, Lecomte-Pradines C, Chauvet E, Gaschak S, Beaugelin-Seiller K, *et al*. Effects of radionuclide contamination on leaf litter decomposition in the Chernobyl exclusion zone. Sci Total Environ. 2016;562:596–603.

14. Fuma S, Ihara S, Kawaguchi I, Ishikawa T, Watanabe Y, Kubota Y, *et al*. Dose rate estimation of the Tohoku hynobiid salamander, *Hynobius lichenatus*, in Fukushima. J Environ Radioact. 2015;143:123–34.

15. Taira Y, Koga Y, Doi M, Motoyama Y, Yamauchi Y. Evaluate of external radiation exposure after the return of residents to their home in Kawauchi Village, Fukushima prefecture: monitoring on long-term variation of integral radiation dose in living spaces. Rep Nagasaki Pref Environ Health Res Center. 2014;60:61–6.

16. Orita M, Hayashida N, Taira Y, Fukushima Y, Ide J, Endo Y, *et al*. Measurement of individual doses of radiation by personal dosimeter is important for the return of residents from evacuation order areas after nuclear disaster. PLoS ONE. 2015;10(3):e0121990.

17. Yoshida K, Hashiguchi K, Taira Y, Matsuda N, Yamashita S, Takamura N. Importance of personal dose equivalent evaluation in Fukushima in overcoming social panic. Radiat Prot Dosim. 2012;151(1):144–6.

18. Tsukazaki A, Taira Y, Orita M, Takamura N. Seven years post-Fukushima: long-term measurement of exposure doses in Tomioka Town. J Radiat Res. 2019;60(1):159–60.

19. Matsuo M, Taira Y, Orita M, Yamada Y, Ide J, Yamashita S, *et al*. Evaluation of environmental contamination and estimated radiation exposure dose rates among residents immediately after returning home to Tomioka Town, Fukushima Prefecture. Int J Environ Res Public Health. 2019;16(9):1481.

20. Cui L, Taira Y, Matsuo M, Orita M, Yamada Y, Takamura N. Environmental remediation of the difficult-to-return zone in Tomioka Town, Fukushima Prefecture. Sci Rep. 2020;10(1):10165.

21. UNSCEAR. UNSCEAR 2013 Report Volume I: Sources, Effects and Risks of Ionizing Radiation: New York: United Nations; 2013.

22. Saito K, Ishigure N, Petoussi-Henss N, Schlattl H. Ambient dose equivalent conversion coefficients for radionuclides exponentially distributed in the ground. J Nucl Sci Technol. 2014;51:1274–87.

23. Taira Y, Matsuo M, Orita M, Matsunaga H, Takamura N, Hirao S. Assessment of localized and resuspended ^{137}Cs due to decontamination and demolition in the difficult-to-return zone of Tomioka town, Fukushima Prefecture. Integr Environ Assess Manag. 2022;18(6):1555–63.

24. MHLW. Guidelines on Prevention of Radiation Hazards for Workers Engaged in Decontamination Works. Tokyo: Ministry of Health, Labour and Welfare, Japan; 2018. [cited 2022 Sep 3]. Available from: https://www.mhlw.go.jp/english/topics/2011eq/workers/ri/gn/gn_141118_a01.pdf.

25. Yamaguchi T, Taira Y, Matsuo M, Orita M, Yamada Y, Takamura N. Local levels of radiation exposure doses due to radiocesium for returned residents in Tomioka Town, Fukushima Prefecture. Radiat Prot Dosim. 2021;193(3–4):207–20.

26. Koarashi J, Atarashi-Andoh M, Matsunaga T, Sanada Y. Forest type effects on the retention of radiocesium in organic layers of forest ecosystems affected by the Fukushima nuclear accident. Sci Rep. 2016;6:38591.

27. Kato H, Onda Y. Determining the initial Fukushima reactor accident-derived cesium-137 fallout in forested areas of municipalities in Fukushima Prefecture. J For Res. 2018;23(2):73–84.

28. e-Stat. Portal Site of Official Statistics of Japan; Search result top page; System of Social and Demographic Statistics; Social Indicators by Prefecture 2019; Social Indicators by Prefecture; Natural Environment. Statistics Bureau, Tokyo: Ministry of Internal Affairs and Communications, Japan [cited 2022 Sep 3]. Available from: http://www.e-stat.go.jp/SG1/estat/GL32020101.do?method= extendTclass&refTarget=toukeihyo&listFormat=hierarchy&statCode=00200502&tstatCode=000001095536&tclass1=&tclass2=&tclass3=&tclass4=&tclass5=.

29. Taira Y, Matsuo M, Yamaguchi T, Yamada Y, Orita M, Takamura N. Radiocesium levels in contaminated forests has remained stable, even after heavy rains due to typhoons and localized downpours. Sci Rep. 2020;10(1):19215.

30. Taira Y, Inadomi Y, Hirajou S, Fukumoto Y, Orita M, Yamada Y, *et al*. Eight years post-Fukushima: is forest decontamination still necessary? J Radiat Res. 2019;60(5):705–7.

31. MEXT. Environmental Radioactivity and Radiation in Japan. Tokyo: Ministry of Education, Culture, Sports, Science and Technology, Japan; 2022 [cited 2022 Sep 3]. Available from: https://www.kankyo-hoshano.go.jp/en/.

32. Japan Chemical Analysis Center. Radioactivity Measurement Method Series. Chiba: Japan Chemical Analysis Center; 2000–2013 [cited 2022 Sep 3]. Available from: http://translate.google.co.jp/translate?hl=ja&sl=ja&tl=en&u=http%3A%2F%2Fwww.jcac.or.jp%2F.