Annex III of Technical Volume 4
LEVELS OF RADIOACTIVITY IN THE TERRESTRIAL ENVIRONMENT

Monitoring of radioactivity in the environment was carried out in Japan before the accident situation developed at the Fukushima Daiichi nuclear power plant (NPP), and soon after the accidental releases began, additional monitoring commenced and is continuing. Of particular note are measurements of ambient dose equivalent rates for external exposures, activity concentrations in air and deposited on the ground, and levels of radionuclides in the terrestrial and marine environments, including activity concentrations in food and drinking water. As discussed in Section 4.2 and Annex I of this volume, direct monitoring of activity concentrations in people was also carried out.

Some of the monitoring infrastructure was severely damaged by the earthquake and tsunami, particularly on the site of the Fukushima Daiichi NPP. Despite this, steps were taken to carry out measurements on the site. For example, ambient dose equivalent rates were measured at fixed locations using a monitoring car as of 11 March. From 19 March onward, ^{131}I and ^{137}Cs activity concentrations in air were measured using a portable sampler mounted on a car that was capable of measuring both airborne particulates and gases. On 23 March, continuous radiation measurements were restarted using temporary equipment at three locations.

The early off-site monitoring response to the accident started on 18 March 2011 and included daily monitoring of ambient dose equivalent rates at fixed locations in the area extending from close to the site to approximately 60 km from the site, and at sea using portable equipment. At some fixed locations between 20 km and 60 km from the site, continuous monitoring was carried out, and the results were used to derive maps of integrated dose. Monitoring was also carried out using car- and aircraft-borne spectrometers to assess the spatial distribution of radioactive material derived from the Fukushima Daiichi NPP. Such surveys have been repeated, leading to changes in the spatial distribution of radionuclides with time to be assessed.

Samples of a range of environmental media were collected at the fixed monitoring points and analysed for activity concentrations of gamma-emitting radionuclides (mainly ^{137}Cs and ^{131}I). Terrestrial media included airborne particulates, soil, pond water, weeds and grass. Seawater and marine sediments were also monitored.

Ambient dose equivalent rates, deposition rates and activity concentrations in drinking water have been monitored on a monthly basis for decades at one location in all 47 prefectures. Following the accident, the monitoring at these locations was increased from monthly to daily monitoring until the end of 2011.

A number of organizations contributed to the offsite monitoring effort. The Ministry of Education, Culture, Sports, Science and Technology (MEXT) is the ministry with lead responsibility for monitoring of radioactivity in the environment. It was assisted by a range of partners, including prefectural governments, research institutes, universities, electric utilities and other government ministries. Assistance was also provided by organizations from other countries, notably the US Department of Energy (DOE) and Department of Defense (DOD). As discussed later, independent monitoring was also carried out by the IAEA and by non-governmental organizations such as Greenpeace and SAFECAST.

The objectives of these monitoring campaigns in the early stages were to ensure the safety of the public and to inform decisions regarding the implementation of appropriate protective actions. Later, monitoring was undertaken as the basis for dose assessment, the revision of evacuation areas, the basis for informed decisions regarding decontamination strategies and the assessment of the migration of radioactivity in the environment.

After conditions at the Fukushima Daiichi NPP had been stabilized a 'Comprehensive Radiation Monitoring Plan' was developed. This signalled a shift from emergency monitoring toward a more comprehensive and consistent assessment of the distribution and migration of radioactive material released during the Fukushima Daiichi accident in the environment. This included a comprehensive assessment of the distribution of radionuclides deposited on the ground and the migration of radionuclides through different media [III–1].

In addition to the large amount of government-led environmental monitoring activities, many volunteer and other organizations gathered information to help understanding of the radiological situation in the environment surrounding the Fukushima area. An overview of information available for various types of measurements and materials is presented below.

III–1. AMBIENT DOSE EQUIVALENT RATE

Ambient dose equivalent rate measurements were performed at a range of locations on-site at the Fukushima Daiichi NPP, more widely in Fukushima Prefecture and in Japan. These comprised a combination of fixed post, portable and mobile measurements (car-borne and airborne).

In the afternoon of 12 March 2011, the wet venting at Unit 1 was carried out, and the pressure of the drywell decreased for the period from 14:00 to 15:00, indicating an atmospheric release of radionuclides from the stack. An increase in the ambient dose equivalent rate of up to 1590 μSv/h was observed at 15:00 at Kamihatori/Futaba Town (5.6 km NW from the site), which then decreased to 37 μSv/h due to radionuclides deposited on the ground. Subsequently, the hydrogen explosion at Unit 1, which occurred at 15:36 on 12 March, led to an increase in the ambient dose equivalent rate at Shinzan/Futaba Town (3.9 km NNW) to 904 μSv/h at 17:00. The dose rate after the passage of the plume remained at a level of around 200 μSv/h due to radionuclides deposited on the ground.

During the night of 14 March to the early morning of 15 March, an increase in the ambient dose equivalent rate was observed to the south of the site. This increase occurred at Iwaki City (43 km SSW) before midnight on 14 March and reached a maximum of 23.72 μSv/h at 04:00 on 15 March. Also, at the Japan Atomic Energy Agency (JAEA) at Tokaimura (120 km S), an increase in ambient dose equivalent rate occurred from about 02:00; a maximum of about 5 μSv/h was reached at 08:00 on 15 March.

In the period between the morning of 15 March to the morning of 16 March, the ambient dose equivalent rate was observed toward the south of the site; from around 07:00 on 15 March at Yonomori/Tomioka Town (7.3 km SSW) and Matsudate/Naraha Town (14.2 km SSW) an increase to 41 μSv/h and 19 μSv/h, respectively, was recorded. The monitoring points detected the clockwise movement of the plume as it moved from the southwest to the west. An increased dose rate of 8.26 μSv/h was measured at 14:05 at Koriyama City (58 km W). Closer to the site, a value of 232 μSv/h was recorded at around 13:00 at Yamada/Futaba Town (4.1 km WNW). In the north-western direction, at Iitate Village (39 km NW) and Fukushima City (63 km NW), ambient dose equivalent rates of up to 44.7 μSv/h and 24.2 μSv/h were measured at 18:20 and 18:40, respectively. The clockwise movement of the plume reached Namie Town (8.6 km NNW) at 21:00, where a dose rate of 32.1 μSv/h was measured. The wind direction then changed in an anticlockwise direction. An ambient dose equivalent rate of 1020 μSv/h was recorded at 00:00 on 16 March, at Yamada/Futaba Town, and 44.5 μSv/h at 03:00 at Matsudate/Naraha Town. Although the plume then moved toward the Pacific Ocean, an increase in dose rates was observed again at Matsudate/Naraha Town at 11:00 on 16 March. These complex and wide movements of plume and precipitation area resulted in heterogeneous and wide ground contamination. After these increases of air dose rates, the wind direction toward the Pacific Ocean continued until in the morning of 20 March.

Between the afternoons of 20 March and 22 March, the major automated monitoring stations near the site were shut down due to the limited emergency electric power supply. Although several portable monitors were available in Fukushima Prefecture, the peaks in dose rates during the passing of the plume were unclear because of the high background level of dose rate resulting from radionuclides deposited on the ground before that date. The lack of monitoring data near the site made it difficult to clarify the movement of the plume. However, the monitoring at JAEA at Tokaimura, Setagaya ward in Tokyo, Chiba City, Wako City and Tsukuba City, mainly in the Kanto plain, detected the increases in dose rate from the morning of 21 March onward. For example, at JAEA, the increase started from about 5:00, and a maximum of about 30 μSv/h was observed at 06:00 [III–2].

Aerial monitoring of ambient dose equivalent was first performed by the US Department of Energy/National Nuclear Security Administration (US DOE/NNSA) from 17 to 19 March (see Fig. III–1) [III–3]. According to results of this monitoring the radionuclides deposited during two significant release periods (12 March and 14–16 March), and not in the third period (20–23 March). The releases in the third period affected mainly areas south of the Fukushima Daiichi NPP and in the Kanto region. Ambient dose equivalent rates extrapolated to 1 m over the ground were measured in the area within 30 km of the Fukushima Daiichi NPP as well as other areas. The results are shown in Fig. III–1.

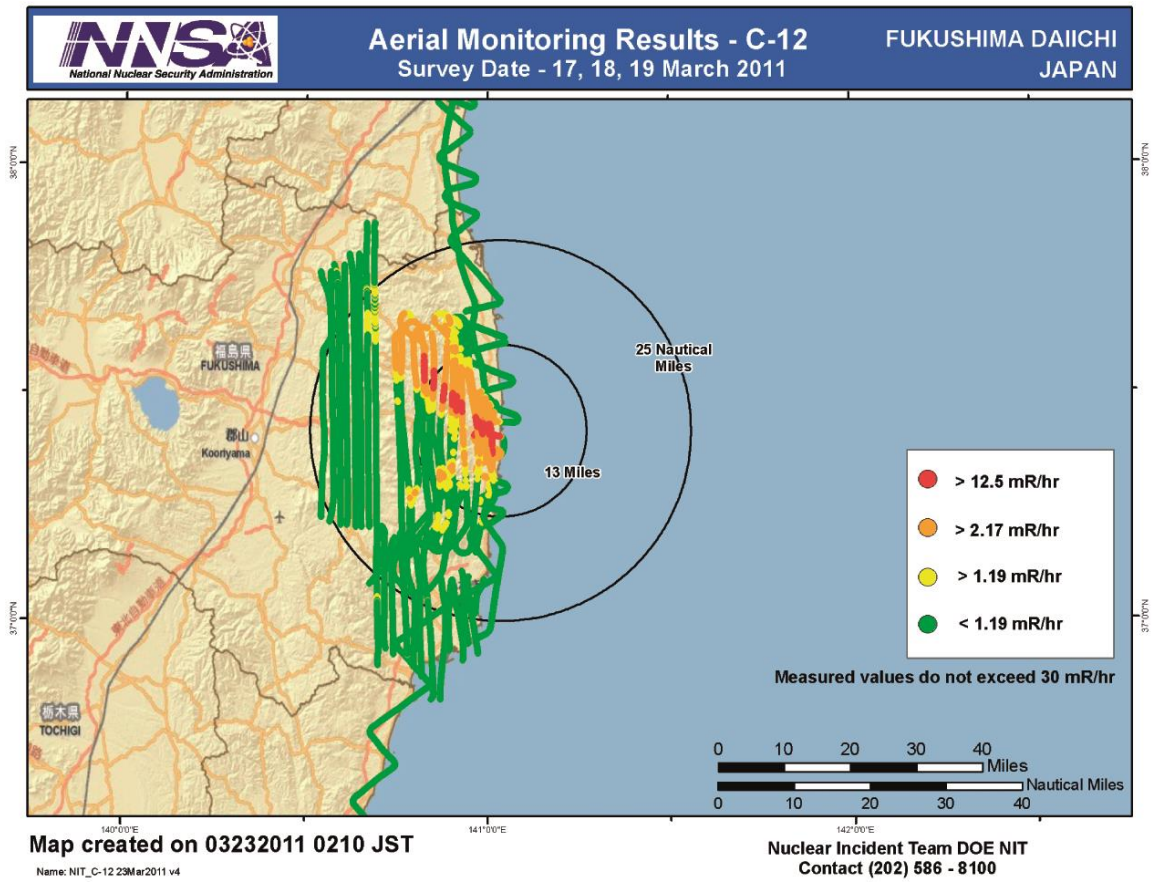


FIG. III–1. Early aerial monitoring of ambient dose equivalent rate measured from 17 to 19 March 2011 [III–3].

Joint aerial surveys were carried out by MEXT and US DOE/NNSA of the area within 80 km of the NPP between 6 and 29 April and 18 and 26 May 2011. Since then, a number of repeat surveys of this

area have been undertaken by MEXT[1]. Additional surveys of the evacuation areas and of wider areas have also been performed, as described in more detail in Appendix I.

An extensive series of ground based measurements of ambient dose equivalent rates were also carried out by MEXT in June 2011, with repeated surveys in December 2011, March 2012, and subsequently thereafter [III–4]. MEXT measured ambient dose equivalent rates continuously using vehicle-borne instruments within the area approximately 100 km from the Fukushima Daiichi NPP and areas in Fukushima Prefecture prior to the rainy season in June 2011 before any changes occurred on the soil surface (the 'first vehicle-borne survey'). A map of the results of this survey is presented in Technical Volume 3 (Fig. 3.3–17).

In order to ascertain the overall picture of the accident and collect basic information for assessing exposures, MEXT repeated the continuous measurement of ambient dose equivalent rates through a vehicle-borne survey again in December 2011, mainly in the areas where relatively higher dose rates (0.2 μSv/h) were found, corresponding to annual ambient dose rates of the order of 1 to 2 mSv (the 'second vehicle-borne survey'). As a result, MEXT ascertained the detailed distribution of ambient dose equivalent rates on roads over a widespread area (covering Ibaraki, Iwate, Kanagawa, Gunma, Saitama, Chiba, Tochigi, Fukushima, Miyagi, and Yamanashi prefectures and the Tokyo metropolitan area) before the snowfall period in December 2011. In this second vehicle-borne survey, it was not possible to cover all the roads that were requested by the municipalities, with some areas having snow coverage. The 'third vehicle-borne survey' was conducted with the cooperation of municipalities, taking into consideration the requests of the municipalities, and in the regions where it had not been possible to ascertain the distribution of ambient dose equivalent rates due to snow coverage, during the period of 13–30 March 2012. Further surveys were carried out subsequently.

In these surveys, ambient dose equivalent rates at the height of 1 m above the ground surface on roads were measured, using the Kyoto University Radiation Mapping (KURAMA) system originally developed by Kyoto University [III–5]. The KURAMA system consists of a high precision radiation detector that is mounted onto a car and determines ambient dose equivalent rates on roads by continuously collecting information on gamma rays around the roads, with locations determined by using GPS systems. The first survey used sodium-iodide (NaI) scintillation survey meters and ionization chamber survey meters separately. Soil samples were collected at measurement points. In the third survey, caesium-iodide (CsI) scintillation detectors that have similar measurement specifications as NaI scintillation survey meters were installed.

It was found that the ambient dose equivalent rates on roads decreased by around 30% during the six months from June 2011, and decreased overall by around 40% during the nine months to March 2012. Similar results were obtained by MEXT using airborne instruments to determine the distribution of ^{137}Cs and ^{134}Cs deposition in the region up to 80 km from the Fukushima Daiichi NPP [III–6].

Monitoring data from all prefectures in Japan has been made available [III–7]. On 19 June 2013, ambient dose equivalent rates (at a height of 1 m above ground) were less than 0.1 μSv/h at fixed monitoring locations in all prefectures other than Fukushima Prefecture. The measurement location in Fukushima City recorded a rate of 0.60 μSv/h corresponding to an unshielded dose rate after decay of short lived radionuclides of approximately 5 mSv/y.

III–2. ACTIVITY CONCENTRATIONS IN AIR

As of 19 March 2011, TEPCO measured particulate and gaseous phase airborne radioactivity at three locations on the Fukushima Daiichi NPP site [III–8]. The monitoring was performed with a portable car-borne air sampler. Sample times at each location were approximately 20 minutes per day. The

[1] These surveys are referred to as 'airborne' surveys in MEXT literature.

results of measurements of airborne ^{134}Cs, ^{137}Cs and ^{131}I performed from this date until the end of 2011 at locations around the Fukushima Daiichi NPP are shown in Fig. III–2.

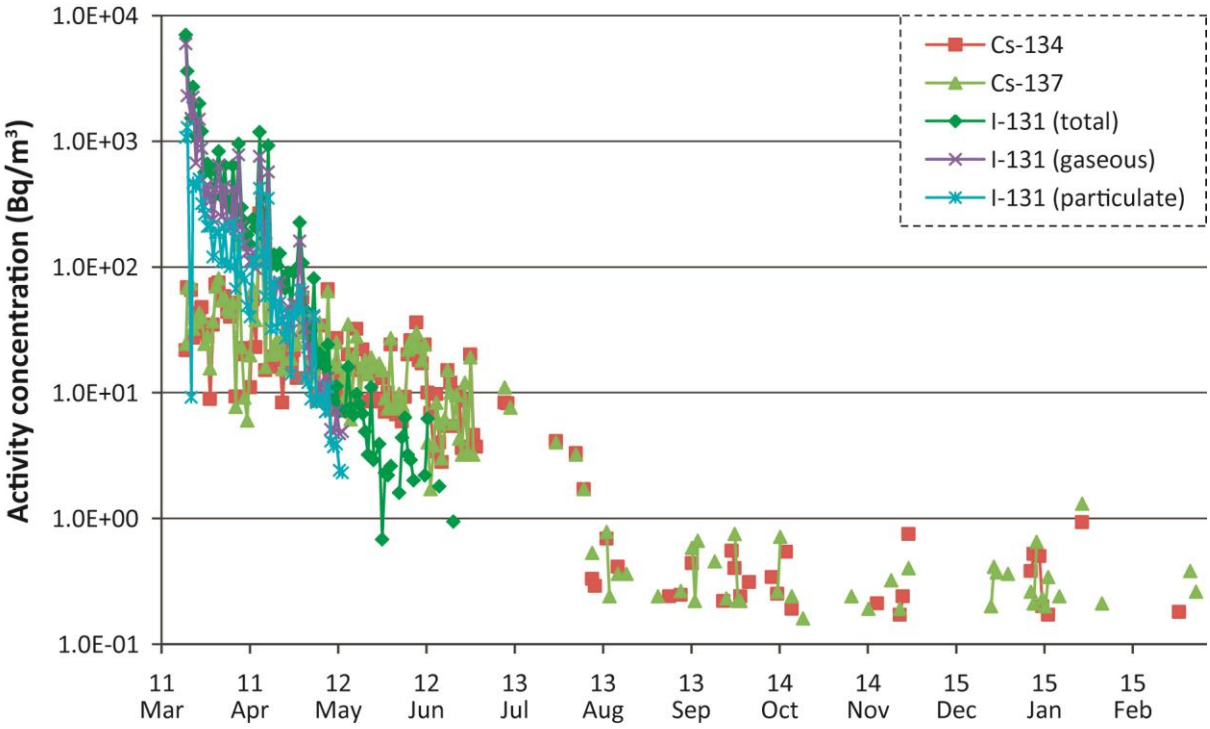


FIG. III–2. Airborne activity concentrations of ^{134}Cs, ^{137}Cs and ^{131}I measured at locations around the Fukushima Daiichi NPP from March to July 2011 [III–8].

Maximum ^{131}I activity concentrations in air of almost 10 000 Bq/m^3 were measured during the period of 19–23 March 2011. Activity concentrations remained greater than 100 Bq/m^3 until mid-April. Activity concentrations of ^{134}Cs and ^{137}Cs exceeded 100 Bq/m^3 for each isotope in early April. This monitoring started too late to detect the sharp increase in airborne radionuclides between 15 and 16 March which, as reported below, was measured by continuous monitoring at sites further away from the Fukushima Daiichi NPP.

On 21 March, MEXT issued a monitoring plan for areas outside the 20 km zone from the Fukushima Daiichi NPP, called the Plan to Conduct Detailed Monitoring in Restricted Area and Planned Evacuation Zone, which was revised three times before a plan to conduct detailed monitoring was issued on 13 June [III–9].

Continuous monitoring of Fukushima Daiichi NPP derived activity concentrations in air was performed by a number of organizations in Japan. The locations, all within a distance of between 100 km and 250 km from the Fukushima Daiichi NPP, are shown in Fig. III–3. A range of sampling instrumentation and frequencies was employed. Table III–1 provides summary information of the monitoring performed at each location. Unfortunately, as air monitoring stations to the north and west of the Fukushima Daiichi NPP were not operating due to damage caused by the earthquake and tsunami, the measurements considered here are all for locations south-west of the site. As a result, only a partial view of the variation of the activity concentrations of radionuclides in air in Japan during this period is available. Additional measurements were performed by KMRIEP & AORI (University of Tokyo)/Osaka University at Tajima (Kawasaki City) [III–2] and by the US DOD and

US DOE/NNSA at Yokota Air Base. Both locations are also in the area south-west of the Fukushima Daiichi NPP.

TABLE III–1. CONTINUOUS MONITORING OF AIR CONCENTRATIONS

(adapted from Terada et al. (2012) [III–10])

Sampling station (Sampling/Measurement Organization)	Sampling equipment (Filters)	Particulate (P)/ Gaseous (G) ^{131}I	Sampling frequency (hours or days)	Sampling period	References
Tokaimura (Ibaraki Prefecture) (JAEA-TRDC)	L.V. (HE-40T & CHC-50)	P & G (separate measurements)	3 h–12 h	14 Mar. 2011–23 May 2011	Furuta et al. (2011) [III–11]
Tsukuba (Ibaraki Prefecture) (NIES/KEK)	H.V. (QF & ACF-KF1700)	P & G (total)	3 h–2 d	15 Mar. 2011–18 Jan. 2013	Masumoto et al. (2011) [III–12] Data: KEK website
Takasaki (Gunma Prefecture) (CTBTO)	RASA (PP-filter)	P	1 d	12 Mar. 2011–31 Dec. 2012	Yonezawa and Yamamoto (2011) [III–13] Data: CTBTO website
Wako (Saitama Prefecture) (RIKEN)	L.V. (HE-40T)	P	0.5 h–1 d	15 Mar. 2011–16 Mar. 2012	Haba et al. (2012) [III–14]
Setagaya (Tokyo Metropolitan Area) (TMITRI)	H.V. (GB100R)	P	1 h–8 h	13 Mar. 2011–30 Sep. 2011	Nagakawa et al. (2011) [III–15] Data: TMITRI (2012) [III–16]
Chiba (Chiba Prefecture) (JCAC)	L.V. (HE-40T & CP-20)	P & G (total)	1 d	14 Mar.2011–14 May 2011	Amano et al. (2012) [III–17] Nagaoka et al. (2012) [III–18]

Notes: JAEA-TRDC: Japan Atomic Energy Agency, Tokai Research and Development Center; NIES: National Institute for Environmental Studies; KEK: High Energy Accelerator Research Organization; CTBTO: Comprehensive Nuclear-Test-Ban Treaty Organization; RIKEN: RIKEN Wako Institute; JCAC: Japan Chemical Analysis Centre; TMITRI: Tokyo Metropolitan Industrial Technology Research Institute. L. V.: Low volume air sampler. H. V.: High volume air sampler. QF: quartz fibre. ACF: Activated carbon fibre.

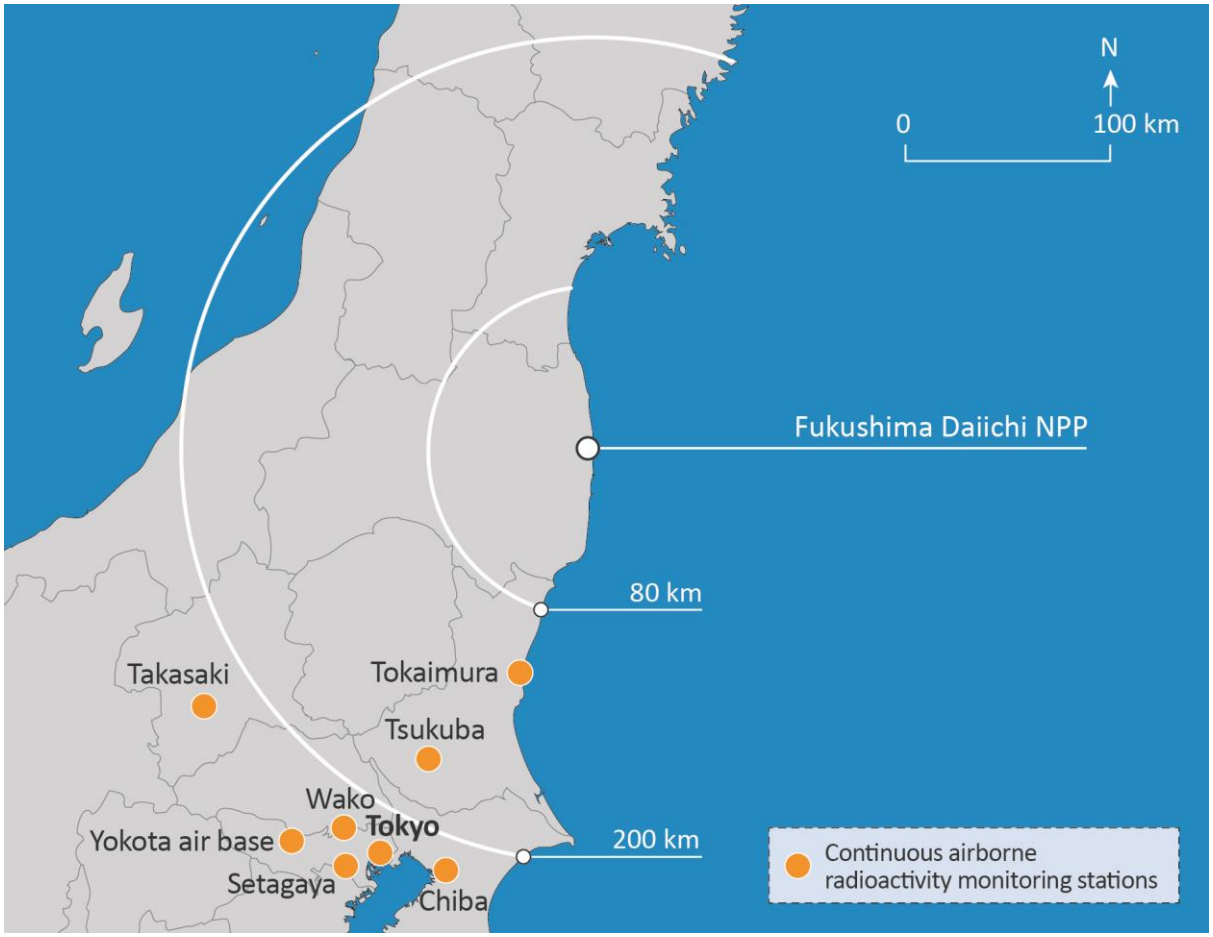


FIG. III–3. Locations of continuous airborne radioactivity monitoring stations (Illustration adapted from Terada et al. (2012) [III–10]).

Selected results from the continuous monitoring of airborne radioactivity are shown below.

Concentrations of ^{137}Cs are shown in Fig. III–4 for all monitoring locations, with the exception of the Yokota Air Base. Concentrations of total ^{131}I (i.e. in both particulate and gaseous chemical forms) are shown in Fig. III–5 for three monitoring locations for which such measurements were performed. A TEDA (triethylene di-amine) impregnated carbon filter, or similar, is required to capture gaseous iodine. As indicated in Table III–1, some stations did not employ such a filter and thus reported only activity concentrations of ^{131}I in particulate form.

Activity concentrations of airborne ^{134}Cs, ^{137}Cs and ^{131}I measured at selected locations in 2011 are shown in Fig. III–6. Activity concentrations of airborne ^{133}Xe, a noble gas, are also shown for the Takasaki station. This radionuclide was measured uniquely at this CTBTO station.

Radiocaesium (^{134}Cs, ^{136}Cs and ^{137}Cs), radioiodine (^{131}I) and radiotellerium (^{132}Te) were detected at all monitoring stations. Other radionuclides detected at one or more stations included ^{132}I, ^{133}I, ^{129}Te, ^{129m}Te and ^{99}Mo/^{99m}Tc.

The figures show that variations of several orders of magnitude in activity concentrations of both ^{137}Cs and ^{131}I were observed during the first two to three months following the accident at the Fukushima Daiichi NPP. A number of peaks can be observed in these figures, detected with a fair degree of consistency at approximately the same dates at each location. The first was observed around 14–16 March. Measured levels of airborne ^{131}I were generally high relative to those of radiocaesium.

Nagaoka et al. (2012) [III–18] reported, on the basis of measurements using an in situ (outdoor) HPGe gamma spectrometer in Chiba, that the sharp rise observed during this period resulted from airborne ^{133}Xe, ^{131}I and ^{132}I. Two subsequent, more-sustained peaks were observed around 20–21 March and 29–30 March. Levels of ^{131}I, ^{134}Cs and ^{134}Cs were more or less equal in these later peaks. These results again support the pattern of releases and dispersion described earlier. Smaller peaks were observed in late April and in May, confirming that lower level releases from Fukushima Daiichi continued after the main release period from 12 to 23 March.

A maximum activity concentration of ^{131}I of 1600 Bq/m^3 was measured in Tokaimura, the closest monitoring point to the Fukushima Daiichi NPP, on the morning of 15 March. Maximum activity concentrations of ^{134}C and ^{137}Cs of 180 and 190 Bq/m^3, respectively, were measured during the same sampling period. Note that these values are of the same order of magnitude as those measured by TEPCO at the site perimeter (Fig. III–2). As can be seen from the figure, the observed ratio of ^{134}Cs/^{137}Cs was approximately 1 at all locations. The maximum concentration of ^{133}Xe measured at Takasaki was 400 Bq/m^3 on 16 and 17 March.

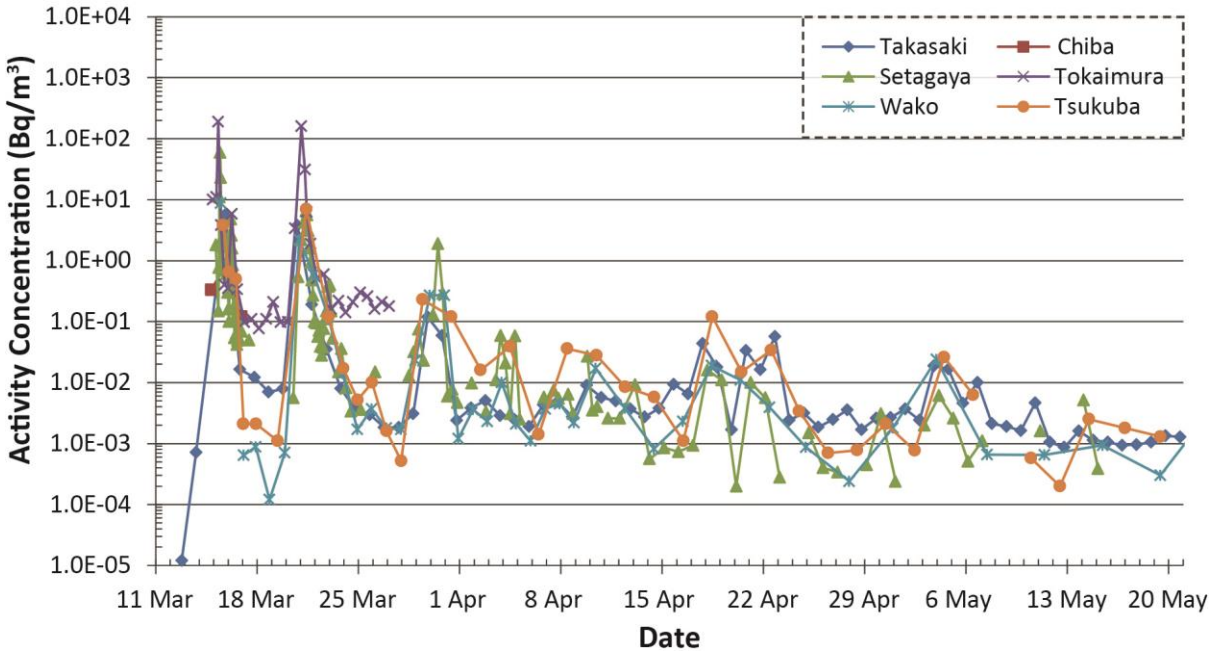


FIG. III–4. ^{137}Cs activity concentrations in air at various locations in 2011 [III–11 to III–18].

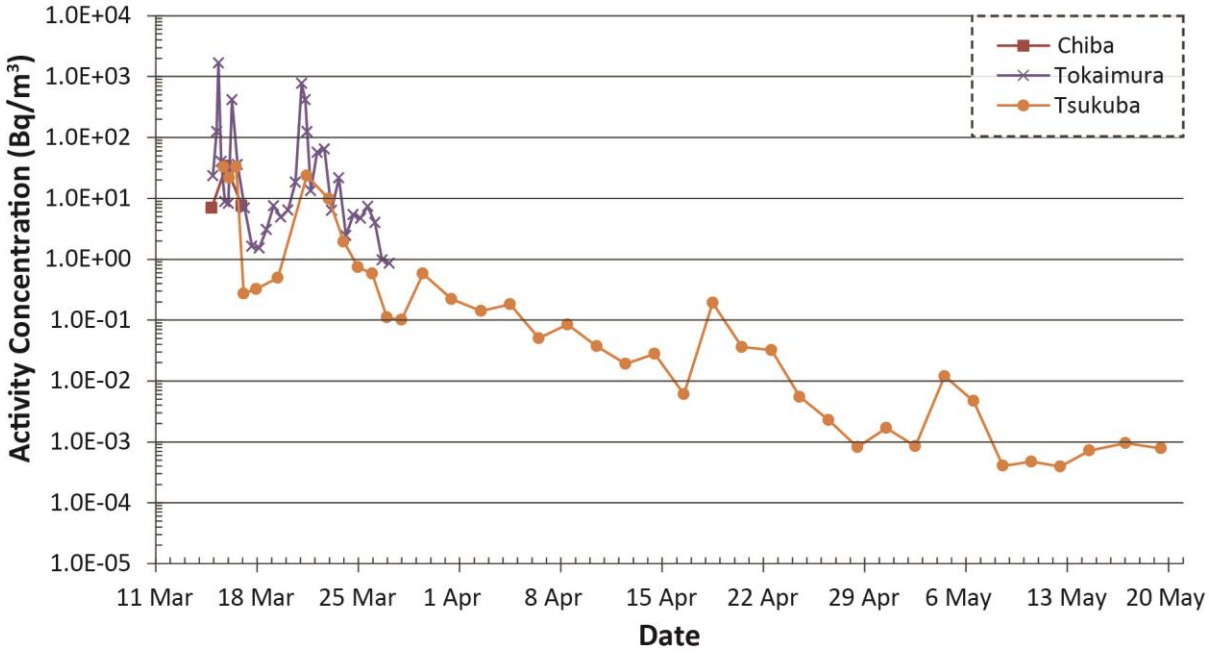
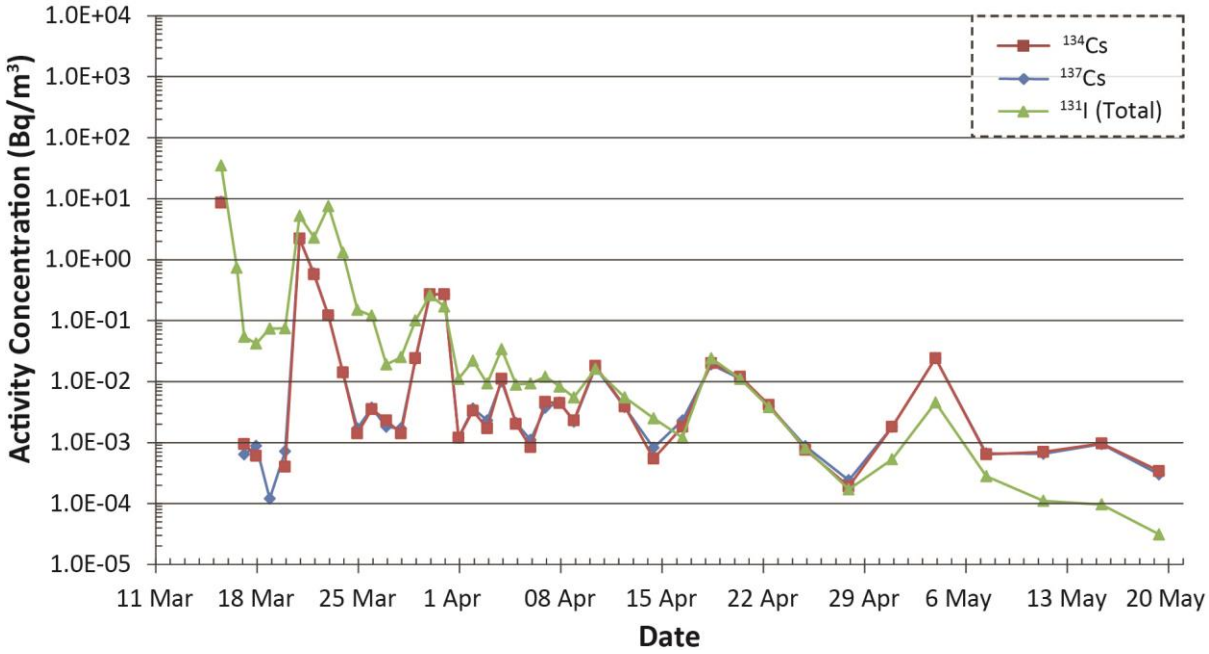
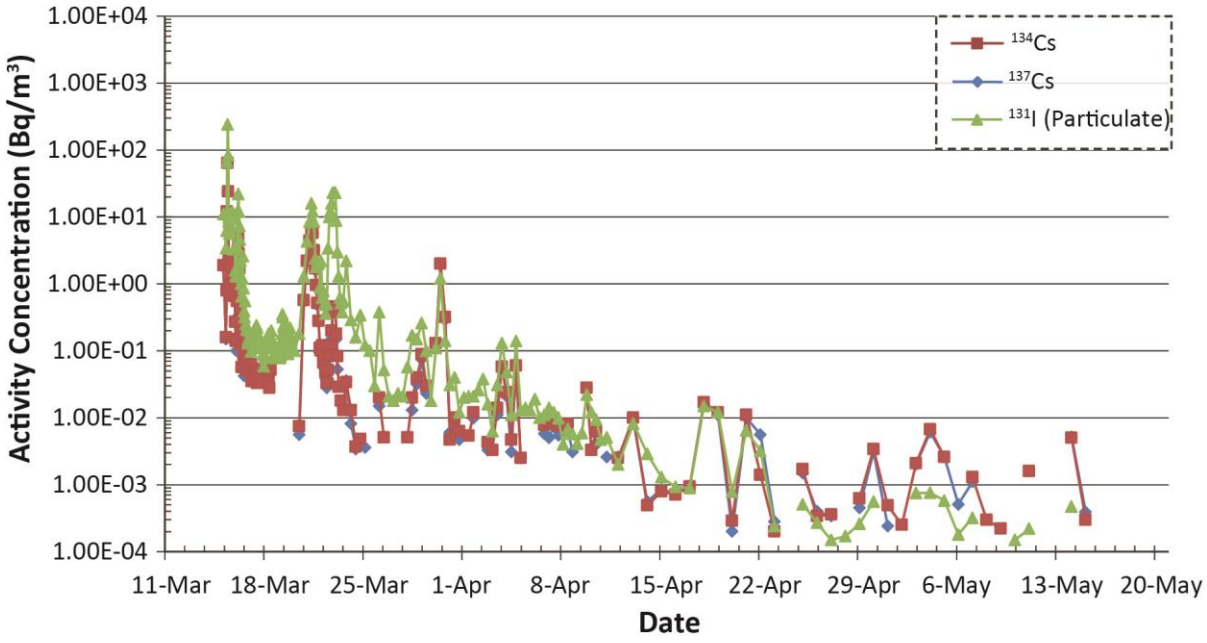


FIG. III–5. Total ^{131}I activity concentration in air at various locations in 2011 [III–11, III–12, III–17, III–18].



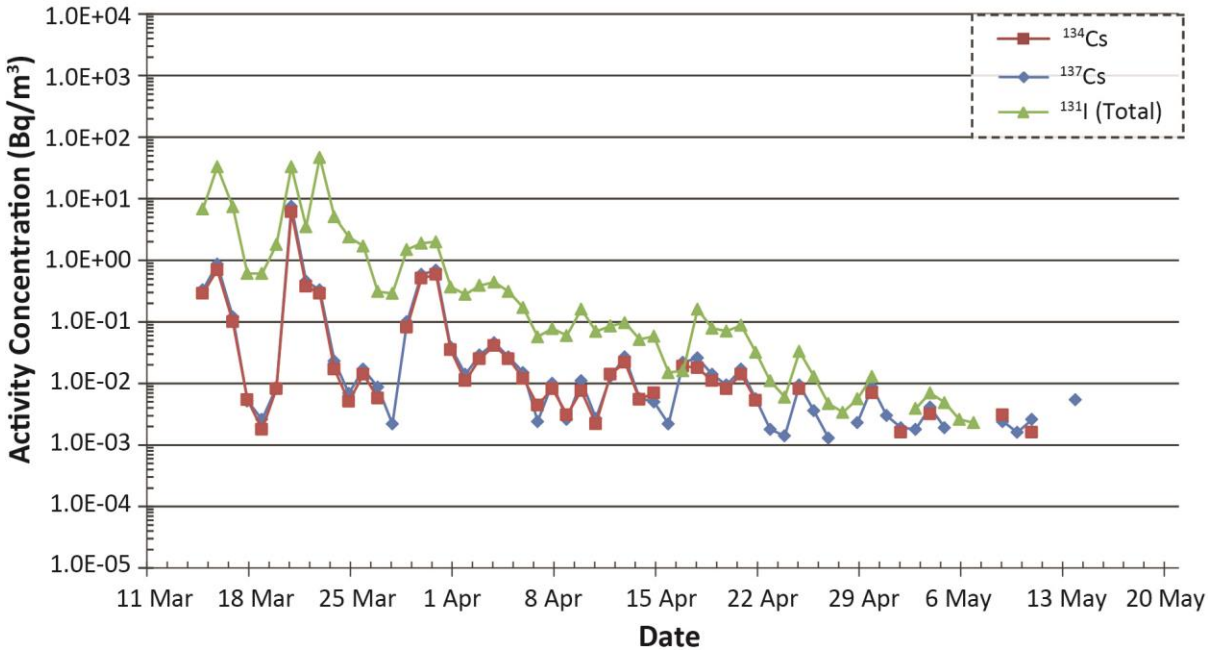
(a)

FIG. III–6(a). Activity concentrations of ^{131}I, ^{134}Cs and ^{137}Cs measured at continuous monitoring stations in Wako City, Saitama Prefecture in 2011. [III–14].



(b)

FIG. III–6(b). Activity concentrations of ^{131}I, ^{134}Cs and ^{137}Cs measured at continuous monitoring stations in Setagaya, Tokyo in 2011. [III–15, III–16]



(c)

FIG. III–6(c). Activity concentrations of ^{131}I, ^{134}Cs and ^{137}Cs measured at continuous monitoring stations in Chiba in 2011[III–17, III–18].

The ratios of ^{134}Cs to ^{137}Cs calculated from these results are shown in Fig. III–7. This ratio was found to be quite constant between the different stations, with an average value of around 1.

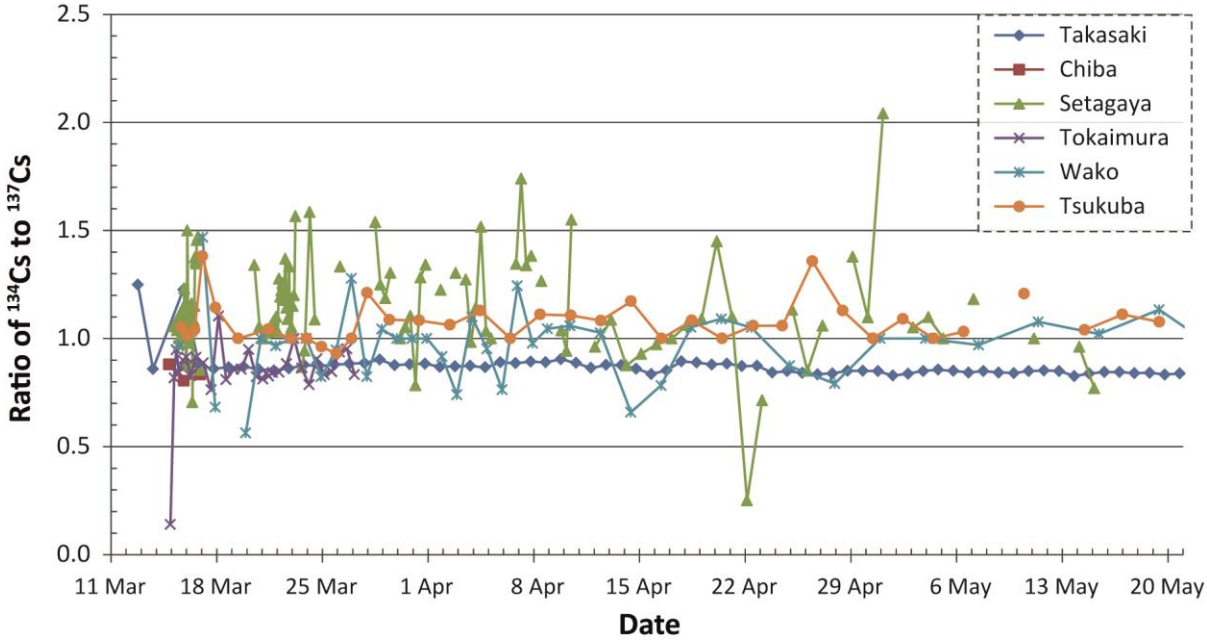


FIG. III–7. Ratios of activity concentrations of airborne ^{134}Cs to ^{137}Cs [III–11 to III–18].

The ratio of ^{131}I in the particulate and gaseous (I_2 and CH_3I) forms, relative to the total ^{131}I activity concentration, is shown in Fig. III–8 [III–19] for measurements performed at the Fukushima Daiichi site and at Tokaimura. It can be observed that the ^{131}I activity concentration in gaseous form was higher throughout the majority of the measurement period at both locations. At the Fukushima Daiichi NPP, the ratio varied significantly. It is impossible to say with confidence whether this is a true observation of rapidly varying relative gaseous and particulate phase activity concentrations close to the release location or simply a reflection of the greater uncertainty of these measurements having been taken using portable instruments with a relatively shorter sampling duration. The results for Tokaimura demonstrated a slight upward trend with time. The contribution of gaseous ^{131}I to total ^{131}I concentration in air was, on average, 0.72 ± 0.10 (range: 0.40–0.90). However, for the period when the plume was transported towards Tokaimura, in the mornings of 15, 16 and 21 March, the ratio was in the range 0.5–0.7.

The ratio could vary with time simply because the gaseous to particulate ratio varied with time over the release period. Another influence is thought to be that the particulate fraction is more subject to wet deposition. In Fukuoka, which is about 1000 km west of Fukushima Daiichi, the ^{131}I gaseous/total iodine ratio varied between 0.30 and 0.67 [III–20]. The increase in gaseous/total ^{131}I ratios with time suggests that ^{131}I remained mainly in its gaseous form during transport. The exchange between gaseous to particulate form, if it exists, was not sufficient to counterbalance the decrease in particulate ^{131}I fraction due to wet deposition. Therefore, the net decrease in concentrations of particulate ^{131}I was faster than that concentrations of gaseous ^{131}I, leading to an increase in gaseous/total ^{131}I ratio.

Amano et al. (2012) [III–17] reported gaseous to total ^{131}I ratios from Chiba of 0.71 during the period 15-16 March, 0.52 for 20–21 March and 0.68 for 22–23 March 2011.

Ohara et al. (2011) [III–21] analysed the data of atmospheric concentrations of radionuclides measured in Tsukuba and demonstrated that the radionuclide composition showed a large degree of temporal variability. The gaseous fraction of ^{131}I was dominant, while ^{137}Cs was present as particulate matter with diameters of several micrometres. They simulated the deposition of ^{131}I and ^{137}Cs in Fukushima Prefecture and the surrounding area (southern Tohoku, Kanto, and eastern Chubu

districts). The high deposition rates were concentrated in two periods from 15 to 16 March and a few days after 21 March, when the peaks of radioactivity in the atmosphere were detected. On average, the amounts of deposition for ^{131}I and ^{137}Cs in ten prefectures in southern Tohoku and Kanto were about 13% of the emissions from the Fukushima Daiichi NPP for both nuclides. Most of ^{131}I deposited in the studied area was due to dry deposition, whereas wet deposition was dominant for ^{137}Cs.

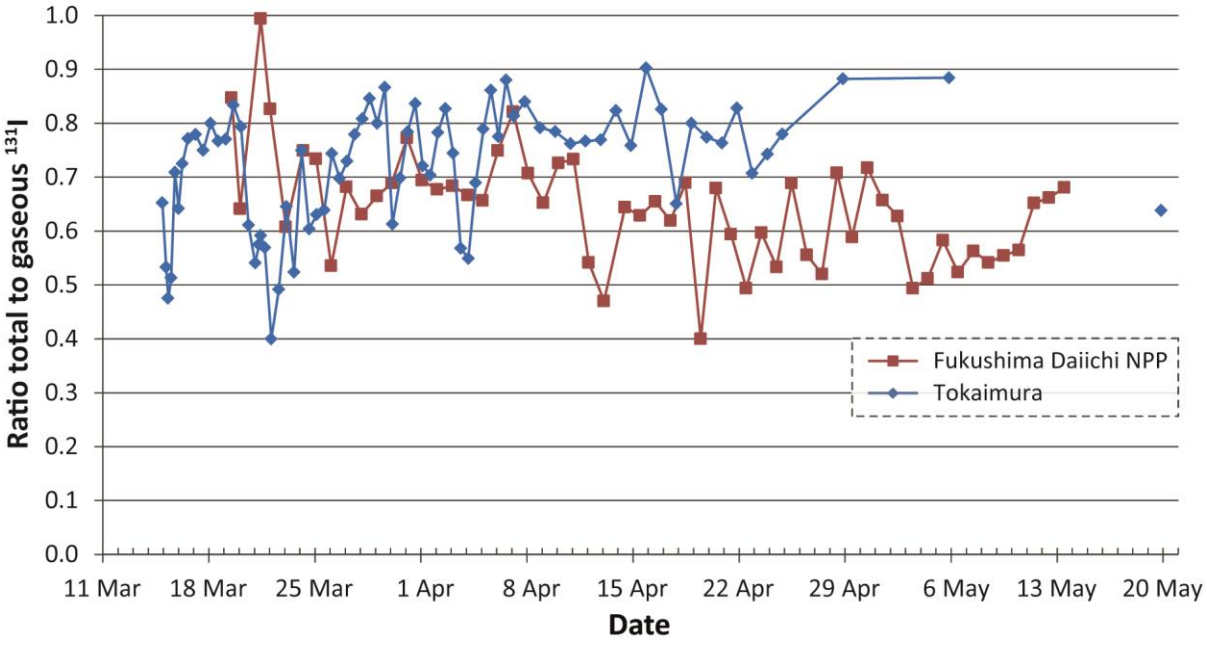


FIG. III–8. Ratio of gaseous ^{131}I to total ^{131}I measured at the Fukushima Daiichi site and at Tokaimura [III–19].

III–3. MEASUREMENTS OF DEPOSITION RATES

Samples of deposited radionuclides are routinely collected and analysed in all 47 prefectures in Japan. In Fukushima Prefecture, monitoring was undertaken in Futaba Town, a distance of approximately 5 km from the Fukushima Daiichi NPP, and monthly records go back to April 1968 [III–22].

Deposition rates are monitored by collecting rain and particulate matter ('dust') over the duration of each month in an elevated stainless steel tray, approximately 0.5 m^2 in area. Water is maintained at a level of approximately 1 cm in the tray to prevent dry material from blowing away. At the end of the month, all contents of the tray are carefully transferred to a container, evaporated to dryness and analysed for gamma emitting radionuclides.

Monthly deposition rates of ^{134}Cs and ^{137}Cs in Fukushima Prefecture, which have been measured since March 2011, are shown in Fig. III–9 [III–23]. Significantly elevated rates for the period March to May 2011 can be attributed directly to the deposition of radioactive material released from the Fukushima Daiichi NPP as a result of the accident.

In subsequent months, deposition rates of ^{134}Cs and ^{137}Cs dropped by between two and three orders of magnitude compared to the peak of over 1 000 000 Bq/m^2 per month in March 2011; however, they remain higher than those measured before the accident. Between April 2008 and March 2009, the period for which the most up to date pre-accident data have been published, an average monthly deposition rate of ^{137}Cs recorded was 0.016 Bq/m^2 per month [III–24]. In contrast, between June 2011 and January 2014, the average rate was 4300 Bq/m^2 per month. The reason for this is thought to be the

secondary transport of radioactive dust, which has been resuspended and redeposited by wind and/or rain.

A slight downward trend in monthly deposition rates over a three year period since the accident is evident from Fig. III–9 in the case of ^{134}Cs, but not ^{137}Cs. The ^{134}Cs decrease is due to radioactive decay. The consistent values measured for ^{137}Cs is a further indicator that resuspension and redeposition of radioactive dust is taking place.

A distinct seasonal variation is also evident from Fig. III–9. Monthly accumulated rainfall measurements from Namie Town, the closest meteorological station to Futaba Town, for the same period are also shown in Fig. III–9. There is an inverse correlation between rainfall levels and deposition rates of radiocaesium. Deposition rates are lower in the wetter summer months and higher in the dry late autumn to early spring period. This is characteristic of resuspension, a transport process which is suppressed when the ground is wet.

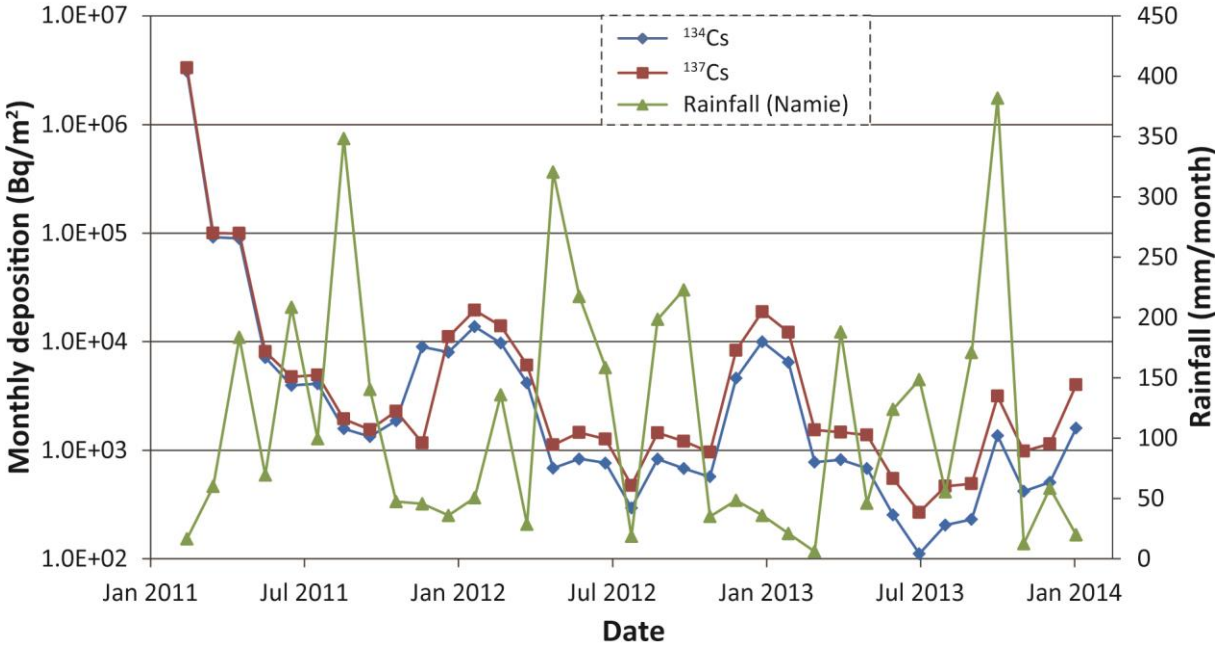


FIG. III–9. Monthly deposition rates of ^{134}Cs and ^{137}Cs and monthly accumulated rainfall measured in Fukushima Prefecture [III–23].

In addition, in March 2011, measurements of daily deposition rates were made at a number of locations at a distance from the Fukushima Daiichi NPP. Figures III–10 and III–11 shows the measured daily deposition rates at a number of different locations for ^{131}I and ^{137}Cs.

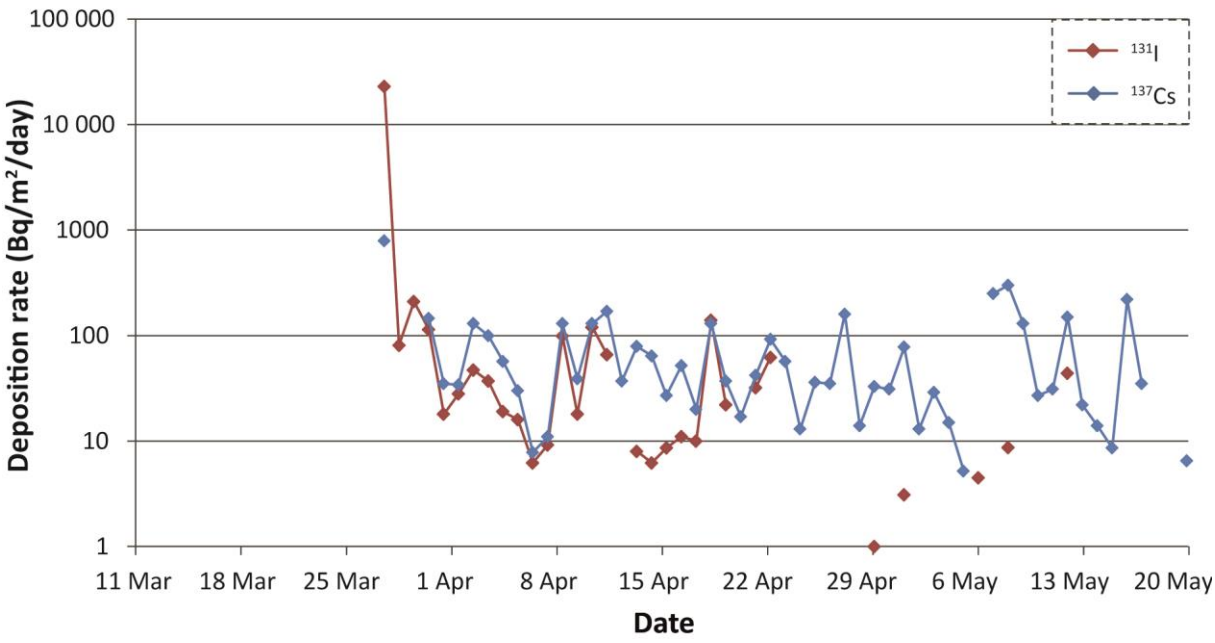
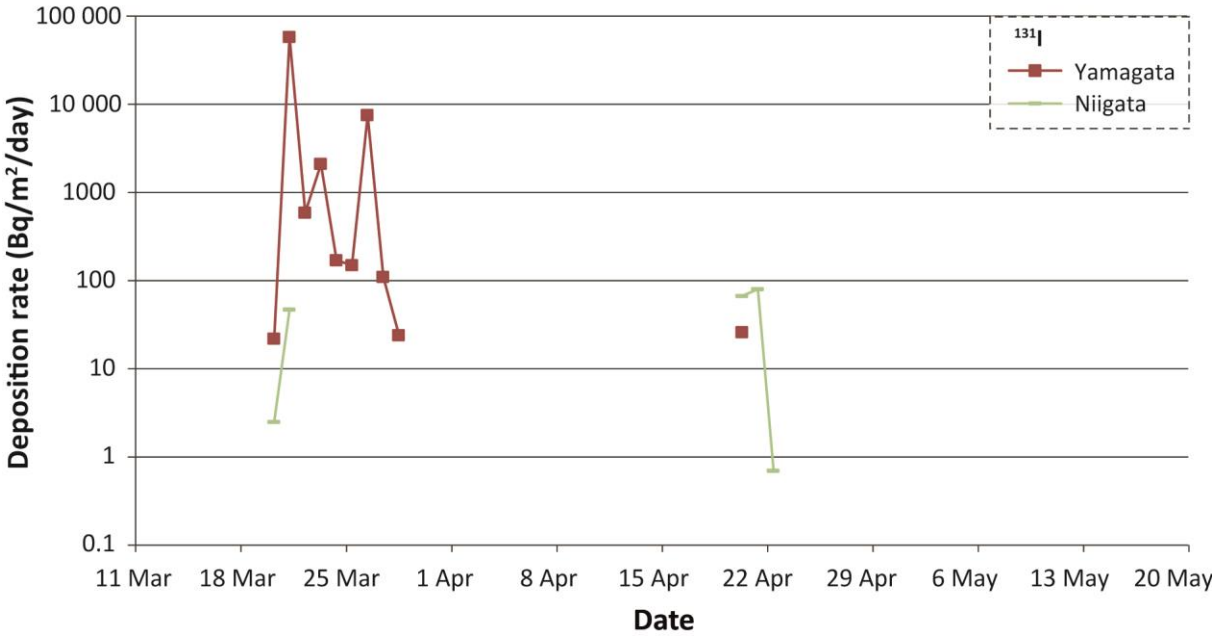
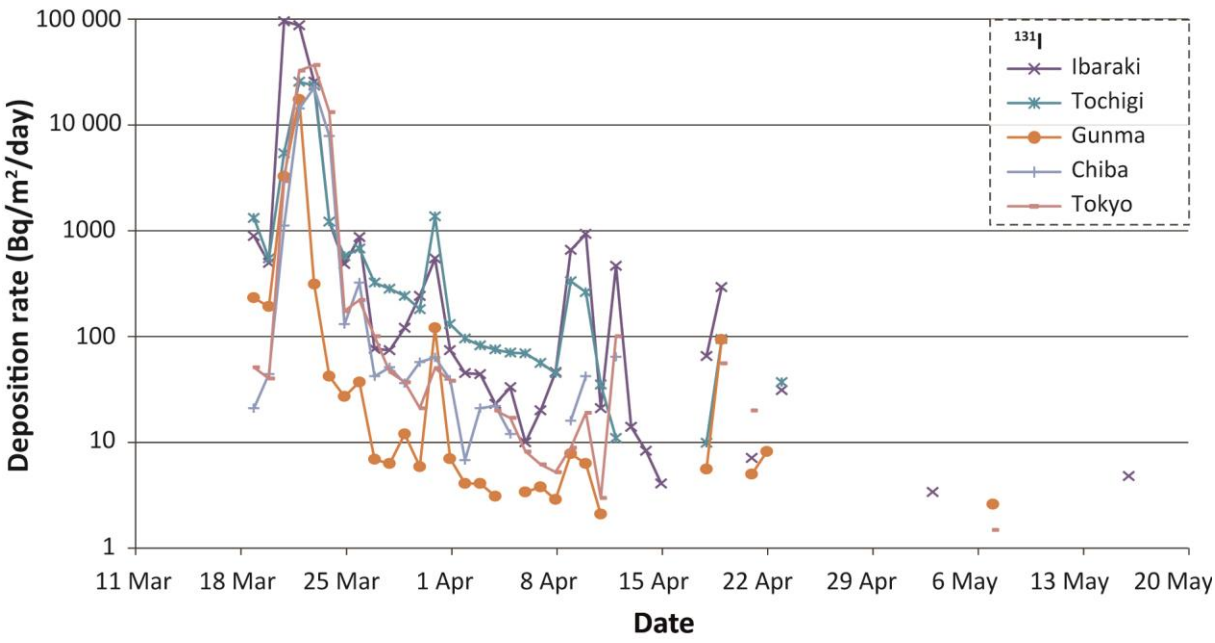


FIG. III–10. Daily deposition rates of ^{137}Cs and ^{131}I measured in Fukushima Prefecture, March–May 2011 [III–23].



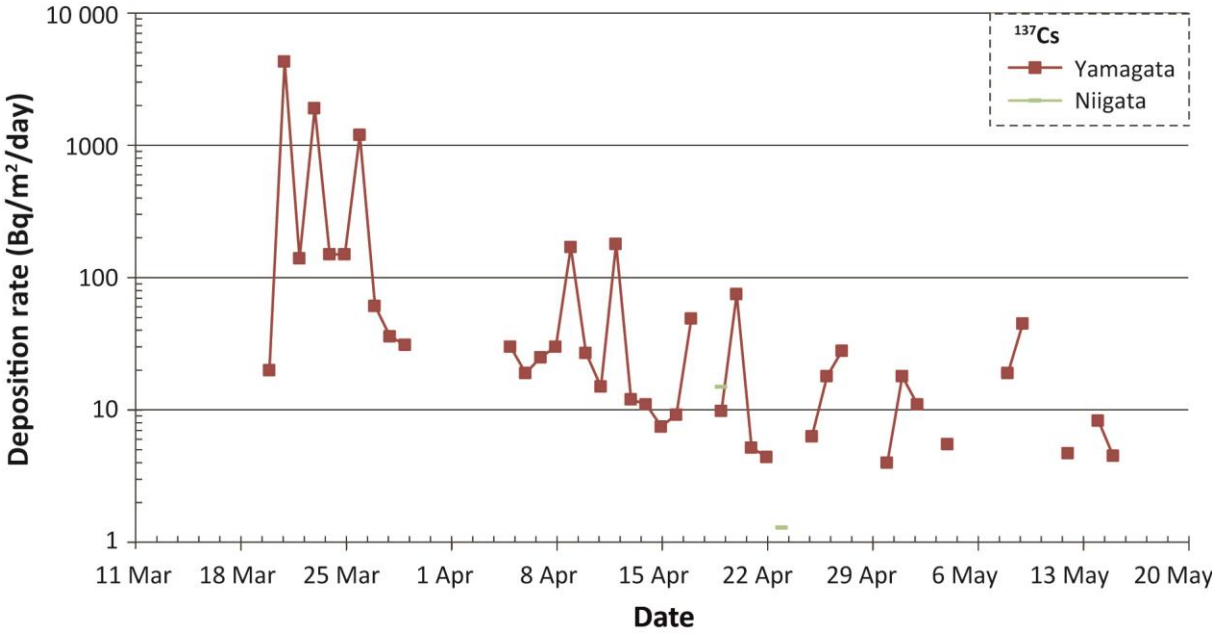
(a)

FIG. III–11(a). Measured daily deposition rates of ^{131}I at Yamagata and Niigata between March and May 2011 [III–23].



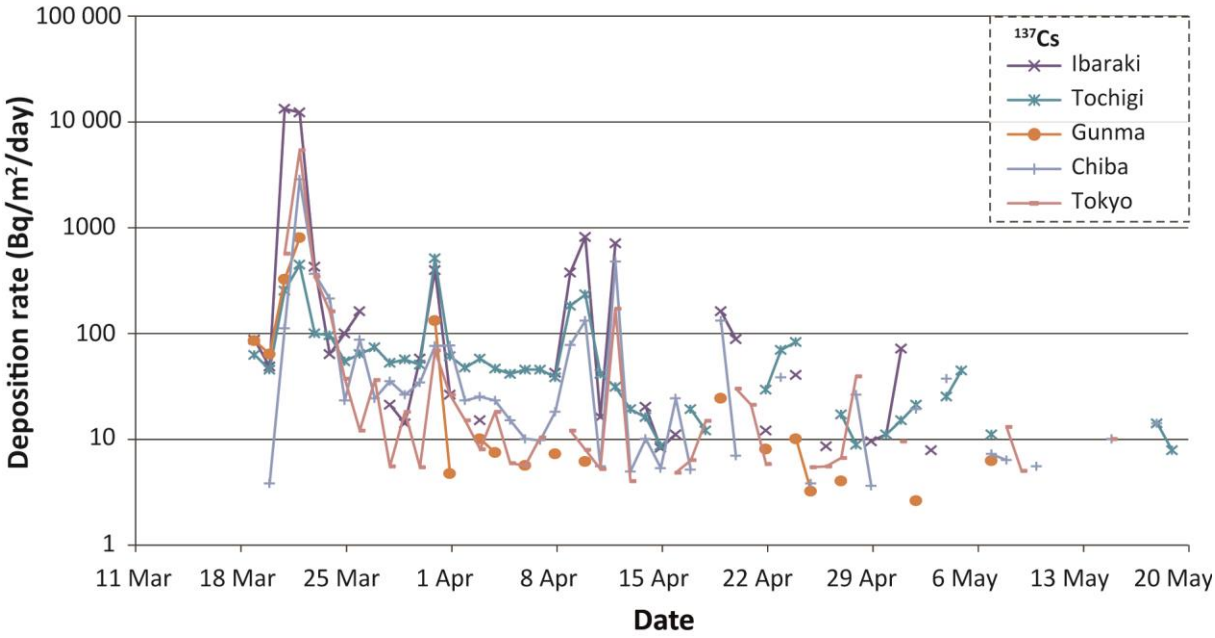
(b)

FIG. III–11(b). Measured daily deposition rates of ^{131}I at different locations between March and May 2011 [III–23].



(c)

FIG. III–11(c). Measured daily deposition rates of ^{137}Cs at Yamagata and Niigata between March and May 2011 [III–23].



(d)

FIG. III–11(d). Measured daily deposition rates of ^{137}Cs at different locations between March and May 2011 [III–23].

III–4. SOIL MEASUREMENTS

Soil sampling, followed by laboratory based measurements, constitute the most accurate means of determining the spatial distribution of deposited radionuclides. Soil samples from around 60 locations in the area between 20 and 60 km from the Fukushima Daiichi NPP were collected by MEXT from 18 March onwards and analysed for ^{131}I, ^{134}Cs, ^{137}Cs, ^{89}Sr and ^{90}Sr. The sampling method used involved taking five individual samples collected at each location which were analysed separately. Samples from a small number of these locations were also analysed for ^{238}Pu and ^{239,240}Pu. Samples were also collected from four locations within the 20 km zone and analysed for the gamma emitting nuclides ^{131}I, ^{134}Cs, ^{136}Cs, ^{137}Cs and ^{129m}Te.

A number of university studies were also undertaken in the area between 20 and 80 km from the Fukushima Daiichi NPP, e.g. Endo et al. (2012) [III–25], Kinoshita et al. (2011) [III–26], Fujiwara et al. (2012) [III–27, III–28]. The results of many of these have been collected in the proceedings of an International Symposium on Environmental Monitoring and Dose Estimation after the Accident at TEPCO's Fukushima Daiichi Nuclear Power Station [III–29].

Endo et al. [III–25] sampled soils in March 2011 in areas north-west of the Fukushima Daiichi NPP. The radionuclides they detected and maximum activity concentrations of each, decay normalized to 17:00 on 15 March, are listed in Table III–2.

TABLE III–2. SOIL ACTIVITY CONCENTRATIONS MEASURED IN MARCH 2011

Radionuclide	Maximum activity concentration (Bq/m^2)	Radionuclide	Maximum activity concentration (Bq/m^2)
Te-129m	2.97×10^6	Cs-134	9.78×10^6
Te-129	1.80×10^6	Cs-136	3.95×10^5
I-131	1.25×10^8	Cs-137	1.01×10^7
Te-132	7.53×10^7	Ba-140	1.03×10^5
I-132	6.98×10^7	La-140	1.16×10^5

Kinoshita et al. (2011) [III–26] analysed soil samples collected in Fukushima and Ibaraki prefectures from soon after the accident until the end of April 2011 for ^{129m}Te, ^{131}I, ^{134}Cs, ^{136}Cs, and ^{137}Cs, and reported their spatial distribution.

The MEXT and university studies indicated that the spatial distribution of radionuclides in soil was very heterogeneous, reflecting the complex situation of releases and dispersion discussed earlier. As a result, a series of initiatives were included in MEXT's Comprehensive Radiation Monitoring Plan to assess the activity concentrations of radionuclides in soil using consistent sampling and analytical procedures (e.g. to eliminate difference due to sampling at different depths). The maps resulting from these surveys are presented in Appendix I.

III–5. MEASUREMENT OF AGRICULTURAL SYSTEMS

As a consequence of the accident at the Fukushima Daiichi NPP, there was significant deposition of radionuclides on agricultural land in the prefectures of Fukushima, Iwate, Miyagi, Ibaraki, Tochigi, Gunma and Chiba. Agriculture systems, including paddy fields for rice, fields for various agricultural products and livestock feed, and storage reservoirs, were affected by the deposited radionuclides. Agricultural land constitutes around 16% of the total land area in these prefectures according to statistics for the year 2010 [III–30]. This is a higher proportion than for Japan as a whole. The proportion of agricultural land used for cultivation of paddy field rice (the principal food in Japan) in these prefectures is about 64%, which is also higher than average for Japan as a whole[2].

In the period from the aftermath of the accident until the early summer of 2011, direct deposition of ^{131}I, ^{134}Cs and ^{137}Cs was observed on the surface of products, especially leafy vegetables and trees. Due to its short half-life, ^{131}I was not detected in agricultural products beyond that date and radiocaesium incorporated in plants by root uptake became dominant. The distribution of radiocaesium concentration in the soil on agricultural lands (on 5 November 2011) was as shown in Fig. III–12. Agricultural lands with activity concentrations exceeding 1000 Bq/kg were found in a wide area in the eastern part of Fukushima Prefecture, in a narrow area in the central part of the prefecture, and widely scattered in areas of the northern part of Tochigi Prefecture.

Storage reservoirs for irrigation water in Fukushima Prefecture were investigated in the period from May to October 2013 by the Ministry of Agriculture, Forestry and Fisheries and the Fukushima Prefectural government [III–31]. As shown in Section 4.1 of this volume, various kinds of agricultural products, such as vegetables fruits, wheat, mushrooms, etc., where concentrations exceeded 100 Bq/kg, were found not only within Fukushima Prefecture, but also in the eastern part of Honshu.

[2] The proportion of agricultural land area for Japan as a whole is about 12%. The proportion of agricultural land used for the cultivation of paddy field rice is 54% of total agricultural land in Japan.

Although the majority of deciduous fruit tree species had no leaves at the time of deposition, it was found that radiocaesium had migrated to new plant parts at harvest time. This indicates that the new leaves and fruits were affected by direct radiocaesium deposition on the above-ground plant parts and absorption by the tree. In 2011, the year of the accident, root uptake of radiocaesium deposited on the soil contributed very little to the overall levels of contamination within the plant compared with absorption through the above-ground plant parts, such as the surface of bark and leaf. The magnitude of radiocaesium translocation from the old to new plant parts was significantly different in 2011 and 2012, when direct deposition was no longer important [III–32]. In early May 2011, it was found that newly emerged tea leaves contained radiocaesium in some areas more than 300 km away from the Fukushima Daiichi NPP. This was not considered to be due to direct deposition on the leaves, but due to some mechanism of radiocaesium transfer to new tissues from leaves subject to deposition [III–33].

The accident occurred before the period of rice planting (which is usually carried out in May in Fukushima Prefecture), the national Government issued a policy on restrictions on planting and cultivating rice on paddy fields where the concentration of ^{134}Cs and ^{137}Cs in soil exceeded 5000 Bq/kg, as described in Technical Volumes 3 and 5. Although concentrations higher than 25 000 Bq/kg were found in the evacuated areas[3], no activity concentrations exceeding 5000 Bq/kg were found in paddy fields outside these areas. Thus, rice planting and cultivation was restricted only within the evacuation zones. The main route of uptake of radiocaesium in rice was from activity applied as organic matter to the soil of paddy fields. In addition, irrigation water introduced to lowland rice paddy fields, which are wetland ecosystems, is an additional source of radiocaesium. However, the level of soluble radiocaesium available for root uptake is usually very low. Radiocaesium adsorbed on organic materials, such as litter in mountain forests, is likely to be one of the long term sources of radiocaesium in water [III–34].

Later in April 2011, just before the planting period for rice, more than 90% of the radionuclides were found to be distributed within 6 cm of the surface at the wheat field and within 4 cm of the surface at the rice paddy, orchard, and cedar forest. Large variations in the concentrations of radiocaesium and radioiodine within the rice paddy were observed [III–35].

[3] Evacuation Zone, Evacuation Prepared Area in Case of Emergency and Planned Evacuation Zone (see Technical Volume 3 for more details).

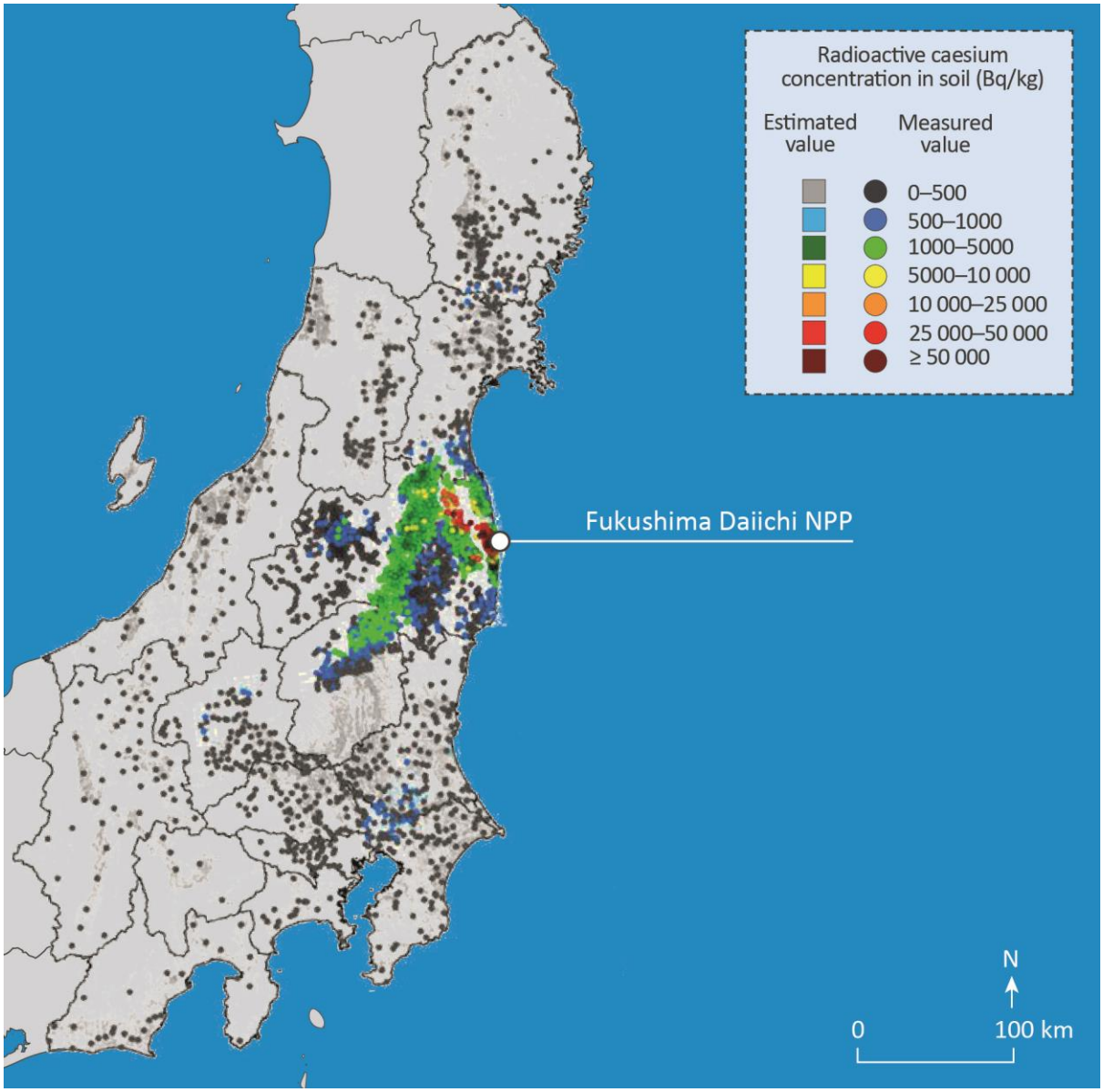


FIG. III–12. Distribution of activity concentrations of radiocaesium in the soil on agricultural land (Bq/kg). The distribution of farmland is based on information from the National Institute of Agro-Environmental Sciences. Activity concentrations are based on the results of the fourth aerial monitoring survey (5 November 2011) [III–36].

Further information on the levels of radionuclides on agricultural land and a description of agricultural measures imposed following the accident are presented in Technical Volume 5.

III–6. MEASUREMENT OF FOREST SYSTEMS

Forests cover around 71% of the land area of Fukushima Prefecture. A significant fraction of the radionuclides deposited on the terrestrial environment was therefore deposited on forests. Some studies have indicated that forest occupies at least 1343 km^2 of the total contaminated area of 1778 km^2 with an ambient dose equivalent rate of more than 5 mSv/y. Thus, understanding the behaviour of radionuclides in forests is important not only for determining the levels of contamination in forest products and radiation doses received by forest workers, but also for estimating the possibility of secondary sources of radionuclides to the surrounding environment.

Since the forest canopy has a wide area, a large part of the deposition of radionuclides was initially located there. Analyses of ^{137}Cs, ^{134}Cs, and ^{131}I in rainwater, throughfall, and stem flow in coniferous forests starting immediately after the accident [III–37] indicated that the similar interception of radiocaesium was observed for the cypress (62.3%) and cedar forests (65.0%), while the interception of ^{131}I differed between the tree species (25.1% for the cypress and 50.9% for the cedar) (see Fig. III-13). This study also indicated that more than 60% of the total deposited radiocaesium remained in the canopy five months after the initial fallout, while the deposited ^{131}I moved through the canopy with rainwater.

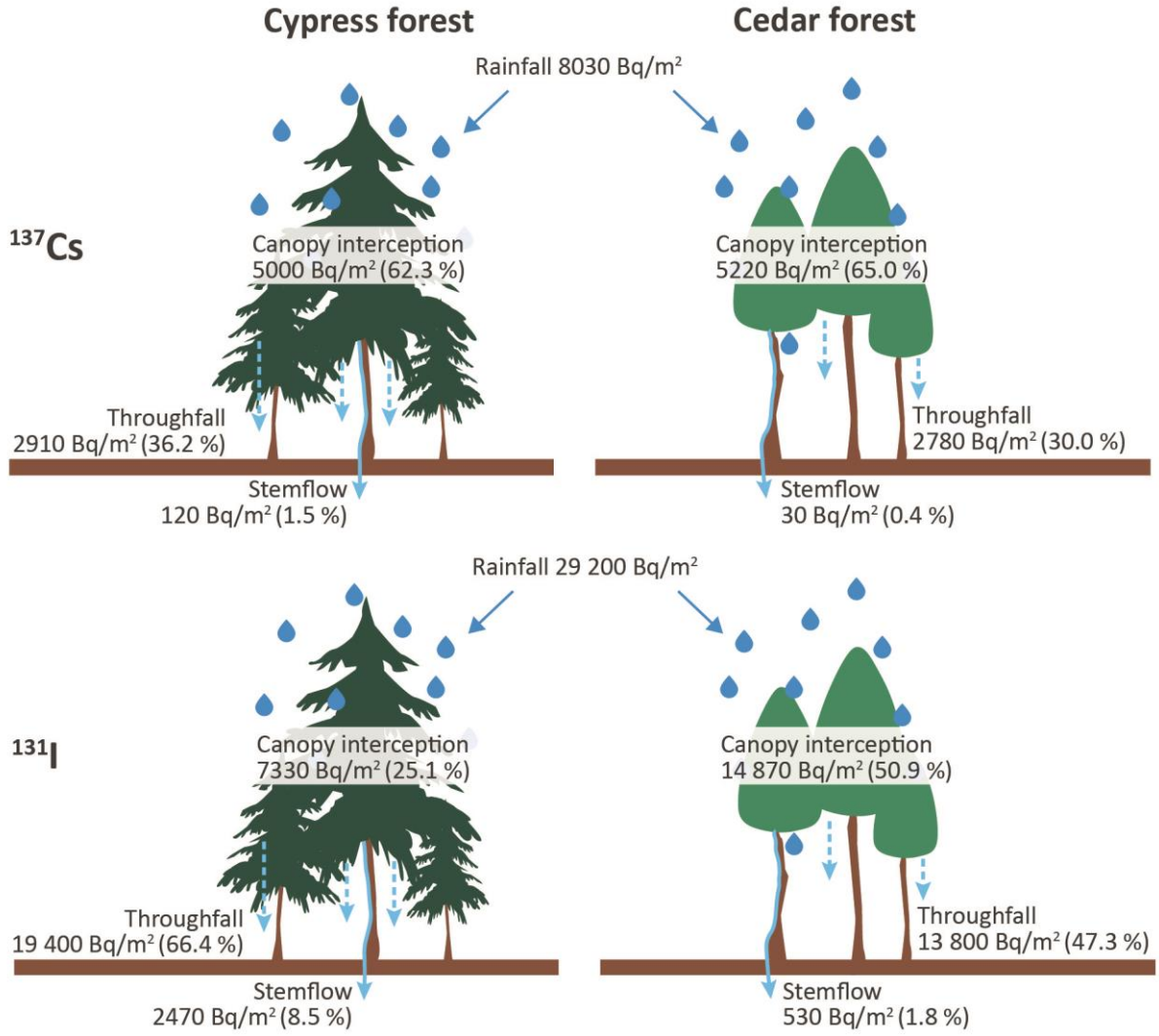


FIG. III–13. Schematic diagram of ^{137}Cs and ^{131}I deposition in rainwater, throughfall, and stemflow in the cypress and cedar forests [III–37].

The surface area of the forest canopy differs depending on forest type and the season. At the time of the accident, trees in deciduous forests were without leaves and deposition on the canopy was relatively limited; radionuclides were deposited directly on the litter layer at the surface of forest floor. On the other hand, the trees in evergreen forests (e.g. Japanese cedar, cypress and pine) retained their leaves, and a greater proportion of radionuclides were deposited onto the canopy.

This difference was clearly demonstrated by some studies started in 2011 on the distribution of radionuclides in several forest sites in Fukushima Prefecture. Measurements of the concentration of

^{137}Cs in leaves at different heights and on different dates in three forests located in Yamakiya District in Kawamata Town, Fukushima Prefecture, were undertaken. In the summer of 2011, ^{137}Cs concentrations were higher in the leaves of the cedar forest than in the leaves of the broadleaf deciduous forest. However, litter samples from the broadleaf deciduous forest contained significantly higher ^{137}Cs concentrations [III–38].

The Forestry Agency (Forest and Forest Products Research Institute) also started a study on the distribution of radionuclides in forest sites in Fukushima Prefecture, including the biomass analyses. The first year study indicated that more than 80% of total deposition of radiocaesium was distributed on the forest floor (litter and soil) in the case of a deciduous forest, whereas the trees (mostly needles and twigs) were up to 45% more important in the case of coniferous forests [III–39]. The distribution of radiocaesium in forests is changing with time, and the percentage present in forest soils is increasing with time.

Activity concentrations of radiocaesium were also measured in 20 woody plant species in the Abiko area, which is located approximately 200 km south-south-west of the Fukushima Daiichi NPP at the end of the first growing season after the accident [III–40]. It was observed that the radiocaesium activities of the foliar parts were higher in evergreen species than in deciduous species because the foliar parts of the evergreen species were directly exposed to radionuclides at the time of fallout. In addition, the leaf longevity and the defoliation timing were found to be associated with the differences among the evergreen species [III–40].

The half-lives of ^{137}Cs were reported by Kato et al. (2012) [III–37] in the cypress and cedar canopies, which were calculated as 620 days and 890 days, respectively, for the period of 0-160 days after the accident.

In a 30 year old Japanese cypress plantation forest stand located on Karasawayama, Tochigi Prefecture, radiocaesium deposited on the forest canopy was found to transfer activity to the forest floor through the following processes: throughfall (53%), stem flow (2.3%) and litterfall (45%) routes in the first year after the accident [III–41].

Six months after the accident it was found that radiocaesium was distributed in bark (the outermost layer of the trunk, mostly composed of dead cells), sapwood (innermost layer responsible by the transport of water and minerals from the roots to the upper parts of the tree) and heartwood (the dense central core of the trunk giving it rigidity) of several different tree species, indicating a very rapid translocation of radiocaesium into the wood [III–42].

The concentration of radiocaesium in oak (*deciduous angiosperm*) bark was higher than that in the bark of Japanese cedar and red pine (*evergreen gymnosperms*). Although both sapwood and heartwood of all trees contained radiocaesium, the activity concentration of ^{137}Cs in those tree compartments was much lower than that in the bark samples [III–42]. The results suggest that radiocaesium contamination six months after the accident was attributable mainly to direct deposition. The radiocaesium concentrations in the Japanese cedar samples taken from five sites rose with the density of radiocaesium accumulation on the ground surface [III–42].

The radial and vertical distribution of radiocaesium in tree stems was investigated 1.5 years after the accident [III–43]. A conifer species (*Japanese red pine*) and a broad leafed species (*Japanese konara oak*) were selected, and stem discs were collected at several heights and separated into outer bark, inner bark, and wood. The radiocaesium concentration was the highest in the outer bark, followed by that in the inner bark and wood. The vertical distribution of the radiocaesium concentration at each stem part differed between the species. The radial distribution in the wood of the studied species showed a common pattern across stem disc heights and species. However, the radiocaesium concentration ratio between sapwood and inner bark was significantly different between species. The

radiocaesium transport pathway and allocation would be different between the species, and the contamination pattern will likely be different between the species at later stages.

Deposited radionuclides are expected to eventually migrate to forest soil. The vertical distribution of radiocaesium in a coniferous forest soil in Tochigi Prefecture was investigated ten months after the Fukushima radioactive fallout [III–41]. The results indicate that radiocaesium is concentrated in the forest floor, and a high radiocaesium transfer factor (3.3) was observed in the undergrowth plants. This made the forest floor an active exchange interface for radiocaesium. At the time of the soil sampling, the raw organic layer ($O_l + O_f$) held 52% (5.3 kBq/m^2) of the radiocaesium derived from the accident at the Fukushima Daiichi NPP and 25% (0.7 kBq/m^2) of the pre-accident ^{137}Cs. Around 99% of the total inventory ^{137}Cs in soil was in the upper 10 cm, in which the organic matter content was greater than 10%. These results suggest that the subsequent distribution depends on the turnover of organic matter.

The levels of radionuclides in forests are of particular interest when considering the effects on non-human biota and this is considered in Section 4.5 of Technical Volume 4.

III–7. IAEA RADIATION MONITORING TEAMS

A number of IAEA radiation monitoring teams undertook environmental monitoring at a range of locations close to the Fukushima site as of 20 March 2011. By 18 April 2011, four monitoring teams had been sent to the Fukushima area with the following objectives:

— To perform environmental monitoring of the area around the Fukushima Daiichi NPP and in Tokyo and surroundings, in order to verify the data provided by Japanese organizations;
— To provide independent monitoring results;
— To provide trend analysis for different parameters at each location when number of monitoring points would allow.

The scope of the monitoring performed included: dose rate, surface activity concentration as well as collection of different samples and gamma spectra for selected locations in the radius from 20 km to around 80 km of Fukushima Daiichi NPP and in Tokyo and surroundings. Several monitoring routes were selected which covered the north, south and west borders of the predicted plume deposition zone. The average monitoring distance along with the routes was about 350 km every day.

The types of monitoring performed included ambient dose equivalent rates, surface contamination for alpha and beta-gamma, high purity germanium (HPGe) in situ gamma spectra, air sampling, smear sampling and some other types of environmental sampling. A portable NaI gamma spectra system with GPS tracking function was also introduced for continuous car-borne measurement and in situ gamma measurement.

Dose rates were measured every day of the monitoring campaigns in different locations in the Fukushima and Tokyo areas. In general terms, the dose rate ranged from a few μSv/h around Fukushima to a maximum 161 μSv/h. In the Tokyo region, the dose rate ranged from 0.03 to 0.22 μSv/h.

Surface activity concentrations were measured every day of the monitoring campaigns in different locations in the Fukushima and Tokyo areas. In general terms, the surface activity concentration ranged from 5 kBq/m^2 measured at Fukushima Prefecture to a maximum of 3.79 MBq/m^2 and 2 kBq/m^2 to 70 kBq/m^2 in the Tokyo region.

The analysis of in situ gamma spectra and the air filter samples collected during monitoring activities showed the presence of a large group of fission products in the environment, with the prevalence of

^{131}I, ^{134}Cs and ^{137}Cs. Radionuclides identified in the in situ gamma spectra are: ^{134,136,137}Cs, ^{131,132}I, ^{129,129m,132}Te, ^{99m}Tc, ^{99}Mo, ^{140}La, ^{140}Ba, ^{110m}Ag and ^{95}Nb. The activity detected in the in situ measurements ranged from 0.1 to 100 kBq/m^2, depending on the measurement location, the radionuclides and the time of the measurements.

The radionuclides identified in air filters were: ^{134,136,137}Cs, ^{131,132}I, ^{129,129m,132}Te, ^{99m}Tc and ^{95}Nb. The activity detected in the air filter measurements ranged from a few Bq/m^3 to 600 Bq/m^3, depending on the measurement location, the radionuclides and the time of measurements. At some monitoring points, hot spots were found. The list of radionuclides and activity ratios are similar to that observed in the in situ gamma spectrometry measurements.

This was the first time that the 'backpack' system, for gamma and neutron dose rates, was used in emergency response operations. It allowed dose rates measured by other systems to be verified, and confirmed the non-detection of neutrons in the field. This measurement campaign also identified other locations that were not included in the initial monitoring plan and that showed high dose rates and the gamma spectra that clearly indicated the presence of ^{131}I, ^{137}Cs and ^{134}Cs.

The IAEA monitoring teams were able to confirm the level of dose rates, surface activity concentrations and the isotopic composition of the spectra, and the major radionuclides contributing to the doses, in areas around the Fukushima Daiichi site and in the Tokyo area, during the period 20 March to 18 April 2011.

III–8. MONITORING BY VOLUNTEER ORGANIZATIONS

These organizations include some that existed before the accident, as well as some that were set up out of a recognized need to provide more information to the public. This section highlights three organizations which collected and distributed large amounts of data publicly and some even continue to do so. SAFECAST, a non-profit, volunteer based organization created in the days immediately following the events of 11 March 2011, initially sought to aggregate available environmental radiation data for Japan and make it publicly available. It rapidly developed a new GPS enabled radiation detection system designed to simplify the data collection, management, and sharing process. The system is based on a calibrated pancake Geiger–Mueller tube. The collection and management process is based on volunteers, including radiation specialists, engineers, designers, software developers, hardware experts, and researchers, as well people from all walks of life. The surveys by SAFECAST volunteers in Japan covered the entire country including most roads in Japan, with complete coverage in some locations such as Koriyama. Since 2012, SAFECAST has also responded to requests for assistance from local governments in Fukushima, providing rapid, detailed surveys of several municipalities (Minamisoma, Tamura, and Koriyama). The exposure rate magnitudes and trends reported by SAFECAST and other large area environmental surveys are consistent. Details of the system and all data are available on the organization's website [III–44].

Greenpeace sent teams of experts to Japan beginning in April 2011 and continuing through 2012. It took hundreds of environmental radiation measurements on many occasions in towns just outside the 20 km exclusion zone around the Fukushima Daiichi site and in Fukushima City and Koriyama, 60 km away. The teams also tested soil, vegetables, seafood, and sediment. Detailed results are available on the Greenpeace website, which provide valuable information to residents and are consistent with those published elsewhere [III–45].

The Kyoto University Research Reactor Institute (KURRI) developed the Kyoto University Radiation Mapping (KURAMA) system in response to the accident at the Fukushima Daiichi NPP to supplement the radiation monitoring being done in Fukushima [III–5]. Beginning in June 2011, large area vehicle-borne survey campaigns sponsored by MEXT were conducted in the eastern area of Japan. The results of these surveys are available through the NRA's database of environmental

monitoring results. KURRI personnel also went to Fukushima to support the screening of people in shelters.

ACRO (Association pour le Contrôle de la Radioactivité de l'Ouest) [III–46] is a French non-profit organization that was created after the Chernobyl accident in 1986 and has been monitoring radioactivity in the environment for 25 years, together with the concerned populations. It runs a laboratory accredited by the French authorities. Its activity is intended to be complementary to the official monitoring, because it aims to allow citizens to measure their own environment.

In Japan, ACRO measured environmental and food samples, as well as urine samples from among the population. It also helped to create an independent laboratory for citizens near Tokyo. The results of ACRO's analyses can be found on its website [III–46].

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