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Large-scale agricultural soil and food sampling and radioactivity analysis during nuclear emergencies in Japan: Development of technical and organisational procedures for soil and food sampling after the accident

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ABSTRACT

Most available measurement methods and protocols for radioactive materials are focused on the use of high-precision sampling and analysis and do not consider the practicality of these techniques in the case of large-scale emergencies involving high numbers of samples and measurements. The experience gained after the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident has demonstrated a need for optimization of sampling and measurement programmes in the case of nuclear emergency that affects food and agriculture. Under these conditions, resources for implementation of monitoring and allocations for sampling and measurements might be limited, and urgent information is needed for effective emergency response. This paper supplies a historical overview of sampling and analytical techniques for assessment of radionuclides in the agricultural environments and foodstuffs and is intended for use in research, policy and decision-making in nuclear emergency preparedness and response, particularly with respect to large scale accidents.

1. Introduction

During the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident, radioactive materials were released to the environment, resulting in contamination of agricultural areas in Fukushima prefecture. Although precise information on the radionuclide composition and concentrations in agricultural fields was necessary in decision-making to avoid the intake of contaminated foodstuffs by the public, it was not possible to obtain estimations of the source term for this contamination, which could be obtained only after the emergency condition (NISA, 2011). Consequently, for other reactor accidents such as the accident at the Chernobyl NPP (Alexakhin et al., 1996, 2007), the main radionuclides of concern were ^{134}Cs, ^{137}Cs and ^{131}I (IAEA, 2015).

Emergency response included gathering of detailed information on soil contamination based on direct sampling and measurement of radionuclide concentrations in soil and plants. Rice was of particular concern, although the accident occurred before the rice-sowing season. Most of the contaminated areas included the rice production regions in Japan, which produced more than 5% of the total rice produced in Japan in 2010 (Rice Steady Supply Organization, 2010), and rice is one of the major agricultural products of Fukushima prefecture. Therefore, it was highly important to delineate the areas where it was possible to reinitiate rice cultivation as early as possible.

Soil surveys in Fukushima prefecture started on March 31, 2011, and the first campaign to assess the spatial distribution of radiocaesium in agricultural fields was based on measurements of the gamma-dose rate in air (Takata et al., 2014).

For the allowable threshold concentration of radiocaesium in soil for rice cultivation, a radiocaesium concentration in soil was determined of less than 5000 Bq kg^{-1} (dry mass). This value was assessed based on a plausible maximum soil-to-brown rice transfer factor value of 0.1 (Bq kg^{-1} brown rice per Bq kg^{-1} dry soil) and the Provisional Regulation Value for radiocaesium activity concentration in food of 500 Bq kg^{-1} (fresh weight) (which was set after the FDNPP accident by the Ministry of Health, Labour and Welfare (MHLW) on March 17, 2011, MHLW, 2011). The value was derived based on extensive research carried out during and after global fallout by the Nuclear Emergency Response Headquarter (NERH), which issued guidance for rice cultivation on April 8, 2011 (NERH, 2011). Based on the NERH guidance and on measurements from 243 agricultural fields (Fukushima prefecture 165,

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Miyagi prefecture 14, Yamagata prefecture 5, Ibaragi prefecture 18, Tochigi prefecture 13, Gunma prefecture 8, Chiba prefecture 10, Kanagawa prefecture 5, and Niigata prefecture 5) in late March to early April in 2011, it was observed that those fields with radiocaesium activity concentrations above 5000 Bq kg^{-1} were located inside the Evacuation Zone, Planned Evacuation Zone and Emergency Evacuation Preparedness Zone (Koyama et al., 2011). Fukushima prefecture decided to allow the cultivation of rice outside the Evacuation Zone, Planned Evacuation Zone and Emergency Evacuation Preparedness Zone (MAFF, 2011). After the Prime Minister (Head of NERH) delivered the restriction on rice cultivation to the director of Fukushima prefecture on April 22, 2011, cultivation of rice was initiated.

The number of the radionuclide analyses was limited due to an insufficient number of germanium (Ge) semiconductor detectors (the officially sanctioned instrument to determine radioactivity of caesium) available for such a purpose, a lack of sampling equipment (e.g. of soil sampling augers) and the lack of staff trained in sampling and management of contaminated materials in agriculture (Hachinohe and Shinano, 2020.

Radionuclide monitoring in foodstuffs is an important component of environmental monitoring and is intended to supply data for evaluation of radionuclide transfer in food chains and assessment of radionuclide levels in food consumed by the public.

Monitoring of foodstuffs can be subdivided according to the following tasks: i) emergency monitoring is driven by the urgent need to deliver information for decision-making (short-term monitoring), ii) post-accidental food monitoring is carried out after the emergency condition (long-term monitoring until the end of the substantial contamination), and iii) routine monitoring generally consists of long-term monitoring during normal operation of the nuclear facilities. Knowledge of the environmental behaviour of radionuclides can be used to predict the radionuclide behaviour and to quantify the transfer parameters used in assessment of the impact on agriculture (Alexakhin et al., 2007). Furthermore, information on long-term behaviour of radionuclides in the environment might assist in justification of countermeasures for radionuclide transfer in the environment. However, in an emergency, it is important to monitor the radionuclide concentrations in the foodstuffs to prevent food items with contamination above the regulation levels from entering the food distribution system. Actual decisions on food restrictions are often dependent on the food self-sufficiency of staple foods in certain areas. Because the radioactivity of agricultural products depends on many factors, such as soil contamination, physico-chemical soil properties and the ability of plants to accumulate radionuclides, carefully elaborated plans are required for sampling and investigations designated to quantify these factors. Post-accidental food monitoring programmes are focused on long-term, low-level radionuclide concentrations, but at the same time, these programmes should meet the requirements of accident detection as soon as possible (Varga et al., 2006).

Nine years have passed since the FDNPP accident, offering a unique opportunity to evaluate the effectiveness of actions implemented in the areas subjected to contamination. The FDNPP accident has shown that it is essential to build up a routine monitoring system under normal conditions that could be easily converted and applied to emergency conditions. This paper addresses this experience and focuses primarily on the build-up of agricultural monitoring and food safety inspection systems for emergency monitoring and post-accidental food monitoring during the nuclear accident in Fukushima.

2. Techniques for measurements of radioactivity in foodstuffs

2.1. Regulation values that limit radionuclide concentrations in foodstuffs

Attention to contamination of agricultural products was raised well before the Fukushima accident. The impact of global fallout from atmospheric nuclear testing and nuclear accident (e.g., Chernobyl), previously raised many concerns related to contamination of agricultural products and agricultural land. One of the most important objectives of long-term monitoring is to explore the radiation levels before a nuclear accident. In Japan, the National Institute for Agro-Environmental Sciences (NIAES) has been analysing the radionuclide levels of agricultural soils (rice paddies, upland agricultural areas), and in brown rice in representative areas throughout Japan since 1959 (Fig. 1).

In the EU (European Union), food monitoring legislation also includes the maximum permissible levels of radioactive contamination of foodstuffs following a nuclear accident or radiological emergency (Máté et al., 2015).

After the FDNPP accident, determination of radionuclide concentrations in foodstuffs imported by Europe follows the EU regulations, which defines special conditions for the import of feed and food originating or consigned from Japan (Commission Implementing Regulation EU No 322/2014 of 28 March 2014, 2014). Similar procedures have been implemented in Switzerland since 1961 (Zehringer, 2016), and also include products such as milk, vegetables, fungi, and nuts. In New Zealand, food monitoring focuses on milk, and data have been collected since 1961 (Matthews, 1994). However, comprehensive analyses of other foodstuffs have not been carried out in New Zealand (Pearson et al., 2016).

The Japanese food monitoring data before and after the FDNPP accident were summarized by Merz et al. (2015), who noted that the activity concentrations of ^{137}Cs and ^{90}Sr in foods were less than 0.5 Bq kg^{-1} (fresh weight) before the accident. Radionuclide monitoring of staple foods (such as rice in Japan) depends on national agricultural practice and consumption habits. Special attention is placed on these products in environmental monitoring programmes for agriculture products. For example, emphasis is placed on potatoes, vegetables and fruits is given in the case of Hungary (Varga et al., 2006), on cereals and tubers in Nigeria (Arogunjo et al., 2005), and on marine products in Ireland (Environmental Protection Agency, 2015).

In a nuclear emergency, it is necessary to pre-determine the Operational Intervention Levels (OIL) (IAEA, 2017). In OIL 7, which supplies guidance levels for activity concentrations in foods, including milk and drinking water, the default OIL values are given for both ^{131}I and ^{137}Cs (OIL7 = 1000 Bq kg^{-1} of ^{131}I or 200 Bq kg^{-1} of ^{137}Cs). Food monitoring is also required in emergency situations for delivery of sufficient information to derive situation-specific OIL.

In Japan, the maximum provisional level of 370 Bq kg^{-1} for imported food was adopted in 1986 (Iwashima and Okubo, 1987). However, there was no regulatory value was given for radionuclide concentrations in locally produced foodstuffs at that time. After the FDNPP accident, the Provisional Regulation Value for foodstuffs in Japan was determined in 2011 (MHLW, 2011) and was replaced by the Standard Limits for radiocaesium in foodstuffs after the FDNPP accident (MHLW, 2012c).

Before the FDNPP accident, regulations of radionuclide activity concentrations in foodstuffs was prepared in response to the concerns raised after the Three Mile Island (TMI) accident. Based on an evaluation of the TMI accident (March 28, 1979) consequences, the Japan Nuclear Safety Commission (NSC) decided to set regulatory levels for radionuclides in foodstuffs (Table 1) (NSC, 1980). These levels were based on the recommendations of an intervention level for the internal doses due to intake of food in the range of 5–50 mSv, accounting for contributions to the internal dose of all radionuclides (ICRP, 1984).

After the Fukushima accident, the MHLW of Japan announced the Provisional Regulation Values based on the regulation level set by NSC (NSC, 2003), which includes radioiodine, radiocaesium, radiostrontium, uranium, plutonium and other transuranic alpha-emitting radionuclides (Table 2). The addition of radioiodine concentration regulation of milk and modified milk powder for infants was set lower than 100 Bq kg^{-1}, a value that was based on the CODEX standard (Codex Alimentarius Commission, 2006). For radiocaesium and radiostrontium, $^{134}Cs + ^{137}Cs$ were used as index values of radiocaesium and radiostrontium, where

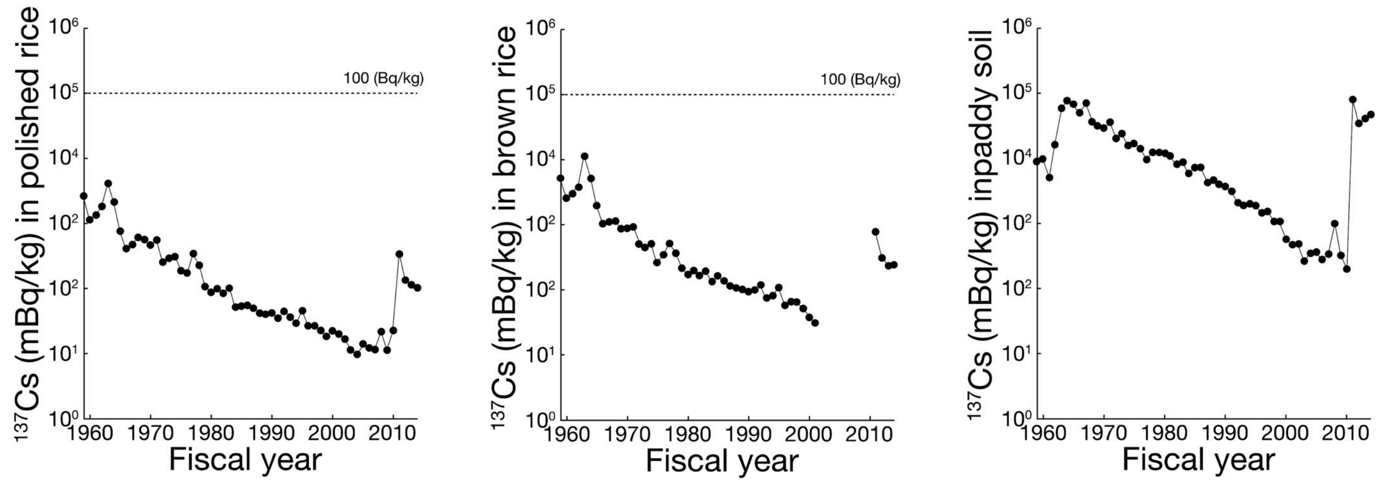

Fig. 1. Time-dependence of ^{137}Cs in polished rice (left), brown rice (centre) and paddy field soil (right). Data are collected from all over Japan and are presented as the average value of n = 10 to 15, 7-15, and 6-15 samples. (https://vgai.dc.affrc.go.jp/vgai-agrip/samples).

Table 1
Regulation value (Bq/kg) for radionuclide activity concentrations in foodstuffs and drinking water (NSC, 1980).

Food and drink	Radionuclide			
	^{131}I	$^{134+137}$Cs	U	Plutonium and transuranic elements
Drinking water	≤300	≤200	≤20	≤1
Milk, Dairy products	≤300	≤200	≤20	≤1
Vegetables (excluding edible roots and tubers)	≤2000			
Vegetables		≤500	≤100	≤10
Grains		≤500	≤100	≤10
Meat, egg, fish, etc.		≤500	≤100	≤10

Table 2
Limitation of radionuclide concentration in food after the accident at FDNPP.

Food category	Provisional Regulation Values for radiocaesium (^{134}Cs+^{137}Cs) as of 2012.03.31* (Bq·kg^{-1})	Food Category	Standard Limits as of 2012.04.01** (^{134}Cs+^{137}Cs, Bq·kg^{-1})
Drinking water	200	General foods	100
Milk, dairy products	200	Food for infants	50
Vegetables	500	Milk	50
Grains		Drinking water	10
Meat, eggs, fish, etc.			

* The Provisional Regulation Values for radiocaesium consider the contribution of ^{90}Sr.
** The Standard Limits consider the contribution of ^{90}Sr, ^{106}Ru, ^{238}Pu, ^{239}Pu and ^{241}Pu but are set by only the radiocaesium concentration (^{134}Cs+^{137}Cs, Bq·kg^{-1}) because of the inspection efficiency. The effect of other radionuclide contributions is considered based on the ratio to radiocaesium.

the ratio of ^{137}Cs to ^{90}Sr is assumed to be 0.1. For plutonium and other transuranic alpha-emitting radionuclides, total alpha radionuclides are considered to coexist in the food. Upon further evaluation of the food safety regulation levels and the actual contamination levels in foodstuffs consumed by the Japanese population after the Fukushima accident, the Provisional Regulation Values were changed to better fit the CODEX recommendations (MHLW, 2011b). In 2012, the Provisional Regulation Value, which was introduced by the recommendation introduced under the concept of intervention under emergency conditions (ICRP, 1984), was updated based on the CODEX committee (Codex Alimentarius Commission, 1995) to reduce internal exposure to levels below 1 mSv year^{-1} (ICRP, 2007). These recommendations based on the situation after the nuclear accident were also introduced into the IAEA General safety requirements (IAEA, 2014). The Standard Limits are shown in Table 2. These levels are set based on the assumption that approximately 50% of the domestic foodstuffs in Japan were contaminated by radiocaesium at a level of 100 Bq kg^{-1} of $^{134+137}$Cs.

The guideline levels for each radionuclide in foods are given in the Codex Alimentarius Commission (2006) and are summarized in Table 3. In addition to this change in the Standard Limit, several revisions were introduced for processed foods to account for the removal of dirt from vegetables prior to consumption, etc. in monitoring of the contaminated foodstuffs (MHLW, 2012b).

2.2. *Techniques for measurements in foodstuffs and soil during emergency monitoring*

2.2.1. *Methods for foodstuff measurements*

Measurement of radioactivity in food following the FDNPP accident was based on the procedure originally adopted by MHLW in 2002 (MHLW, 2002), which was modified to adjust to practical responses under the emergency conditions. The procedure includes the option to use detectors other than the Ge semiconductor for food monitoring and is based on use of a NaI(Tl) scintillation survey meter. However, because the NaI(Tl) scintillation survey meter has a limited energy resolution and cannot be used in accurate identification of radionuclides, all

Table 3
Joint FAO/WHO Codex Alimentarius Commission guideline levels for ^{134}Cs, ^{137}Cs, ^{90}Sr and ^{131}I in foods for use in international trade at different self-sufficiency levels.

Food items	Radionuclide concentrations in foodstuffs, Bq kg^{-1}			
	^{134}Cs	^{137}Cs	^{90}Sr	^{131}I
Self-sufficiency rate 10%				
Infant foods	1000	1000	100	100
General foods	1000	1000	100	100
Self-sufficiency rate 50%				
Infant foods	200	200	20	20
General foods	200	200	20	20
Self-sufficiency rate 100%				
Infant foods	100	100	10	10
General foods	100	100	10	10

nuclides are assumed to be ^{131}I. This assumption means that if the sample contains other radioactive nuclides, such as ^{137}Cs, the measurements overestimate the radionuclide activity concentration because the counting efficiency for ^{137}Cs is lower than that for ^{131}I.

The procedure for the measurement of milk is shown in Fig. 2. Milk sampling is performed at the bulk level by sampling from each cooler station that collects milk from neighbouring farmers. The conversion efficiency is given by the Japan Ministry of Education, Science, Sports and Culture (MEXT) (in the MEXT, 2002, it is indicated as the 1975 version but has been revised in 2002). If the NaI(Tl) scintillation detector shows a net value of 20% higher than background levels, the precise measurement of the sample by the Ge semiconductor detector was applied.

The procedure for measurement of vegetables is shown in Fig. 3.

By using these procedures, it was possible to detect values of 100 Bq L^{-1} for milk, and 1000 Bq kg^{-1} for vegetables.

Gamma spectrometry using the Ge semiconductor detector was applied for the precise measurements of radioactive iodine and caesium in agricultural samples. Sample preparation was the same as described previously for the NaI(Tl) scintillation survey meter. It is important to mention that other radionuclides might be of concern in emergency conditions. The presence of these radionuclides can change the detection levels typical for routine and emergency conditions (Table 4). As shown in Table 4, the relative efficiency of the detector is 15%.

In 2012, the MHLW (MHLW, 2012a) approved a set of screening methods for measurements of radioactive caesium in foodstuffs. Before publishing this document, the measurements were based on MEXT Radiation Measurement Method Series 6 (MEXT, 1974), 7 (MEXT, 1992a), 15 (MEXT, 2002) and 24 (MEXT, 1992b). These measurement techniques were replaced by the procedures described in the new documents “Screening Method of Radioactive Caesium in Food” (MHLW, 2012a) and “Testing Methods for Radioactive Substances in Food” (MHLW, 2012b). The standard operational procedure (SOP) for sample washing (dirt removal) was recommended for use in measurements of radionuclide levels in foodstuffs. The introduction of this recommendation in pre-treatment of foodstuffs samples was also updated as following.

For measurement of radionuclide concentrations in foodstuffs after the accident, samples were pre-treated by washing and removing the root and/or deteriorated leaves, etc. Subsequently, each sample was shredded and packed into a measurement beaker. The measurement times were 2000 s with a U-8 vessel[1] for meat, fish and shellfish, 2000 s for barley; and 600 s for other products (raw milk, vegetables, fruits, mountain vegetables, and fungi) in a 0.7 litter Marinelli beaker. In case of foraging products, the analysis was carried out by external facilities. Based on these procedures, the measurement capacity of the Fukushima Agricultural Technology Centre (FATC) was approximately 150 samples per a day, and on average, more than 30,000 samples were analysed per year. From March 19, 2011 until the end of 2016, in total 181,348 samples were analysed (Fukushima prefecture, 2017). Further details on the monitoring activities are given elsewhere (FATC, 2017).

2.2.2. Evaluation of croplands in the frame of environmental monitoring

Before the FDNPP accident, environmental monitoring had been carried out in Japan since 1961 to monitor artificial radionuclides in the environment due to global fallout from atmospheric testing of nuclear weapons in the 1950s and 1960s and from releases due to past nuclear accidents, such as Chernobyl. In addition, environmental monitoring was performed around every nuclear facility. Under normal operations, this activity includes monitoring of aerosols, liquid radioactive effluent releases, dose rates and periodic sampling of soil and vegetation at selected predefined sampling sites. In certain countries, such monitoring programmes also include sampling of crops and selected animal products, such as cow milk (Howard et al., 2009; Fesenko et al., 2007, 2009). The only type of measurements that requires continuous daily measurements is monitoring of radioactive noble gasses. Other types of radiation must be monitored weekly, monthly or even annually, according to the regulations (NSC, 2008). Before 1986, the deposited radionuclides primarily originated from radionuclide deposition from the stratosphere caused by nuclear weapons tests conducted in the United States, the former USSR, France, the UK and China (UNSCEAR, 2000). Most of these tests were conducted at the end of the 1950s and in the early 1960s, and long-lived radionuclides released into the atmosphere included ^{90}Sr and ^{137}Cs, with physical half-lives of approximately 29 and 30 years, respectively.

In Japan, during normal nuclear facility operations, food samples are taken as follows: approximately 3 kg of polished rice once a year (at harvest), approximately 500 g of tea (samples were taken at the first tea crop), approximately 3 kg of cow milk once a year (June). It is required that each food item is representative for a production of this food within a certain area. Samples are collected from sites all over the country and ^{137}Cs concentrations are determined by gamma-spectrometry.

Sampling of dairy food is conducted twice per year (June and November–December) and targets common food items. Typical food items consumed during breakfast, lunch, supper, and snacks for members from 5 different families are collected in a wide-mouthed polyethylene pot. The non-edible portions are removed prior to measurements. Water and other drinks are collected and evaporated by heating. The samples are dried at 105 °C and converted into ash by an electric muffle furnace at 450 °C for approximately 24 h. The ash samples are subsequently used in measurements. Data are collected all over the Japanese prefectures and are summarized and published by the Japan Chemical Analysis Centre on behalf of the NRA.[2]

2.3. Development of alternative methods for soil and food analysis

Measurements of radioactivity were carried out based on the manuals prepared by MEXT (MEXT, 1974; MEXT, 1992aMEXT, 1992b) and NRA (2018). These manuals include methods requiring simple equipment, such as NaI(Tl) scintillation survey meters for measurements of radioiodine (MEXT, 2002). For measurements of radioactive caesium, Ge-semiconductors are required because in the manuals no method is included for the use of NaI(Tl) scintillation survey meters. There are several limitation of the usage of Ge-semiconductor, such as the number of machines are very limited (there was 2 Ge-semiconductors in Fukushima prefecture at the time of accident, but one was not able to use because it was too close to the FDNPP) and trained expert as operator was also limited. Therefore, an alternative measurement method to Ge-semiconductor, a caesium measurement technique using a survey meter has been developed as following.

The FATC published a method for measuring the radiocaesium concentration in soil with concentrations between 1000 and 4500 Bq kg^{-1} via a NaI(Tl) scintillation survey meter (Nemoto and Sato, 2011; Nemoto et al., 2014). The procedure is shown in Fig. 4. Soil sampling was performed with the aid of the HS-30 soil sampler produced in Japan (Hand sampler HS-30, Fujiwara Seisakusyo). After mixing the samples collected from the field, the samples were weighed and packed according to the protocol. The soil sample was shaped to cover the detector of the NaI(Tl) scintillation survey meter (LUDLUM 2241-2). Thereafter, the measured value was recorded every 10 s, and each group of 10 data points was averaged. The background level of the dose rate without soil was also measured. The soil caesium radioactivity was separately determined using the Ge semiconductor, and the relationship between the counts per second indicated by the NaI(Tl) scintillation survey meter was plotted against the radioactivity of radioactive caesium measured

[1] The widely used U8 vessel for sample measurement is a cylindrical polystyrene bottle (100 ml) with external and internal diameters of 5.6 cm and 5.0 cm, respectively, and a height of 6.8 cm.

[2] See http://www.kankyo-hoshano.go.jp/07/07_1.html.

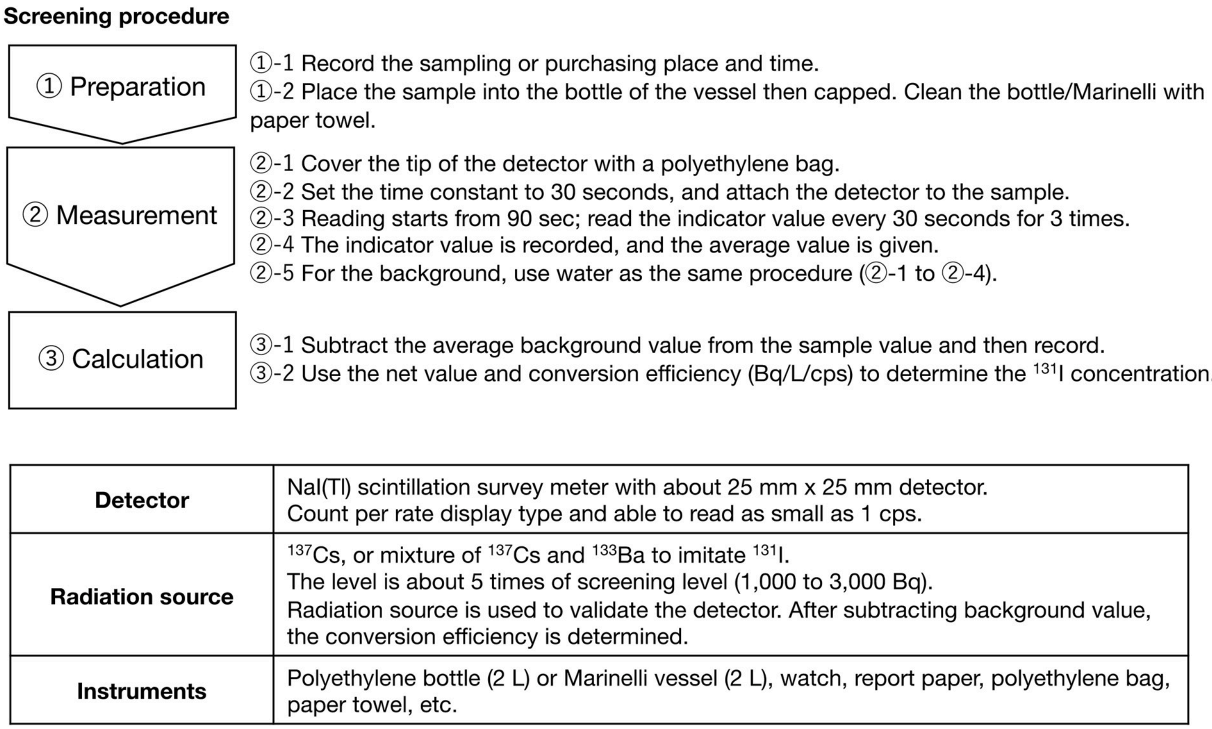

Fig. 2. Measurement of milk by using the NaI(Tl) scintillation survey meter (modified from MHLW, 2002).

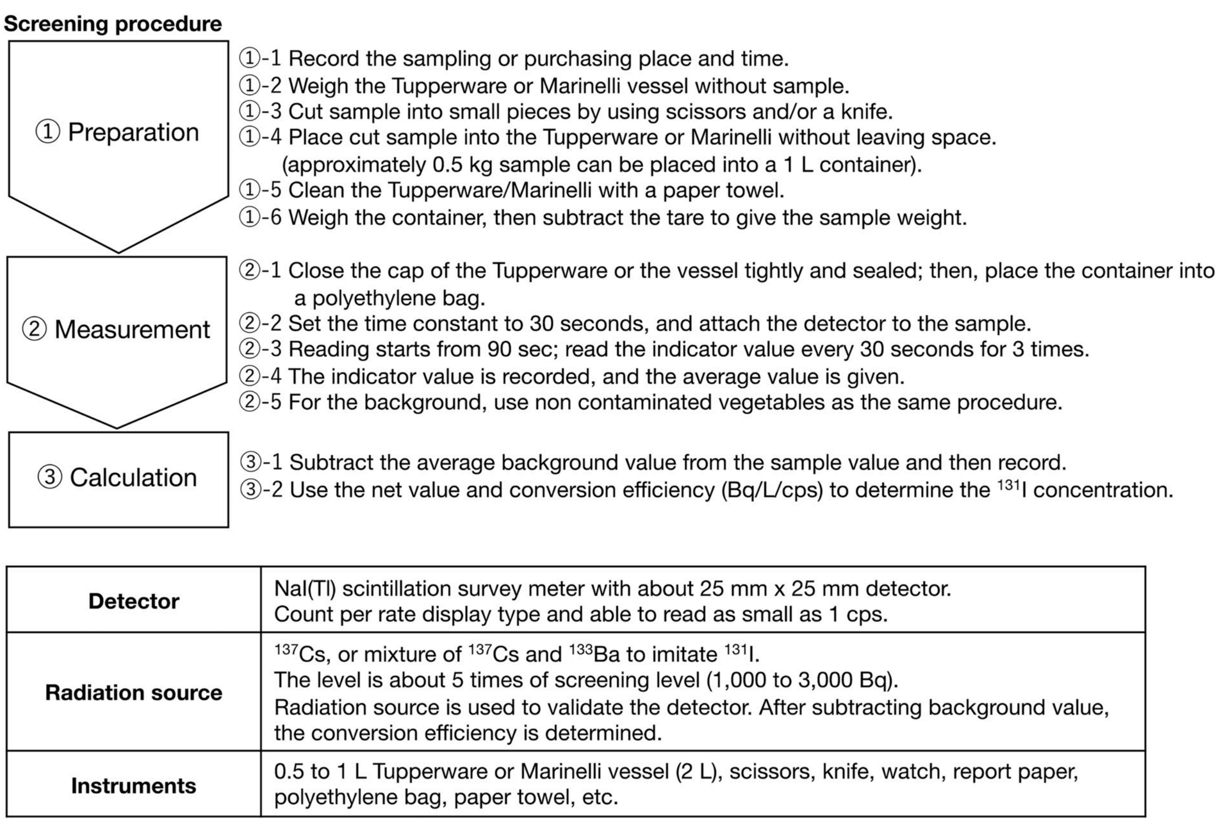

Fig. 3. Measurement of vegetables by using the NaI(Tl) scintillation survey meter (modified from MHLW, 2002).

by the Ge semiconductor (Bq kg^{-1}) (Fig. 5). The relationship between the count rate (count per second) and radioactivity (Bq kg^{-1}) should be determined for each type of counter.

A similar approach was used in measurements of foodstuffs (Kameya et al., 2011). The approach based on the Provisional Regulation Level required the measurement of samples with activity concentrations greater than 500 Bq kg^{-1}. However, because the air dose rate was approximately 0.1 μSv/hr in a room of Tsukuba city (approximately 300

Table 4
Measurement time and detection limit under emergency and normal conditions.

Sample name		Sample amount	^{131}I quantitative detection level (Measurement time, min)				^{137}Cs quantitative detection level (Measurement time, min)				Units
			10	30	60	600	10	30	60	600	
Milk	Emergency (multiple nuclides detection)	2L	18	10	8		40	24	16		Bq/L
	Normal				0.4	0.2			0.8	0.3	
Vegetable (leafy)	Emergency (multiple nuclides detection)	1 kg	36	20	16		80	48	32		Bq/kg (Fresh)
	Normal				0.8	0.4			1.6	0.6	
Seaweed, Fish	Emergency (multiple nuclides detection)	2 kg	18	10	8		40	24	16		Bq/kg (Fresh)
	Normal				0.4	0.2			0.8	0.3	
Grain	Emergency (multiple nuclides detection)	2 kg	18	10	8		40	24	16		Bq/kg (Fresh)
Meat, Egg	Normal				0.4	0.2			0.8	0.3	

Fig. 4. Preparation of soil sample for simplified method by using the NaI(Tl) scintillation counter (adapted from Nemoto and Sato, 2011).

km from FDNPP) at that time, it was impossible to measure the statistically significant exceedance of the radiocaesium concentration of 500 Bq kg^{-1} in barley grain because of the external radiation from the environment. Therefore, lead shielding of 0.2 mm thickness was installed around the detector to decrease the contribution of the external radioactivity. This shielding allowed statistically significant detection of radiocaesium concentrations of 500 Bq kg^{-1} in barley grain. However, this shielding setup did not allow measurement of radiocaesium concentrations in the grains with an activity of approximately 100 Bq kg^{-1}. Thus, the radiation background affected precise measurements, especially in highly contaminated areas.

2.4. Introduction of screening method for post-accidental food monitoring

After the emergent condition, post-accidental food monitoring was initiated. The major difference between foodstuffs monitoring conducted before and after the nuclear emergency is wide introduction of screening methods for food inspection in the latter cases (MHLW, 2012a). Before 2011, analysis of radioactive caesium in food was mainly based on the use of Ge semiconductor detectors. After the FDNPP accident, use of screening methods tremendously increased the speed and number of analyses performed. The screening methods implemented after the FDNPP accident focused on all food items and the determination of radiocaesium which was the only radionuclide of concern after June 2011. The screening method is a test that checks whether the radionuclide concentration in the sample is well (statistically significantly) below the Standard Limit or not. In this method, a level (screening level) is set that is lower than the Standard Limit to ensure that the activity concentration in the food intended for consumption is below the limit. The screening level is used as a criterion to judge whether the activity in the sample complies with the regulatory limits. If the screening measurement results in activity concentrations that exceed the screening level, the radionuclide concentration in the sample must be analysed by the Ge semiconductor detector to check the compliance

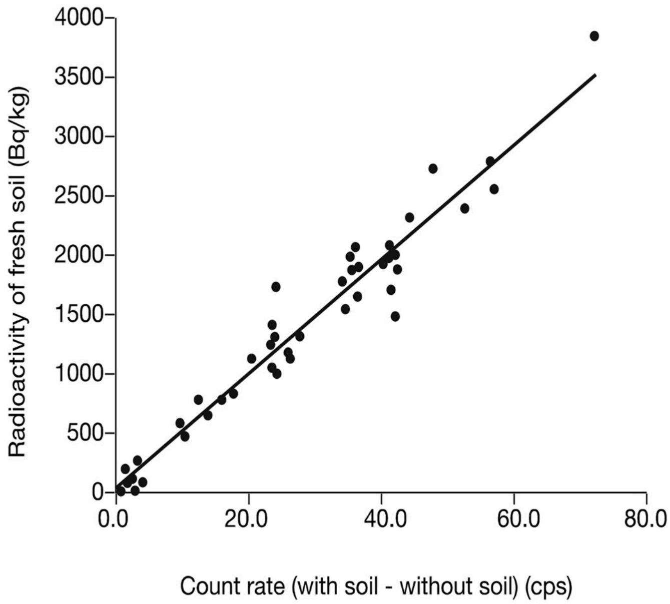

Fig. 5. Relationship between count rate and radioactivity of soil (adapted from Nemoto and Sato, 2011Nemoto et al., 2014).

of the food sample with the Standard Limit of radionuclide concentrations. According to the requirement, the screening devices must be operated under a sufficiently low background level, and an appropriate screening level must be set. If the essential requirements are met, devices other than the Ge semiconductor, such as the NaI(Tl) scintillation detector, are also available for the screening method.

The results of radionuclide activity concentrations in foods are always associated with uncertainties. Therefore, it was not recommended to set a screening level equal to the limitation level because certain of the samples could be accepted as non-contaminated even if they exceed the limitation value (Fig. 6-A). To avoid this risk, an increase in the accuracy of the measurement (by decreasing the measurement error) is one of the options that can be applied (Fig. 6-B). The other approach is to set a screening level for radionuclide concentration in the foodstuff such that the probability that the measured value is below the limitation level is 100%. Based on the latter idea, the screening level of 50 Bq kg^{-1} was introduced as a performance requirement for the equipment (Fig. 6-C). This screening level was more robust in ensuring that samples did not exceed the radiocaesium activity concentration of 100 Bq kg^{-1}. This screening method was also introduced into all inspection systems for bags of brown rice.

3. Organisation of sample measurements at the early phase of the accident

Since 1973, with the start of operation of the new nuclear power plant, the Environmental Radioactivity Monitoring Centre (ERMC) of Fukushima Prefecture was located in Okuma town to monitor the area of Futaba and Okuma towns. Because of the damage from the Great Eastern Japan Earthquake and the impact of the FDNPP accident, the monitoring activities supplied by the ERMC were terminated, and until June 2011, measurements of radioactivity after the accident were conduced only by the Fukushima branch in Fukushima city of the ERMC with assistance of the Japan Food Research Laboratories.

Before the accident, measurements of radionuclides in foodstuffs were performed based on the Food Sanitation Act issued by the Ministry of Health, Labour and Welfare (MHLW) under routine monitoring associated with the normal operation of the nuclear facilities. Based on this law, measurements of radioactivity in foodstuffs were restricted to the Food Sanitation Inspection Facilities of the prefectures and private inspection agencies that were registered as official institutions for analysis of radioactive materials. The number of food inspection facilities of registered inspection agencies was 50 by March 25, 2016. Before June 2011, there were two registered private inspection agencies, namely, the Japan Food Research Laboratories and the Japan Inspection Association of Food and Food Industry Environment. Subsequently, MHLW announced 4 additional administrative institutes that could supply assistance with such measurements. Additional inspection support through the involvement of other research laboratories, universities, etc. was organized with the aid of the Ministry of Agriculture, Forestry and Fisheries (MAFF) and MEXT.

During the initial stage of the accident in Fukushima, the prefectural staff collected food samples and carried out measurement of radionuclides (^{131}I, ^{134}Cs and ^{137}Cs) in environmental samples. Although those samples were referred to as environmental samples, the targets were food samples such as vegetables, fruits, milk, egg, meat, fungi, mountain vegetables, grass, grains and fisheries. Because of the lack of analytical capacity for radioactivity measurement in the prefecture, by June 2011, most of the samples were forwarded to the Kyushu Environmental Evaluation Association (http://www.keea.or.jp), which has used the Ge semiconductor detectors in analysis of radiocaesium and radioiodine since 1976. To establish the monitoring system for agricultural products inside Fukushima prefecture, 10 Ge semiconductor detectors were supplied by the Japanese government (4 from the Ministry of Economy, Trade and Industry (METI) and 6 from MEXT) by September 2011 in FATC, and an analytical section was established with 16 staff members for measurement of radioactivity in food.

By April 2017, 11 Ge semiconductor detectors were in operation with 11 staff members involved. FATC does not accept any private samples, and the samples are restricted to research monitoring and precise measurements for prefectural management. The schedule for the

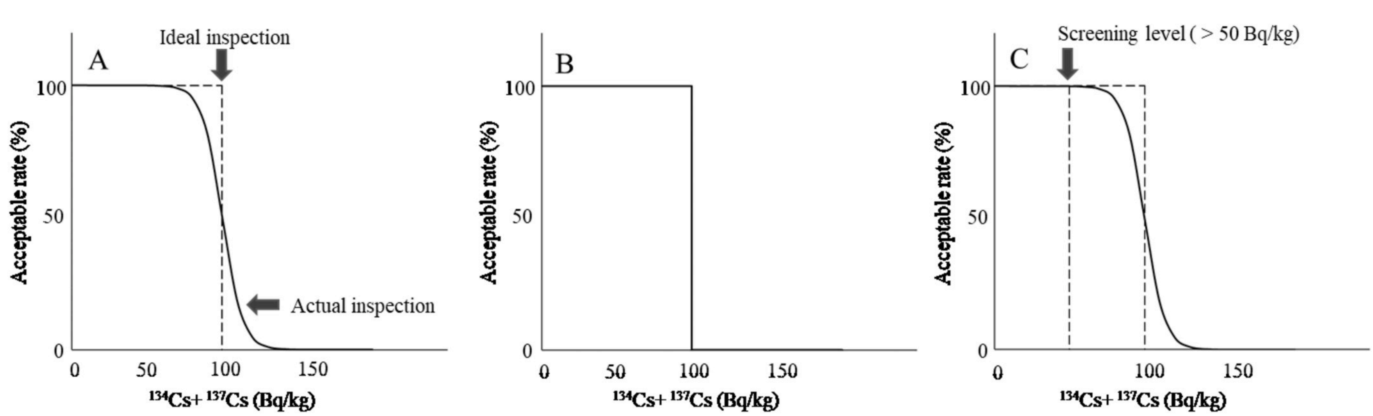

Fig. 6. Example of operating characteristic curve of inspection for radioactive caesium (Japan Food Hygiene Association, 2014).

analysis is shown in Table 5. In addition, Hama Agriculture Regeneration Research Centre has opened a new research branch since 2016 in which 2 Ge semiconductor detectors were established, primarily for monitoring of samples from fields intended for testing remedial options.

Because FATC did not perform soil measurements, the soil samples collected from agricultural fields in Fukushima prefecture were analysed with the aid of NIAES. FATC was able to take samples from approximately 2000 places and examine the distribution of radioactive caesium around the prefecture with the assistance of NIAES (Sato, 2012).

4. Development of equipment for radioactivity analysis

4.1. Complete inspection of brown rice (Fukushima prefecture)

The Fukushima Association for Securing Safety of Agricultural Products was established by Fukushima prefecture, producer groups, distributor groups, retailer groups, and consumers in May 2012 (Fukushima Association for Securing Safety of Agricultural Products, 2012) with 37 regional councils. The purpose of this association was to supply data on concentrations of radiocaesium in rice produced in Fukushima prefecture prior to shipping. This action was taken because monitoring of rice contamination was insufficient to respond to public concerns, and the extra inspection served to eliminate rumours related to high contamination of the foodstuffs in Fukushima prefecture.

Monitoring started on August 25, 2012 with the examination of rice in Nihonmatsu city. Subsequently, machines for rice inspections were placed in each municipality. In 2012, more than 10 million 30-kg rice bags were surveyed. The survey machines were developed by Shimadzu, Hitachi Zosen Corporation, Canberra, Mitsubishi Heavy Industries and Fuji Electric (Table 6). In Fukushima prefecture, 192 machines (e.g., Fig. 7) were installed and used in total bag inspection by 2017.

The total bag inspection survey was applied for initial screening of the radiocaesium concentration in rice. If the concentration of radiocaesium in rice exceeded the screening level, the bag was sent for precise analysis with the Ge semiconductor detector in FATC. The monitoring flow of brown rice inspection is summarized in Fig. 8.

The important objectives of the rice bags inspection were to control the radiocaesium concentrations in all bags produced by Fukushima prefecture and to ascertain the rice producer. Such traceability makes it possible to react as early as possible and to take necessary actions at the source if the sample exceeded the screening level.

4.2. Screening of Anpogaki: total sample inspection

Anpogaki is one of the major agricultural products in Date city and in Fukushima city. Anpogaki consists of persimmon fruit dried with fumigation using sulphur. As the drying process decreases the water content, the concentration of radionuclides in the final product increases accordingly. The concentration of radioactive caesium in the fruit flesh is increased by 3–4 times via this drying process. To grasp the state of radiocaesium contamination of persimmon fruit, the production of Anpogaki was completely terminated for the first 2 years after the accident.

Table 5
Schedule for sending-in day of the week.

	Monday	Tuesday	Wednesday	Thursday	Friday
Vegetables and fruits	○		○	○	
Fish and shellfish	○	○			
Grains, mountain vegetables and fungi		○			○
Pork, chicken, horsemeat, honey, egg and forage				○	
Raw milk	○				
Beef		○	○	○	○

Table 6
Characteristics of machines used in rice bag inspection.

Manufacture, name	Detector	Weight	Price
Fuji Electric, NMU3	NaI(Tl) (top(4)+bottom(4))	2,300 kg	10 million JPY
Shimadzu Seisakujyo, FOODS EYE	BGO (top(1)+bottom (1))	1,570 kg	20 million JPY
Mitsubishi Heavy Industries Mechatronics Systems, MS-RO2	Plastic scintillator (top (1)+bottom (1))	4,500 kg	20 million JPY
Hitachi Zosen, ASUKA HTX-100	CsI(Tl) (6)	2,300 kg	20 million JPY
Canberra, FOODSAFE	NaI(Tl) (bottom (1))	2,500 kg	15 million JPY

Fig. 7. Inspection machine used in complete bags inspection for brown rice in Fukushima, Japan (https://www.pref.fukushima.lg.jp/uploaded/attachment/262176.pdf). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

A monitoring survey of each orchard was carried out during the juvenile stage of the fruit, and if the level of radiocaesium in the fruits exceeded 10 Bq kg^{-1}, the orchard was not allowed to produce persimmon for Anpogaki that year. The final product, packaged as a set of 8 fruits, was inspected with the aid of inspection machines (1 sample inspection system for large Anpogaki was also in operation since 2017) (Fig. 9).

The results of radiocaesium measurements in Anpogaki are regularly posted at the -Japan Agricultural Cooperative website (Japan Agricultural Cooperatives, 2019). The fractions of packages exceeding radiocaesium concentrations of 50 Bq kg^{-1} were 0.1% in 2013, 0.2% in 2014, 0.3% in 2015, 0.07% in 2016 and 0.011% in 2017. The fractions of the packages in which the radiocaesium concentrations were less than 25 Bq kg^{-1} were 90.8% in 2013, 94.5% in 2014, 94.5% in 2015, 98.3% in 2016 and 99.99% in 2017.

Radioactivity measurement equipment for Anpogaki measurement was developed by Canberra (Fig. 9A and B) and Hitachi-Zosen (Fig. 9C). The machine included 16 individual NaI(Tl) detectors placed on the upper side and lower side of the machine (32 detectors in total). This process allows non-destructive inspection of the product (Fig. 9). This machine could also be used in measurement of individual fruits. The lower limit was less than 25 Bq kg^{-1}, whereas if the screening level was greater than 70 Bq kg^{-1}, this level was higher than the normally required value of 50 Bq kg^{-1}. Measurement of each package typically took 80 s.

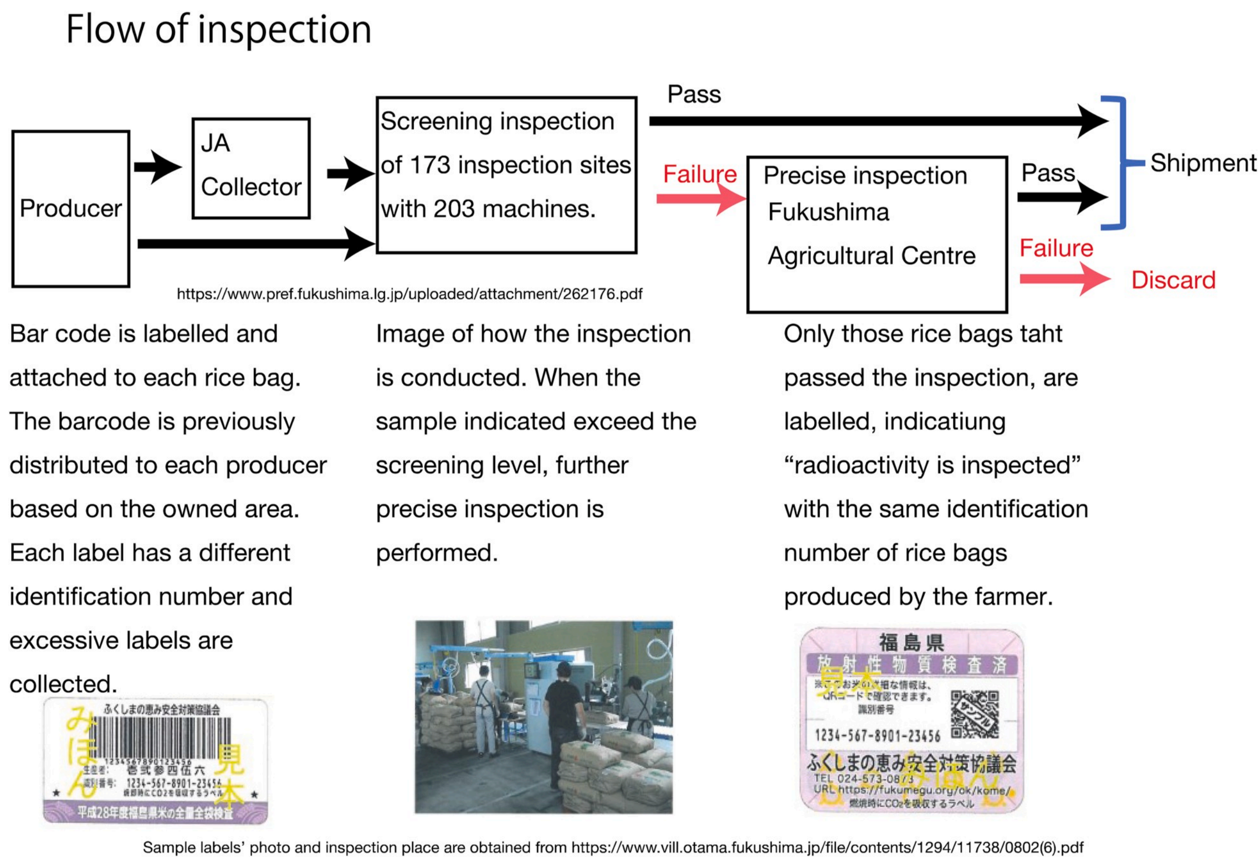

Fig. 8. Flow chart for the inspection of brown rice in Fukushima prefecture. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

During each measurement, one package of 8 trays (with 3–5 fruits in each tray) or individually wrapped fruits were inspected first by the box unit. If the concentration of radiocaesium in any of the trays exceeded the action level, all of the contents of the package were discarded. The inspection flow is summarized in Fig. 10. The use of multiple detectors makes it possible to simultaneously obtain spatial information. This process allows for analysis of the two-dimensional radiation distribution in a package. This method is also applicable for the complicated shapes of other agricultural products.

4.3. Non-destructive radioactivity measurements during post-accidental food monitoring

Many inspections of foodstuffs for radioactivity required application of non-destructive analysis, and several instruments have been developed for such a purpose. One of these tools was developed by Tohoku University and contains multiple NaI(Tl) scintillator detectors. To date, approximately 40 machines have been procured for use in the areas affected by the FDNPP accident (Ishii, 2015). Similar tools that use multiple CsI(Tl) scintillator detectors or large NaI(Tl) scintillation detectors are also available.

A key requirement in application of non-destructive analysis is the homogeneity of radionuclides within the edible portions of the measured sample. This approach is sometimes challenging to apply to fruit samples because they contain edible and non-edible components. In the case of prunes, because the seed (non-edible) concentration of radiocaesium is lower than in the edible portion, non-destructive measurements might underestimate the contamination concentration (Gurunabi Co, 2013). For prune fruit, the ratio of radiocaesium concentration of the seed to that of the flesh is below 1. However, in peach and apple, the ratios of radiocaesium, in the non-edible portions to that in the edible portions are greater than 1.0. In the latter case, the non-destructive measurement might overestimate the concentration of radiocaesium in the edible portion, although it is acceptable for such assessments.

Another important point is that the non-destructive techniques (MHLW, 2015) that are accepted as radiocaesium screening methods for food (MHLW, 2012a) can reliably determine radiocaesium concentrations less than the Standard Limit, if the concentrations are lower than the screening level.

4.4. Airborne and in situ measurements

The areal deposition density of gamma-emitting radionuclides can be assessed with the aid of an airborne survey. Such data have been updated in Japan every year after the accident, and the most recent data were presented in the MAFF report (MAFF, 2017). As substantial inhomogeneities of contamination exist even within a single field (Kubo et al., 2020), an airborne survey supplies rather rough estimates of the areal contamination density, and more detailed field measurements using in situ gamma-spectrometers are also required (Fesenko et al., 2009). Several instruments have been developed and available for field measurement after the accident. Such as KURAMA tool[3] was developed by Kyoto University and used for measurement in the orchard fields (Kuwana et al., 2015; Yuda et al., 2016; Sekizawa et al., 2019). The National Agriculture and Food Research Organization (NARO) also developed a GPS connected NaI(Tl) field spectrometer that was used in evaluation of decontamination effects in the fields (NARO, 2013, 2015).

[3] http://www.rri.kyoto-u.ac.jp/kurama/index_en.html, updated as KURAMA II.

Fig. 9. Facility for Inspection of Anpogaki. A: Canberra system for inspection. B: Inside of the inspection machine. C: System for inspection of Hitachi-Zosen type. D: Measurement of Anpogaki packages.

Similar instruments have also been developed by selected private companies. Furthermore, JAEA developed a dispersion energy recognition model that was able to distinguish the radioactivity distribution below the soil surface (JAEA, 2014). Additionally, FATC developed a method that uses the NaI(Tl) spectrometer in non-destructive silage roll measurement (Saito et al., 2015).

5. Ensuring the reliability of radioactivity measurement

5.1. Calibration of equipment for conventional measurements

Considering the increase in demand for analyses of radioactivity in food, the MHLW declared that the alternative methods for beef analysis by using the NaI(Tl) scintillation spectrometer, survey meter, or other instruments can fulfil the requirement for such instruments (MHLW, 2011c). Such methods were widely used in areas affected by the Chernobyl accident and demonstrated high effectiveness in use as a countermeasure applied to animals (Fesenko et al., 2001, 2006).

The categories of food for which this option can be applied were extended by the inclusion of rice and wheat (or other cereals) (MHLW, 2011d) and drinking water (MHLW, 2011e) in October. By November, this list was expanded to general foodstuffs except for milk and dairy products (MHLW, 2011f). Finally, at the time of introduction of the Standard Limits in foods, another screening method that uses the NaI(Tl) scintillation spectrometers for detection of radioactive caesium in food samples was also introduced (MHLW, 2012c). The equipment used in screening methods (e.g., with application of NaI(Tl) scintillation spectrometers) was required to be calibrated at least once per year with the appropriate gamma-ray standards.

For measurement of radioactive iodine, conventional methods were defined even before 2011 (MHLW, 2002), but as the detection sensitivity differs among the used instruments used, application of a calibration standard limit was required for each instrument before measuring the actual iodine concentrations. For this reason, the Japan Radioisotope Association (JRA) published the calibration value for major instruments for radioiodine (JRA, 2011a) (Table 7), and the same was also applied for radiocaesium (JRA, 2011b) (Table 8).

The application of simplified methods required measurement of the same geometry of a ^{131}I sample by using counting efficiency. However, most of the survey meters use the dose equivalent rate (μSv hr^{-1}). For this purpose, the ^{131}I standard solution (ca. 5 kBq kg^{-1}) was filled into a 2 L Marinelli beaker, 2 L polyethylene pot and a round shaped V-type container. The geometry of these measurements is shown in Fig. 11. For detection inside a solution, the detector was dipped into the water at a 5 cm depth.

During the early stage of the nuclear emergency, ^{131}I, ^{134}Cs and ^{137}Cs are the major dose-forming radionuclides. Thus, earlier measurements using the NaI(Tl) detectors focused on ^{131}I, whereas the later measurements after a few months focused on ^{134}Cs and ^{137}Cs instead of ^{131}I. For calibration to measure the conversion efficiency, the ^{137}Cs standard solution (ca. 5 kBq kg^{-1}) was filled into 2 L Marinelli beaker, 2 L polyethylene pot and round shaped V-type container. It is known that the counting efficiency of the NaI(Tl) scintillation counter for ^{134}Cs is higher than that for ^{137}Cs. If the conversion efficiency for ^{137}Cs was applied for the mixture of ^{134}Cs and ^{137}Cs (approximately 1:1 at the time of the accident), the converted value was also higher than the realistic value. Although it is impossible to obtain exact values for ^{134}Cs and ^{137}Cs of radiocaesium, the value attained is acceptable for screening. The conversion efficiencies for ^{131}I and ^{137}Cs are summarized in Tables 7 and 8 For detection inside a solution, only those detectors with a 1 inch $\times$ 1 inch NaI(Tl) crystal can be used because of the insertion size of the container.

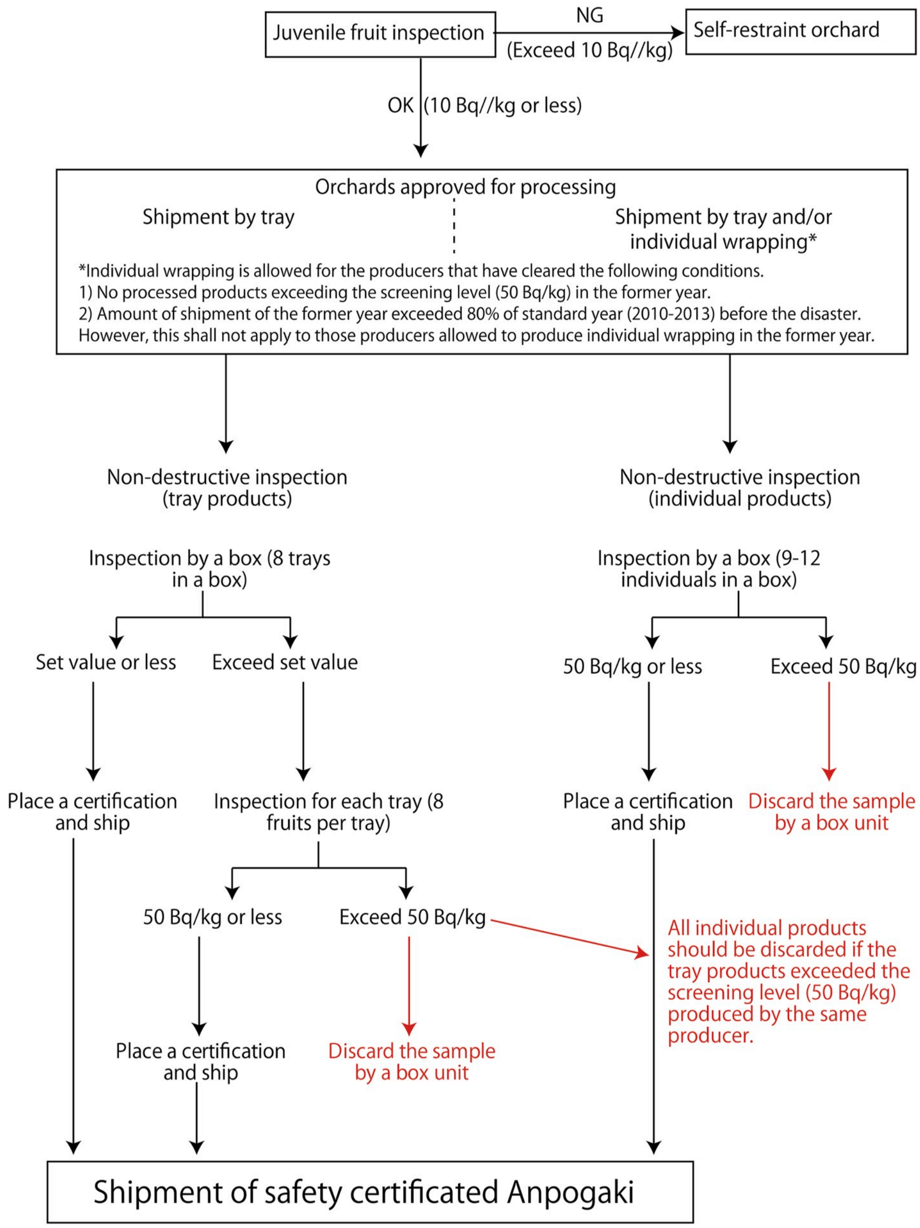

Fig. 10. Flow chart for the inspection of Anpogaki in 2017 (Fukushima prefecture, 2017).

5.2. Proficiency test

A review of monitoring systems in the EU countries is presented in Máté et al. (2015). The review noted the need for standardized and integrated methods with well-defined measurement and calculation protocols for radionuclides in foodstuffs, especially for emergency exposure situations. Upon request of the EC Directorate General for Energy, an inter-laboratory comparison for emergency measurements of the environmental samples and foodstuffs was organized biennially to harmonize the results obtained by different laboratories in the EU (Sobiech-Matura et al., 2017). To guarantee the accuracy of radiological measurement, it is essential to maintain the following factors.

1. Verification of the soundness of the detectors.
2. Management of the measurement process.
3. Improvement of measurement skill via a proficiency test administered by external quality control.

The last factor is essential for objective certification, and a proficiency test was positioned as one of the external quality controls. The IAEA began in 2012 in the Japan Proficiency Test (PT) programme covering measurements of water, soil, grass, air filter samples and feedstuffs (Japan Proficiency Test, 2012; IAEA, 2013). Most of institutions conducting radioactivity measurement participated in exercises to ensure the reliability of the measurements. Proficiency tests using brown rice have been conducted since 2012 with the collaboration of NARO and the National Institute of Advanced Industrial Science and Technology (AIST) (Unno et al., 2016). The results of the proficiency test showed that most of the participants of the programme have highly reliable measurement skills (Unno et al., 2016).

5.3. Unauthorised measurements by citizens

The National Consumer Affairs Centre of Japan noted the difficulties in obtaining actual values of the radiocaesium concentrations in the foodstuff samples (National Consumer Affairs Centre of Japan, 2011). Furthermore, MAFF announced to the head of the Domestic Food Industry Group in Japan that only certified analysis methods should be

Table 7
List of conversion efficiency for ^{131}I at different measurement geometries (modified based on JRA, 2011a).

Manufacture	Model	Geometry				
			2 L Marinelli	2 L Round shaped V type container	2 L Polyvinyl container (side detection)	2 L Polyvinyl container (solution immersed detection)
Fuji Electric	NHC610B1	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	196	595	337	177
Hitachi Aloka medical	TCS-172(B), TCS-172	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	45.7	135	103	47.5
Hitachi Aloka medical	TCS-171(B), TCS-171	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	30700	77600	63100	27600
Health Physics Instruments	5000S	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	44.8	146	97.2	47.8
LUDLUM	44-2 (Model 3)	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	45.0	127	96.3	50.1
LIR Radiation	Identi FINDER	Sample weight (kg)	2	0.63	2	
		Conversion efficiency (Bq/kg/cps)	26.5	58.6	41.4	
Berkeley Nucleonics Corporation	940-GN	Sample weight (kg)	2	0.63	2	
		Conversion efficiency (Bq/kg/cps)	9.23	31.0	22.2	
Berkeley Nucleonics Corporation	940-2G	Sample weight (kg)	2	0.63	2	
		Conversion efficiency (Bq/kg/cps)	9.14	30.3	21.0	
Berkeley Nucleonics Corporation	940-3G	Sample weight (kg)	2	0.63	2	
		Conversion efficiency (Bq/kg/cps)	2.65	16.0	10.2	

Table 8
List of conversion efficiency for ^{137}Cs at different measurement geometries (modified based on JRA, 2011b).

Manufacture	Model		Geometry			
			2 L Marinelli	2 L Round shaped V type container	2 L Polyvinyl container (solution immersed detection)	2 L Polyvinyl container (side detection)
Fuji Electric	NHC610B1	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	313	841	335	634
Fuji Electric	NHC710B1	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	711	187	81.4	128
Hitachi Aloka medical	TCS-172(B)	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	71.0	198	67.8	168
Hitachi Aloka medical	TCS-171(B)	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	24,500	73,400	19,200	49,200
Health Physics Instruments	5000S	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	79.6	253	73.4	144
LUDLUM	44-2 (Model 3)	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	72.7	204	–	144
LIR Radiation	identiFINDER	Sample weight (kg)	2	0.63		2
		Conversion efficiency (Bq/kg/cps)	–	–		59.4
Berkeley Nucleonics Corporation	940-GN	Sample weight (kg)	2	0.63		2
		Conversion efficiency (Bq/kg/cps)	14.00	44.4		30.1
Berkeley Nucleonics Corporation	940-2G	Sample weight (kg)	2	0.63		2
		Conversion efficiency (Bq/kg/cps)	14.0	46.2		29.6
Berkeley Nucleonics Corporation	940-3G	Sample weight (kg)	2	0.63		2
		Conversion efficiency (Bq/kg/cps)	5.40	20.1		13.9
CANBERRA	SG-1R	Sample weight (kg)	2	0.63	2	2
		Conversion efficiency (Bq/kg/cps)	71.20	206.0	70.8	148.0
CANBERRA	SG-2R	Sample weight (kg)	2	0.63		2
		Conversion efficiency (Bq/kg/cps)	14.20	47.7		33.3

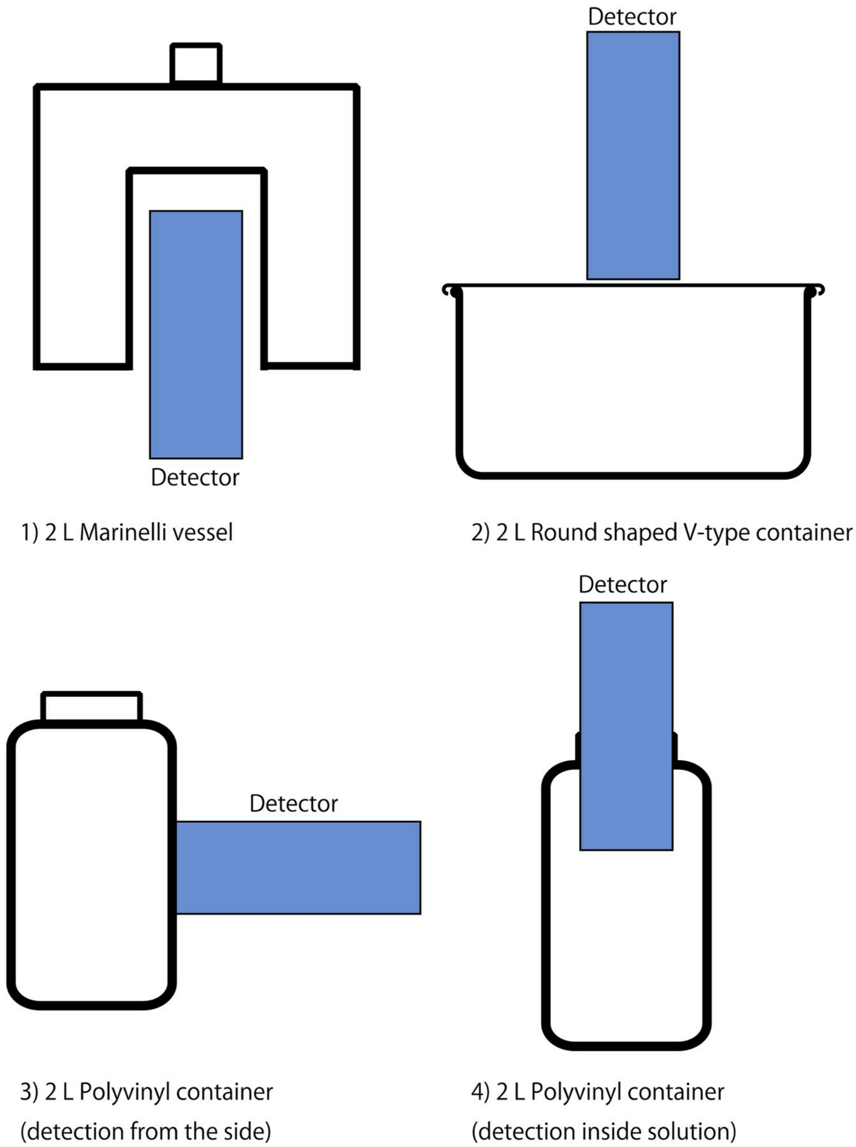

Fig. 11. Geometries of detector and radiation source (figure is modified based on Japan Radioisotope Association, 2011).

used to apply quality control management and that regular proficiency tests should be performed (MAFF, 2012). This request was repeatedly pointed out by the National Standard Organization for Radiation Measurement in Japan, AIST (AIST, 2011). However, insufficient instruments and operators were one of the major concerns, especially at the early stages of the emergency in Japan.

It was during this time that voluntary sampling was performed by concerned citizens. While it is worth noting that such unauthorised and informal measurements produced much confusing information and rumours, the quick and voluntary response by the private sector and citizens increased the pool of environmental data that served as a validation for each municipality's measurement. This information in turn allowed an acceleration of information availability for the radioactivity level of foodstuff.

6. Cost-related issues

The inspection of all rice bags is very expensive. These expenses, including costs for facilities rental and costs of rice transportation, were more than 5 billion JPY per year. Furthermore, the salaries for operators and the operation of the council (Fukushima Association for Securing Safety of Agricultural Products) cost an additional few hundreds of millions JPY every year. The costs of operation were covered by TEPCO as compensation for damage because of the FDNPP accident. The salaries for the operators and the operation of council were covered by the Japanese government from 2016 onwards. From 2017, Fukushima prefecture established a special budget known as "Agriculture, forestry and fishery reproduction comprehensive program for Fukushima prefecture" of MAFF, which is supported by the Reconstruction Agency. Approximately 500 JPY per 30 kg bag was required for inspection. However, as the purpose of the complete bag inspection is also to supply public reassurance, it is still difficult to terminate it without acceptable assurance related to the radiocaesium levels in brown rice. Although, it is more realistic for the municipality to select sampling inspection to reduce the local economic burden and maintain the local economy, it was decided to inspect all bags to obtain and maintain public reassurance. In Japan, complete bag inspection for the whole prefecture started as a decision made to improve the reputation of agricultural items produced in Fukushima prefecture, and this decision was associated with a notably large amount of costs. This initiative is technically feasible, but continuation of the system requires thorough consideration of the cost and benefit involved. Fukushima prefecture announced that complete bag inspection will terminate for the whole prefecture, if no bags are detected exceeding the threshold over 5 years, except for those areas in which evacuation orders have been issued (12 municipalities) (Fukushima prefecture, 2018), and this effort continues through FY 2020.

7. Conclusions (lessons learned)

For effective emergency response to accidents, emergency infrastructure such as equipment for analytical measurements, trained staff, and predefined sampling points should be in place before an accident. The accident at the FDNPP lead to many challenges related to sampling and monitoring of the agricultural environment and foodstuffs. One of the lessons learned is that preparedness for a nuclear accident is a necessary not only for countries with nuclear power, but also for adjacent countries. Guidance on environmental monitoring of radionuclides to be performed following emergencies is provided by IAEA (2005), where the sampling times for soil and each foodstuff are described, e.g., once for soil, daily sampling for leafy vegetables and milk, and at harvest for other vegetables, fruits and grains after the contaminated radioactive cloud has passed. In Japan, the procedures for soil and food monitoring were carried out in the same manner. The difficulty arose in deciding on the area for monitoring. Collection of samples from the field (soils and plants, including crops) during the emergency phase requires a systematic approach that can be based on a grid-based sampling scheme. However, it was difficult to collect samples from the private fields. This is an example of legislative issues to be resolved in case of a nuclear emergency, specifically, official predefinition of the agricultural fields around the nuclear power plant for sampling after an emergency. The shortage of instruments and equipment such as Ge semiconductor detectors, and soil samplers during the early phase of the accident and the lack of trained staff for sampling and analytical measurements caused delays in provision of the information required for implementation of countermeasures. To resolve the above issues, new approaches for optimising agricultural monitoring were suggested. Specifically, after the FDNPP accident, the wide use of screening methods in monitoring of radiocaesium concentrations in foodstuffs allowed a significant reduction in the time required for radionuclide monitoring of food. Large amounts of new equipment, machines and tools were developed, validated and implemented for monitoring of crops (first of all, rice) and selected sensitive fruits (Anpogaki) in which high concentrations of radiocaesium could be anticipated.

This plan allowed a tremendous increase in the number of analyses performed and supplied a decrease in public concerns related to food safety at the regional and national scales. One of the key issues in monitoring of soil and agricultural products in areas affected after the FDNPP accident was optimising the use of human resources for sampling and measurements and permanent training of the staff involved. The proficiency tests organized in Japan with IAEA support showed high competence in measurement of radionuclide activity concentrations in the water, soil, atmosphere and rice. The experience of such training deserves documentation and sharing with other countries. Therefore, although many well-known methods were used in sampling, sample processing and measurements, many new procedures, guides and techniques were developed and implemented to optimise monitoring of foodstuffs after the FDNPP accident. This experience deserves to be considered as a component of emergency preparedness in other countries.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvrad.2020.106265.

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