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＜ Original ＞

Estimating of internal radiation doses due to food consumption and its reduction applying the food regulation after the Fukushima nuclear accident using national food-monitoring data

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Abstract

Objectives: The study examined the public health policies implemented after the Fukushima nuclear accident using the monitoring data on food.

Methods: The amount of radioactive material ingested was determined and converted into doses using the Japan National Health and Nutrition Survey and food radioactive concentration monitoring data sampled by each prefecture in June of each year between 2011 and 2019. The study also examined the effects of public health policies on the basis of the differences between (1) calculation using all food monitoring data in the absence of interventions and (2) application of the restriction.

Results: In June 2011, the median committed effective dose for adult males was estimated at 18.3 μSv (with regulation) in Fukushima Prefecture. The effect of food restriction was 42.2% for the population for intaking foods with median radiation dose (the median population) in Fukushima in 2011.

Conclusion: The effect of food restriction was 42.2% for the median population in Fukushima in 2011, which points to the effectiveness of public health mitigations.

keywords: internal radiation doses, food consumption, food regulation, Fukushima nuclear accident, national food-monitoring data

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I. Background

Protective measures against radiation that aim to ensure the safety of food and drinking water are critical against disasters that lead to environmental contamination[1].

Previous nuclear disasters, such as the Chernobyl nuclear power plant accident, resulted in dire health consequences such as thyroid cancer due to exposure to radiation especially due to food consumption of affected milk without countermeasures [2] . In this case, high doses of radiation were absorbed mainly through ingestion[3].

Previous studies analyzed the monitoring data of radioactive materials in food in Japan before and after the Fukushima accident and confirmed that the concentration of radioactive materials in food has increased due to the accident[4]. Whole-body counting (WBC) measurements in Fukushima Prefecture demonstrated that 26 out of 344,762 (0.008 %) residents were exposed to >1 mSv as committed effective doses due to annual foodstuff consumption between June 2011 and March 2020 [5]. This finding suggested that although the median dose was low, residents received prolonged and wide range of doses due to the Tokyo Electric Power Company (TEPCO) Fukushima Daiichi Nuclear Power Plant (FDNPP) accident, which occurred in 2011 reflecting the diversity of dietary habits that lead to the consumption of non-tradable products.

The Japanese government has taken measures in response to the nuclear accident. Specifically, each prefectural government implemented the monitoring of radioactive substances in food. The Nuclear Emergency Response Headquarters carried out the "establishment of items and areas for inspection plans, shipping restrictions, and other

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measures" on April 4, 2011, which is revised on an annual basis [6]. The national guideline on sampling plan was established according to this principal document. Foodstuff samples were collected in accordance with the sampling plans of the local governments and measured using the test methods prescribed by the national government [7-9]. A comprehensive monitoring plan was formulated on August 2, 2011, which is also revised every year. Lastly, the government collected data on the concentrations of radioactive substances in foodstuffs measured in each prefecture.

An important issue of the measures for radiation protection regarding the actual implementation in society is socio-economic factors assuming an appropriately representative individual and considering the wide range of dose distribution among residents. Therefore, evaluating the regulations and taking the plan-do-check-act (PDCA) cycle into consideration are necessary [10-11]. Assessing the regulations requires the use of a broad range of data to acquire a holistic picture of the scenario. The concentration of radiation in food products varies across regions; thus, aggregating and refining data by region as well is crucial. In addition, carrying out the evaluation for a prolonged period is important as mentioned previously and the half-life of ^{137}Cs is 30 years.

The study examined the public health policies implemented after the nuclear accident using the monitoring data on radionuclide concentration in food to estimate radiation doses through ingestion. Moreover, the study aimed to examine the reduction of internal exposure as a result of the public health measures for health protection after the nuclear accident through shipping food restrictions.

Note: Tokyo is indicated as a reference.

Figure 1 Targeted prefectures

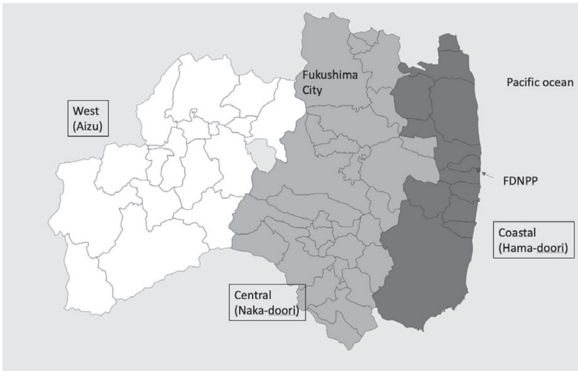

Figure 2 Three regions in Fukushima Prefecture

II. Method

1. Database

Data on concentration of radioactive materials (Bq/kg) in food

A total of 2,626,497 samples on the concentration of radioactive materials (Bq/kg) in food have been collected from March 2011 to April 2020. Data from each prefecture were formally provided to the Ministry of Health, Labour and Welfare (MHLW). Internal radiation doses from ingestion of food were estimated by simulating food consumption in June of each year between 2011 and 2019 (n = 1,484,266) among each target population (i.e., residents in Fukushima Prefecture and six neighboring prefectures as indicated at Figure 1). Among them, Fukushima Prefecture was divided into three areas, namely, the central (Naka-doori), west (Aizu Region), and coastal (Hama-doori) regions as indicated at Figure 2. The radionuclides targeted were radioactive iodine 131 (^{131}I), radioactive cesium 134 (^{134}Cs), and radioactive cesium 137 (^{137}Cs). Data on radioactive strontium and other radionuclides were not used because of the paucity of measurements of these radionuclides in food. It was assumed that 10 grams of tealeaves were used for 500 ml of tea in order to relate the measured concentration of radioactive substances in tea leaves to the amount of radioactive substances ingested by drinking tea and the concentration of rice was assumed to be 1/4 regarding polishing effect since the concentration of radioactive cesium in polished rice is about 10% lower than that in brown rice according to Research Center for Agricultural Information Technology.

2. Data on food intake (kg/month)

Data on food intake (g/day) of 99 food types as identified by the Japan National Health and Nutrition Survey (JNHNS) were collected every year. Apart from the 99 food types, other food categories such as livestock, agricultural, and marine products, others, milk and infant food, wild meat, and drinking water were used to summarize data. Food intake amounts were selected randomly using log-normal distributions created by applying the mean and the standard deviation (both were published) for each food type of the data for males over 20 years of age. Here the dependence of this coefficient (DC_{ing}) on age is relatively small (food intake has a more direct effect on the dose).

3. Estimating the amount of radioactive materials through ingestion and conversion to radiation doses

Radioactive concentration (RC_k) and monthly foodstuff consumption in kg (MFC_k) with a consideration of the precise food category (k = 99) were used to determine the amount of monthly ingested radioactive material (Bq/month) (MIR) (Formula (1)). MIR was then converted into monthly committed effective doses due to ingestion (Sv/month) ($CED_{m,ing}$) using the internal radiation dose due to food consumption in Sv/Bq (DC_{ing}) taken from International Commission On Radiological Protection (ICRP) [12] (Formula (2)). The variable DC_{ing} of ^{137}Cs for an adult member of the public is 1.3×10^{-08} (Sv/Bq).

$$\mathrm{MIR\ (Bq/month)} = \sum_{k=1}^{99} \mathrm{RC}_k \left(\frac{\mathrm{Bq}}{\mathrm{kg}}\right) \times \mathrm{MFC}_k\ \mathrm{(kg/month)}\ (1)$$

$$\mathrm{CED}_{m,ing}\left(\frac{\mathrm{Sv}}{\mathrm{month}}\right) = MIR\left(\frac{\mathrm{Bq}}{\mathrm{month}}\right) \times DC_{ing}\mathrm{(Sv/Bq)}.\ (2)$$

4. Estimating population doses

Radiation doses for every 10th percentile from the minimum to the 90th percentile with incremental additions of 95th, 99th, 99.9th, and 99.99th percentiles were calculated and weighted together by population size to obtain the population doses.

5. Assessing variation in estimated doses

The concentration (Bq/kg) and volume of foodstuff (kg/month) were randomly sampled 100,000 times to estimates the median dose of the targeted population.

The uncertainty of the estimates was assessed by repeating the calculation for 10 times.

6. Evaluating the effectiveness of public health policies

The study examined the effects of public health policies on the basis of the differences between (1) calculation using all food monitoring data in the absence of interventions and (2) application of the restriction then conversion to monetary value assuming the value of a statistical life (VSL) [13].

7. Handling radioactivity measurement data below the detection limit

The percentage of samples below the detection limit for each food item in each prefecture was calculated on a monthly basis. If the percentage exceeds 60% of the total number of samples, then the concentration of each food item was replaced with a surrogate concentration, which was calculated by converting the detection limit and dividing by two. Otherwise, the detection limit concentration was used to determine food concentration.

We open our program code through the site of National Institute of Public Health (NIPH) (Appendix (https://www.niph.go.jp/journal/data/70-1/202170010010ap01.pdf)) and data is published monthly from MHLW [14] and database for analysis is open to the public from NIPH (URL: http://www.radioactivity-db.info), respectively. All analyses were conducted using R 3.5.1 [15].

8. Disclosure of information on conflicts of interest

There is no conflict of interest to disclose in relation to submission of this manuscript.

9. Ethical consideration

All data were derived from secondary sources that are publicly accessible through the Internet. Thus, ethical approval was not required based on the official guidelines in Japan.

10. Funding source

The study was funded by the National Institute of Public Health, Japan.

III. Results

1. Radioactive concentration of food items

Basic statistics for the concentration of radioactive substances in food

Table 1 (A)-(D) provides the number of samples and the maximum, upper 5th percentile, arithmetic mean, and median of radioactive Cs concentrations in each food category, such as vegetables (A), wild meats (B), fishery products (C), and livestock products (D). Milk and Infant Foods, drinking water and others are omitted in these tables due to lower concentrations.

The largest number of cases was found for livestock meat, which accounted for 1,125,949 out of the 1,484,266 samples (75.8%) (Table 1(D). The ratio of livestock samples increased every year from 2011 to 2019. Out of the total 1,119,894 were below the detection limit (99.4%). Among all samples including other food categories, 1,401,345 did not exceed the detection limit (1,401,345/1,484,266 =

Table 1A Basic statistics of radiocesium concentration in food samples of vegetables by year and prefecture

Prefecture	Callender year	2011	2012	2013	2014	2015	2016	2017-2019 [*1]	total
Fukushima	N [*2] (n)	9309	12213	12593	13256	10095	7598	17238	82302
	N [*2]: beyond the criteria (n)	294	199	152	53	11	6	39	754
	RC [*3]: Maximum (Bq/kg)	82000	5600	12000	700	260	180	310	82000
	RC [*3]: Upper 5 percentile (Bq/kg)	280	77	75	25	19	19	20	47
	RC [*3]: Mean (Bq/kg)	130	22	23	11	10	10	11	28
	RC [*3]: Median (Bq/kg)	10	9	9	9	8	9	9	9
	Detected samples N [*2] (n)	2889	3312	3830	2348	1698	1258	2816	18151
	Detected samples Mean (Bq/kg)	391	55	53	18	13	15	17	91
	Detected samples Median(Bq/kg)	47	23	19	8	7	9	10	14
Miyagi	N [*2] (n)	921	5923	7399	6347	4604	4612	9493	39299
	N [*2]: beyond the criteria (n)	3	67	46	30	41	33	98	318
	RC [*3]: Maximum (Bq/kg)	1400	1600	1700	1200	690	720	630	1700
	RC [*3]: Upper 5 percentile (Bq/kg)	62	27	35	25	28	28	25	31
	RC [*3]: Mean (Bq/kg)	27	16	18	17	18	18	16	17
	RC [*3]: Median (Bq/kg)	10	9	10	11	11	14	10	10
	Detected samples N [*2] (n)	203	1003	1639	1508	695	961	1546	7555
	Detected samples Mean (Bq/kg)	77	37	29	27	37	29	11	33
	Detected samples Median(Bq/kg)	50	14	19	16	20	17	8	17
Yamagata	N [*2] (n)	670	940	1096	1049	598	623	1430	6406
	N [*2]: beyond the criteria (n)	0	0	2	2	2	3	5	14
	RC [*3]: Maximum (Bq/kg)	62	50	240	200	129	260	300	300
	RC [*3]: Upper 5 percentile (Bq/kg)	50	25	25	25	25	25	26	25
	RC [*3]: Mean (Bq/kg)	14	11	13	14	12	12	14	13
	RC [*3]: Median (Bq/kg)	10	10	11	14	10	10	12	10
	Detected samples N [*2] (n)	127	38	49	57	17	30	126	444
	Detected samples Mean (Bq/kg)	30	17	25	37	33	40	41	33
	Detected samples Median(Bq/kg)	50	22	11	20	15	21	29	24
Ibaraki	N [*2] (n)	1771	4894	2293	2344	1718	1665	3094	17779
	N [*2]: beyond the criteria (n)	48	31	1	3	0	0	11	94
	RC [*3]: Maximum (Bq/kg)	8000	2080	110	140	78	98	630	8000
	RC [*3]: Upper 5 percentile (Bq/kg)	232	29	25	25	25	25	25	33
	RC [*3]: Mean (Bq/kg)	52	16	14	14	13	13	14	18
	RC [*3]: Median (Bq/kg)	10	9	10	10	10	9	9	10
	Detected samples N [*2] (n)	592	708	188	455	224	252	649	3068
	Detected samples Mean (Bq/kg)	132	46	14	17	11	14	19	45
	Detected samples Median(Bq/kg)	50	11	8	12	7	9	9	12
Tochigi	N [*2] (n)	1235	7236	4571	4296	3194	3349	6433	30314
	N [*2]: beyond the criteria (n)	38	126	9	11	3	2	0	189
	RC [*3]: Maximum (Bq/kg)	6940	31000	500	400	450	2200	68	31000
	RC [*3]: Upper 5 percentile (Bq/kg)	183	43	25	25	25	25	25	28
	RC [*3]: Mean (Bq/kg)	70	27	11	10	10	12	11	17
	RC [*3]: Median (Bq/kg)	19	7	7	7	8	8	8	8
	Detected samples N [*2] (n)	402	2924	1142	818	565	703	1024	7578
	Detected samples RC [*3]: Mean (Bq/kg)	173	55	14	13	12	20	13	38
	Detected samples RC [*3]: Median(Bq/kg)	47	10	8	7	8	9	9	9
Gunma	N [*2] (n)	1095	2750	2217	1706	1329	1135	2035	12267
	N [*2]: beyond the criteria (n)	11	19	12	2	3	1	34	82
	RC [*3]: Maximum (Bq/kg)	2867	2500	590	530	420	2000	780	2867
	RC [*3]: Upper 5 percentile (Bq/kg)	79	40	25	25	25	25	33	40
	RC [*3]: Mean (Bq/kg)	36	15	13	12	13	14	18	17
	RC [*3]: Median (Bq/kg)	11	19	12	9	10	10	15	10
	Detected samples N [*2] (n)	193	407	210	113	117	99	396	1535
	Detected samples RC [*3]: Mean (Bq/kg)	116	43	34	26	26	40	39	47
	Detected samples RC [*3]: Median(Bq/kg)	36	15	19	17	14	15	19	18
Niigata	N [*2] (n)	1114	1608	1900	1616	1145	922	1475	9780
	N [*2]: beyond the criteria (n)	0	1	1	5	2	1	17	27
	RC [*3]: Maximum (Bq/kg)	106	450	230	280	210	220	260	450
	RC [*3]: Upper 5 percentile (Bq/kg)	10	12	11	17	18	17	25	20
	RC [*3]: Mean (Bq/kg)	10	10	8	8	8	8	12	9
	RC [*3]: Median (Bq/kg)	10	10	7	7	7	7	7	7
	Detected samples N [*2] (n)	26	26	48	49	44	46	134	373
	Detected samples RC [*3]: Mean (Bq/kg)	23	34	22	38	22	21	41	32
	Detected samples RC [*3]: Median(Bq/kg)	13	11	10	17	9	9	19	13
Total	N [*2] (n)	16115	35564	32069	30614	22683	19904	41198	198147
	N [*2]: beyond the criteria (n)	394	443	223	106	62	46	204	1478
	Detected samples N [*2] (n)	4432	8418	7106	5348	3360	3349	6691	38704

[*1] The three years were tabulated together since similar trends followed, so we compiled a summary of the three years.
[*2] Number of samples
[*3] Radiocesium concentration
Data provided to Ministry of Health, Labour and Welfare (MHLW) by each prefecture were used for the analysis.
The monthly percentage of samples below the detection limit for each food item (number of items is 99) by prefecture was calculated, and if the percentage was more than 60%, the detection limit value divided by two was used; otherwise, the detection limit value was used for each sample.

Table 1B Basic statistics of radiocesium concentration in food samples of wild poultry and animal meats by year and prefecture

Prefecture	Callender year	2011	2012	2013	2014	2015	2016	2017-2019 [*1]	total
Fukushima	N [*2] (n)	0	266	363	362	275	388	805	2459
	N [*2]: beyond the criteria (n)	0	166	271	201	178	171	160	1147
	RC [*3]: Maximum (Bq/kg)	— [*4]	33000	61000	15000	30000	13000	14000	61000
	RC [*3]: Upper 5 percentile (Bq/kg)	— [*4]	1575	7400	1100	1760	1265	620	2500
	RC [*3]: Mean (Bq/kg)	— [*4]	645	2063	387	733	349	209	637
	RC [*3]: Median (Bq/kg)	— [*4]	170	370	120	190	75	28	88
	Detected samples: N [*2] (n)	0	261	350	347	266	356	604	2184
	Detected samples: Mean (Bq/kg)	— [*4]	657	2139	404	758	379	273	715
	Detected samples: Median(Bq/kg)	— [*4]	180	400	130	200	92	45	120
Miyagi	N [*2] (n)	0	53	78	122	134	162	724	1273
	N [*2]: beyond the criteria (n)	0	27	25	35	44	39	56	226
	RC [*3]: Maximum (Bq/kg)	— [*4]	470	640	1300	820	3800	670	3800
	RC [*3]: Upper 5 percentile (Bq/kg)	— [*4]	378	334	290	390	288	130	250
	RC [*3]: Mean (Bq/kg)	— [*4]	150	112	97	108	104	38	68
	RC [*3]: Median (Bq/kg)	— [*4]	110	69	55	57	44	17	24
	Detected samples: N [*2] (n)	— [*4]	53	76	117	131	150	428	955
	Detected samples: Mean (Bq/kg)	— [*4]	150	114	100	110	111	53	86
	Detected samples: Median(Bq/kg)	— [*4]	110	71	58	58	53	24	41
Yamagata	N [*2] (n)	0	14	6	23	31	29	56	159
	N [*2]: beyond the criteria (n)	0	2	1	0	0	0	3	6
	RC [*3]: Maximum (Bq/kg)	— [*3]	110	180	63	48	53	160	180
	RC [*3]: Upper 5 percentile (Bq/kg)	— [*3]	110	144	59	41	49	103	66
	RC [*3]: Mean (Bq/kg)	— [*3]	42	47	30	17	21	28	27
	RC [*3]: Median (Bq/kg)	— [*3]	36	19	29	11	13	20	18
	Detected samples: N [*2] (n)	— [*3]	10	5	21	15	18	54	123
	Detected samples: Mean (Bq/kg)	— [*3]	53	53	32	23	27	29	31
	Detected samples: Median(Bq/kg)	— [*3]	50	20	29	15	22	20	22
Ibaraki	N [*2] (n)	0	30	40	35	36	29	79	249
	N [*2]: beyond the criteria (n)	0	5	10	6	3	1	1	26
	RC [*3]: Maximum (Bq/kg)	— [*3]	240	250	330	180	110	160	330
	RC [*3]: Upper 5 percentile (Bq/kg)	— [*3]	187	152	150	120	85	70	140
	RC [*3]: Mean (Bq/kg)	— [*3]	65	70	61	51	41	25	48
	RC [*3]: Median (Bq/kg)	— [*3]	48	50	40	35	38	18	34
	Detected samples: N [*2] (n)	0	27	39	33	35	28	60	222
	Detected samples: Mean (Bq/kg)	-	72	72	64	52	42	31	53
	Detected samples: Median(Bq/kg)	-	57	50	42	36	39	26	38
Tochigi	N [*2] (n)	0	241	282	299	141	199	1150	2312
	N [*2]: beyond the criteria (n)	0	58	79	53	48	20	61	319
	RC [*3]: Maximum (Bq/kg)	— [*3]	1100	1000	450	500	250	600	1100
	RC [*3]: Upper 5 percentile (Bq/kg)	— [*3]	360	240	211	260	141	110	180
	RC [*3]: Mean (Bq/kg)	— [*3]	105	87	66	85	49	34	57
	RC [*3]: Median (Bq/kg)	— [*3]	53	56	40	48	36	25	29
	Detected samples: N [*2] (n)	— [*3]	233	271	277	125	196	860	1962
	Detected samples: RC [*3]: Mean (Bq/kg)	— [*3]	107	91	70	95	50	39	63
	Detected samples: RC [*3]: Median(Bq/kg)	— [*3]	55	58	44	67	37	23	37
Gunma	N [*2] (n)	2	214	218	183	134	111	367	1229
	N [*2]: beyond the criteria (n)	0	85	72	63	43	22	72	357
	RC [*3]: Maximum (Bq/kg)	160	1100	500	1100	370	440	880	1100
	RC [*3]: Upper 5 percentile (Bq/kg)	— [*3]	280	262	377	214	270	250	270
	RC [*3]: Mean (Bq/kg)	128	115	98	118	86	73	73	93
	RC [*3]: Median (Bq/kg)	128	85	72	63	43	22	30	62
	Detected samples: N [*2] (n)	2	195	209	176	129	100	294	1105
	Detected samples: RC [*3]: Mean (Bq/kg)	128	124	102	121	89	79	86	101
	Detected samples: RC [*3]: Median(Bq/kg)	128	94	76	76	76	40	44	69
Niigata	N [*2] (n)	0	8	54	79	22	21	27	211
	N [*2]: beyond the criteria (n)	0	2	0	1	0	0	0	3
	RC [*3]: Maximum (Bq/kg)	— [*3]	130	75	130	32	83	87	760
	RC [*3]: Upper 5 percentile (Bq/kg)	— [*3]	540	45	61	20	78	40	59
	RC [*3]: Mean (Bq/kg)	— [*3]	30	16	19	9	26	15	21
	RC [*3]: Median (Bq/kg)	— [*3]	2	37	57	13	19	7	8
	Detected samples: N [*2] (n)	0	7	37	57	13	19	19	152
	Detected samples: RC [*3]: Mean (Bq/kg)	— [*3]	147	20	24	12	28	17	27
	Detected samples: RC [*3]: Median(Bq/kg)	— [*3]	36	10	12	10	17	9	12
Total	N [*2] (n)	2	826	1041	1103	773	939	3208	7892
	N [*2]: beyond the criteria (n)	0	345	458	359	316	253	353	2084
	Detected samples: N [*2] (n)	2	786	987	1028	714	867	2319	6703

[*1] The three years were tabulated together since similar trends followed, so we compiled a summary of the three years.
[*2] Number of samples
[*3] Radiocesium concentration
[*4] Not existence
Data provided to Ministry of Health, Labour and Welfare (MHLW) by each prefecture were used for the analysis.
The monthly percentage of samples below the detection limit for each food item (number of items is 99) by prefecture was calculated, and if the percentage was more than 60%, the detection limit value divided by two was used; otherwise, the detection limit value was used for each sample.

Table 1C Basic statistics of radiocesium concentration in food samples of fishery products by year and prefecture

Prefecture	Callender year	2011	2012	2013	2014	2015	2016	2017-2019 *1	total
Fukushima	N *2 (n)	2378	6294	8396	10462	9069	9227	24481	70307
	N *2: beyond the criteria (n)	161	792	341	118	13	4	19	1448
	RC *3: Maximum (Bq/kg)	14400	18700	12000	740	260	170	480	18700
	RC *3: Upper 5 percentile (Bq/kg)	640	314	91	37	20	19	19	70
	RC *3: Mean (Bq/kg)	178	79	28	19	16	16	16	29
	RC *3: Median (Bq/kg)	67	19	16	16	16	15	16	16
	Detected samples N *2 (n)	1921	3693	2805	2125	1189	773	1573	14079
	Detected samples Mean (Bq/kg)	217	123	53	34	22	19	16	83
	Detected samples Median(Bq/kg)	94	51	25	17	14	13	16	28
Miyagi	N *2 (n)	415	2837	2601	3272	2952	2738	6763	21578
	N *2: beyond the criteria (n)	0	60	16	5	1	0	0	82
	RC *3: Maximum (Bq/kg)	305	3300	310	190	240	68	71	3300
	RC *3: Upper 5 percentile (Bq/kg)	50	71	33	25	25	24	25	25
	RC *3: Mean (Bq/kg)	16	22	13	13	12	12	13	14
	RC *3: Median (Bq/kg)	7	10	9	9	9	8	9	9
	Detected samples N *2 (n)	270	1733	1240	549	314	211	349	4666
	Detected samples Mean (Bq/kg)	22	30	16	12	12	9	11	20
	Detected samples Median(Bq/kg)	10	12	9	6	6	6	8	9
Yamagata	N *2 (n)	16	65	53	59	69	43	79	384
	N *2: beyond the criteria (n)	0	0	0	0	0	0	0	0
	RC *3: Maximum (Bq/kg)	50	57	25	25	20	20	25	57
	RC *3: Upper 5 percentile (Bq/kg)	49	25	19	16	18	17	16	20
	RC *3: Mean (Bq/kg)	16	12	13	11	11	11	11	12
	RC *3: Median (Bq/kg)	10	11	11	11	10	11	11	11
	Detected samples N *2 (n)	7	14	2	1	0	0	0	24
	Detected samples Mean (Bq/kg)	28	20	5	6	— *4	— *4	— *4	21
	Detected samples Median(Bq/kg)	27	18	5	6	— *4	— *4	— *4	18
Ibaraki	N *2 (n)	890	2967	3070	3148	2649	2159	3305	18188
	N *2: beyond the criteria (n)	7	59	6	2	0	0	0	74
	RC *3: Maximum (Bq/kg)	1374	600	1000	180	68	80	60	1374
	RC *3: Upper 5 percentile (Bq/kg)	129	88	37	26	24	18	13	41
	RC *3: Mean (Bq/kg)	41	26	13	11	9	10	9	14
	RC *3: Median (Bq/kg)	50	12	12	10	10	9	9	10
	Detected samples N *2 (n)	761	2232	1610	1305	691	320	368	7287
	Detected samples Mean (Bq/kg)	46	30	16	11	10	13	11	22
	Detected samples Median(Bq/kg)	24	19	9	6	5	6	7	11
Tochigi	N *2 (n)	33	901	591	368	296	333	631	3153
	N *2: beyond the criteria (n)	0	52	9	4	3	1	3	72
	RC *3: Maximum (Bq/kg)	460	420	210	260	130	110	160	460
	RC *3: Upper 5 percentile (Bq/kg)	384	140	25	25	14	49	19	73
	RC *3: Mean (Bq/kg)	128	35	16	14	11	17	11	21
	RC *3: Median (Bq/kg)	50	12	12	10	10	9	9	11
	Detected samples N *2 (n)	27	535	168	72	40	96	86	1024
	Detected samples RC *3: Mean (Bq/kg)	155	48	22	27	23	38	24	41
	Detected samples RC *3: Median(Bq/kg)	117	26	12	10	9	43	9	20
Gunma	N *2 (n)	33	292	463	349	340	266	694	2437
	N *2: beyond the criteria (n)	10	9	25	9	3	1	3	60
	RC *3: Maximum (Bq/kg)	741	768	340	260	380	120	230	768
	RC *3: Upper 5 percentile (Bq/kg)	688	315	110	95	71	43	34	85
	RC *3: Mean (Bq/kg)	231	49	24	22	24	14	12	25
	RC *3: Median (Bq/kg)	50	12	12	10	10	9	9	10
	Detected samples N *2 (n)	15	104	192	156	196	126	235	1024
	Detected samples RC *3: Mean (Bq/kg)	492	117	40	37	35	20	18	45
	Detected samples RC *3: Median(Bq/kg)	563	45	20	19	23	13	10	16
Niigata	N *2 (n)	62	142	181	224	159	115	122	1005
	N *2: beyond the criteria (n)	0	0	0	0	0	0	0	0
	RC *3: Maximum (Bq/kg)	21	44	39	25	25	25	25	44
	RC *3: Upper 5 percentile (Bq/kg)	10	10	14	9	16	9	25	14
	RC *3: Mean (Bq/kg)	10	9	8	8	8	7	7	8
	RC *3: Median (Bq/kg)	10	10	8	8	8	7	4	8
	Detected samples N *2 (n)	6	3	10	2	6	5	1	33
	Detected samples RC *3: Mean (Bq/kg)	11	9	15	6	4	4	2	9
	Detected samples RC *3: Median(Bq/kg)	9	7	14	6	4	5	2	6
Total	N *2 (n)	3827	13498	15355	17882	15534	14881	36075	117052
	N *2: beyond the criteria (n)	178	972	397	138	20	6	25	1736
	Detected samples N *2 (n)	3007	8314	6027	4210	2436	1531	2612	28137

*1 The three years were tabulated together since similar trends followed, so we compiled a summary of the three years.
*2 Number of samples
*3 Radiocesium concentration
*4 Not existence
Data provided to Ministry of Health, Labour and Welfare (MHLW) by each prefecture were used for the analysis.
The monthly percentage of samples below the detection limit for each food item (number of items is 99) by prefecture was calculated, and if the percentage was more than 60%, the detection limit value divided by two was used; otherwise, the detection limit value was used for each sample.

Table 1D Basic statistics of radiocesium concentration in food samples of livestock products by year and prefecture

Prefecture		Callender year	2011	2012	2013	2014	2015	2016	2017-2019 *1	total
Fukushima		N *2 (n)	4436	11292	17003	16928	18575	17807	47682	133723
		N *2: beyond the criteria (n)	127	42	0	0	0	0	0	169
		RC *3: Maximum (Bq/kg)	14600	2030	56	83	45	51	25	14600
		RC *3: Upper 5 percentile (Bq/kg)	171	50	25	25	25	25	25	25
		RC *3: Mean (Bq/kg)	73	25	22	22	23	23	23	24
		RC *3: Median (Bq/kg)	17	18	25	25	25	25	25	25
	Detected samples	N *2 (n)	1189	380	108	65	26	17	48	1833
		Mean (Bq/kg)	216	134	14	14	13	12	9	170
		Median(Bq/kg)	37	22	10	10	10	9	8	27
Miyagi		N *2 (n)	8079	18280	28654	29245	25557	21158	68823	199796
		N *2: beyond the criteria (n)	56	1	0	0	0	0	0	57
		RC *3: Maximum (Bq/kg)	1400	402	47	67	38	54	45	1400
		RC *3: Upper 5 percentile (Bq/kg)	109	50	25	25	25	25	25	50
		RC *3: Mean (Bq/kg)	52	43	25	25	25	25	25	28
		RC *3: Median (Bq/kg)	40	50	25	25	25	25	25	25
	Detected samples	N *2 (n)	1086	78	33	26	20	7	12	1262
		Mean (Bq/kg)	146	74	29	32	29	32	30	132
		Median(Bq/kg)	70	55	28	31	28	28	28	61
Yamagata		N *2 (n)	8128	16387	18916	19066	17191	15547	47329	142564
		N *2: beyond the criteria (n)	2	1	0	0	0	0	0	3
		RC *3: Maximum (Bq/kg)	590	560	35	25	25	25	25	590
		RC *3: Upper 5 percentile (Bq/kg)	50	50	25	25	25	25	25	25
		RC *3: Mean (Bq/kg)	24	31	25	25	25	25	25	26
		RC *3: Median (Bq/kg)	10	25	25	25	25	25	25	25
	Detected samples	N *2 (n)	1631	7	1	0	0	0	25	1664
		Mean (Bq/kg)	26	97	27	— *4	— *4	— *4	15	26
		Median(Bq/kg)	12	25	27	— *4	— *4	— *4	15	12
Ibaraki		N *2 (n)	6076	15020	21831	22712	22946	22715	64020	175320
		N *2: beyond the criteria (n)	6	2	0	0	0	0	0	8
		RC *3: Maximum (Bq/kg)	1040	850	64	26	25	25	26	1040
		RC *3: Upper 5 percentile (Bq/kg)	50	50	25	25	25	25	25	50
		RC *3: Mean (Bq/kg)	38	36	25	25	25	25	25	26
		RC *3: Median (Bq/kg)	50	25	25	25	25	25	25	25
	Detected samples	N *2 (n)	320	65	12	1	1	25	89	513
		Mean (Bq/kg)	57	121	25	1	2	20	20	56
		Median(Bq/kg)	13	67	21	1	2	20	20	20
Tochigi		N *2 (n)	5928	19273	27272	28619	29545	32878	97655	241170
		N *2: beyond the criteria (n)	24	4	0	0	0	0	0	28
		RC *3: Maximum (Bq/kg)	2356	2490	85	27	25	40	38	2490
		RC *3: Upper 5 percentile (Bq/kg)	50	50	25	25	25	25	25	25
		RC *3: Mean (Bq/kg)	56	32	25	25	25	25	25	26
		RC *3: Median (Bq/kg)	50	25	25	25	25	25	25	25
	Detected samples	N *2 (n)	138	100	25	7	18	29	106	423
		RC *3: Mean (Bq/kg)	322	106	29	19	8	15	17	138
		RC *3: Median(Bq/kg)	177	50	25	20	7	19	18	31
Gunma		N *2 (n)	6128	19460	24030	27066	27589	27945	78980	211198
		N *2: beyond the criteria (n)	0	2	0	0	0	0	0	2
		RC *3: Maximum (Bq/kg)	482	368	80	36	25	25	33	482
		RC *3: Upper 5 percentile (Bq/kg)	50	50	25	25	25	25	25	25
		RC *3: Mean (Bq/kg)	45	31	25	25	25	25	25	26
		RC *3: Median (Bq/kg)	50	25	25	25	25	25	25	25
	Detected samples	N *2 (n)	112	112	10	1	0	8	50	293
		RC *3: Mean (Bq/kg)	113	98	26	36	— *3	21	20	86
		RC *3: Median(Bq/kg)	75	76	16	36	— *3	21	20	58
Niigata		N *2 (n)	354	2089	3959	3793	2592	2189	7202	22178
		N *2: beyond the criteria (n)	0	0	0	0	0	0	0	0
		RC *3: Maximum (Bq/kg)	470	70	30	28	25	27	25	470
		RC *3: Upper 5 percentile (Bq/kg)	143	50	25	25	25	25	25	25
		RC *3: Mean (Bq/kg)	55	31	25	25	25	25	25	26
		RC *3: Median (Bq/kg)	50	25	25	25	25	25	25	25
	Detected samples	N *2 (n)	62	0	4	1	0	0	0	67
		RC *3: Mean (Bq/kg)	120	— *4	18	28	— *4	— *4	0	113
		RC *3: Median(Bq/kg)	100	— *4	14	28	— *4	— *4	0	91
Total		N *2 (n)	39129	101801	141665	147429	143995	140239	411691	1125949
		N *2: beyond the criteria (n)	215	52	0	0	0	0	0	267
	Detected samples	N *2 (n)	4538	742	193	101	65	86	330	6055

*1 The three years were tabulated together since similar trends followed, so we compiled a summary of the three years.
*2 Number of samples
*3 Radiocesium concentration
*4 Not existence
Data provided to Ministry of Health, Labour and Welfare (MHLW) by each prefecture were used for the analysis.
The monthly percentage of samples below the detection limit for each food item (number of items is 99) by prefecture was calculated, and if the percentage was more than 60%, the detection limit value divided by two was used; otherwise, the detection limit value was used for each sample.

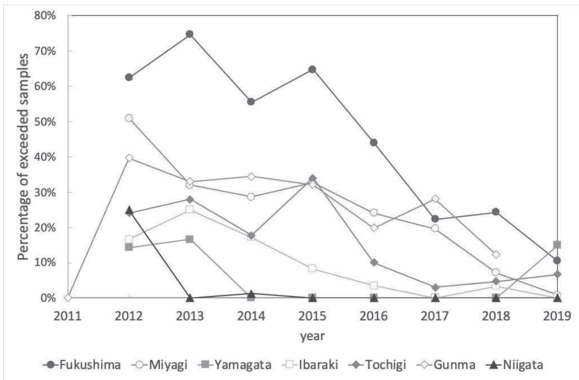

Figure 3 Annual change in the percentage of wild bird and animal meat above the standard among each prefecture

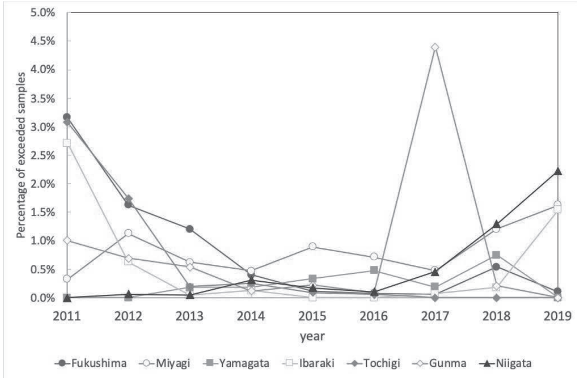

Figure 4 Annual change in the percentage of vegetables above the standard among each prefecture

94.4%).

The percentage of samples above the regulatory limit was the highest (1.34%) in 2011, which dropped to 0.1% in 2019. According to food category, wild bird and animal meat obtained the highest percentage of exceeding the limit, with 2,084 of the 7,892 cases exceeding the standard (26.4%) (Table 1(B)). Annual changes in the percentage of vegetables and wild bird and animal meat above the standard are shown in Figure 3 and Figure 4, respectively.

In general, the maximum and average concentrations decreased over time. In certain cases, however, the average concentrations, such as those for Fukushima, Ibaraki, Gunma, and Niigata Prefectures for vegetables, Yamagata Prefecture for wild game, and Miyagi Prefecture for fish and shellfish, increased since 2017 (Figure.4).

For vegetables, an increase in the number of cases that exceeded the standard was observed in Gunma and Niigata Prefectures since 2016, whereas no downward trend was noted for Miyagi and Yamagata Prefectures (Table 1A).

For wild bird and animal meat, increases were observed in Yamagata and Gunma Prefectures since 2016, whereas the opposite is true for Tochigi Prefecture. In Miyagi Prefecture, a similar upward trend was observed since 2012 (Table 1B).

For fish and shellfish, an increase was found for Ibaraki Prefecture since 2016 (Table 1C). Moreover, deviations between the medians and means were observed.

2. Dose estimation

In June 2011, the median committed effective dose for adult males was estimated at 18.3 μSv (without regulation: 31.6 μSv) in Fukushima Prefecture (Table 2). Doses generally decreased with time since the accident. However, the estimated dose for 2011 was not the highest in Yamagata and Niigata Prefectures. The committed effective dose due to internal exposure by ingestion demonstrated regional

Table 2 Commited effective dose for adult males in Fukushima prefecture and neighbouhood prefectures in June of each year

Radiation dose		Median among population				
Prefecture	year	Without restriction [μSv] a	sd [μSv]	With restriction [μSv] b	sd [μSv]	Effect of restriction (*) (b-a)/a
Fukushima	2011	31.6	0.083	18.3	0.018	-42.2%
	2012	3.9	0.004	3.7	0.004	-6.9%
	2013	6.4	0.011	6.0	0.007	-6.7%
	2014	5.3	0.008	5.2	0.009	-1.9%
	2015	1.8	0.002	1.8	0.003	-0.1%
	2016	2.4	0.003	2.4	0.003	-0.3%
Miyagi	2011	5.5	0.010	5.5	0.016	-0.1%
	2012	2.6	0.004	2.5	0.005	-6.3%
	2013	3.2	0.004	3.1	0.004	-3.0%
	2014	1.6	0.002	1.6	0.002	-0.0%
	2015	1.9	0.002	1.9	0.002	-1.3%
	2016	2.0	0.004	1.9	0.002	-1.5%
Yamagata	2011	1.3	0.001	1.3	0.001	-0.0%
	2012	1.1	0.002	1.1	0.002	-0.0%
	2013	1.1	0.002	1.1	0.002	-0.0%
	2014	1.0	0.002	1.0	0.002	-0.0%
	2015	1.0	0.002	1.0	0.002	0.0%
	2016	0.8	0.002	0.8	0.001	0.0%
Ibaraki	2011	6.9	0.009	6.9	0.013	0.1%
	2012	2.8	0.005	2.8	0.004	-0.8%
	2013	2.3	0.004	2.3	0.004	-0.1%
	2014	2.5	0.002	2.5	0.003	-0.0%
	2015	2.0	0.002	2.0	0.002	0.0%
	2016	2.1	0.004	2.1	0.003	-0.2%
Tochigi	2011	3.7	0.007	3.7	0.007	0.2%
	2012	2.6	0.004	2.5	0.004	-4.6%
	2013	1.9	0.004	1.8	0.003	-3.9%
	2014	1.9	0.002	1.8	0.002	-0.8%
	2015	1.6	0.002	1.6	0.003	-1.0%
	2016	1.5	0.002	1.5	0.002	-0.9%
Gunma	2011	4.4	0.009	4.4	0.015	0.0%
	2012	2.3	0.004	2.2	0.005	-1.6%
	2013	2.4	0.007	2.2	0.005	-6.0%
	2014	1.8	0.002	1.8	0.002	-0.0%
	2015	1.8	0.002	1.8	0.003	0.0%
	2016	1.8	0.003	1.8	0.003	-0.4%
Niigata	2011	1.4	0.001	1.4	0.001	-0.0%
	2012	2.2	0.004	2.2	0.004	-0.1%
	2013	1.3	0.002	1.3	0.002	0.0%
	2014	1.2	0.002	1.2	0.002	-0.0%
	2015	1.0	0.001	1.0	0.001	-0.0%
	2016	1.1	0.002	1.1	0.002	-0.0%

(*) The impact of the regulation was defined as the difference between real-life dose calculations using only food concentrations below the reference value and unrealistic dose calculations using all food concentrations.
Dose distributions were calculated for each region using the concentrations of radiocesium in 99 different food items by year.
Consumed food amounts were established using the annual National Health and Nutrition Survey for the 99 food items.
The distribution of doses in each area was determined by repeated resampling 100,000 times. This calculation was carried out for 10 trials and the average value was obtained.
The monthly percentage of samples below the detection limit for each food item (number of items is 99) by prefecture was calculated, and if the percentage was more than 60%, the detection limit value divided by two was used; otherwise, the detection limit value was used for each sample.

differences even in Fukushima Prefecture.

High concentrations of radioactive materials have been detected in food even after 2017, but the attribution to dose was limited. Even at the 99.99th percentile in Fukushima Prefecture for 2018, the dose reduction effect reached only 46%.

3. Effects of regulation on radiation safety of food after the nuclear accident

In June 2011, a median of committed effective dose among adult males in Fukushima Prefecture was estimated at 18.3 μSv (without regulation: 31.6 μSv) (Table 2). In 2018, no reduction was observed at the median, where the 99.99th percentile values reached 67 μ Sv with a reduction of only 26%. In the case of the coastal region, 40% of the collective dose consisted of the upper 10% of residents.

Cardis used the concept of collective dose to estimate population risk[11)].

Additional risk from accidents due to the consumption of marine products from an international perspective was compared to the existing risk from natural radioactive materials [16]. During 2011 to 2019, the total collective dose reduction among Fukushima Prefecture was 23.9 man·Sv for every June (Table 3). Assuming a VSL of 600,000 US dollar per 1 man·Sv [13], savings due to the radiation protection measures for food safety was estimated at 14 million US dollars.

IV. Discussion

Estimation of committed effective dose from ingestion of radioactive materials due to the TEPCO FDNPP accident

The median dose was estimated at 0.29 mSv among the central part of Fukushima Prefecture during 2011 to 2019.

The dose estimates obtained by the study were less than those of studies conducted after the Chernobyl accident because such studies reported that 57% of subjects obtained an annual committed effective dose of 0.1 mSv or more even 23 years after the accident not showing a monotonous decrease[17]. The difference depends on the amount of radioactive material reaching the soil per unit area, the initial shipment limit, and the soil-to-plant transfer factor

Table 3 Commited effective dose for adult males at three regions in Fukushima prefecture in June of each year

Radiation dose		Median among population					Population dose				
Area	Year	Without restriction	sd	With restriction	sd	Effect of restriction (*)	Without restriction	With restriction	Averted dose	sd	Value of Saved lives
		[μSv]	[μSv]	[μSv]	[μSv]		[man·Sv]	[man·Sv]	[man·Sv]	[man·Sv]	
		a		b		(b-a)/a	a	b	a-b		
Central region	2011	7.7	0.025	4.6	0.015	-40.6%	15.2	9.3	5.88	0.06	$3.53M
Naka-doori	2012	2.5	0.005	2.3	0.004	-9.3%	4.8	3.6	1.22	0.02	$0.73M
	2013	5.6	0.015	5.0	0.011	-11.1%	8.2	6.3	1.82	0.04	$1.09M
	2014	4.6	0.006	4.4	0.006	-4.5%	5.9	5.5	0.33	0.02	$0.20M
	2015	1.5	0.002	1.5	0.003	-1.0%	3.1	3.1	0.02	0.02	$0.01M
	2016	4.0	0.007	4.0	0.005	-0.5%	5.0	4.9	0.04	0.02	$0.02M
	2017	1.6	0.002	1.6	0.002	0.4%	2.2	2.1	0.01	0.01	$0.01M
	2018	2.5	0.001	2.4	0.002	3.0%	3.4	3.1	0.22	0.01	$0.13M
	2019	2.6	0.004	2.6	0.004	0.0%	3.2	3.2	0.00	0.01	$0.00M
East region	2011	1.8	0.003	1.8	0.003	-1.3%	2.7	2.6	0.09	0.01	$0.05M
Aizu Region	2012	2.0	0.003	2.0	0.003	-0.4%	2.9	2.9	0.02	0.01	$0.01M
	2013	2.8	0.004	2.7	0.004	-1.1%	3.5	3.4	0.08	0.02	$0.05M
	2014	1.7	0.002	1.7	0.002	-1.1%	2.2	2.1	0.12	0.01	$0.07M
	2015	1.5	0.002	1.5	0.002	0.0%	1.9	1.9	0.00	0.01	$0.00M
	2016	1.6	0.002	1.6	0.002	-0.0%	2.1	2.1	0.00	0.01	$0.00M
	2017	1.6	0.002	1.6	0.002	0.0%	2.1	2.1	0.00	0.01	$0.00M
	2018	2.2	0.003	2.1	0.003	3.5%	3.0	2.8	0.27	0.01	$0.16M
	2019	1.9	0.002	1.9	0.002	-0.0%	2.3	2.3	0.00	0.01	$0.00M
Coastal region	2011	12.0	0.045	2.8	0.045	-76.9%	26.3	5.1	21.21	0.11	$12.72M
Hama-doori	2012	1.7	0.004	1.6	0.004	-5.7%	3.0	2.5	0.44	0.01	$0.26M
	2013	3.3	0.008	3.0	0.008	-9.8%	6.4	3.8	2.62	0.03	$1.57M
	2014	3.9	0.005	3.9	0.005	-1.5%	5.0	4.9	0.11	0.02	$0.07M
	2015	3.5	0.007	3.5	0.007	0.0%	4.4	4.4	0.00	0.03	$0.00M
	2016	0.6	0.001	0.6	0.001	-2.3%	0.9	0.8	0.07	0.00	$0.04M
	2017	0.6	0.001	0.6	0.001	0.0%	0.8	0.8	0.00	0.00	$0.00M
	2018	1.0	0.001	1.0	0.001	0.0%	1.2	1.2	0.00	0.01	$0.00M
	2019	1.0	0.001	1.0	0.001	-0.0%	1.2	1.2	0.00	0.01	$0.00M

(*) The impact of the regulation was defined as the difference between real-life dose calculations using only food concentrations below the reference value and unrealistic dose calculations using all food concentrations.
Dose distributions were calculated for each region using the concentrations of radiocesium in 99 different food items by year.
Consumed food amounts were established using the annual National Health and Nutrition Survey for the 99 food items.
The distribution of doses in each area was determined by repeated resampling 100,000 times. This calculation was carried out for 10 trials and the average value was obtained.
The monthly percentage of samples below the detection limit for each food item (number of items is 99) by prefecture was calculated, and if the percentage was more than 60%, the detection limit value divided by two was used; otherwise, the detection limit value was used for each sample."

[18]. The obtained median results were consistent with the estimation presented in a report of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) for 2013. The estimation was presented as the "25% local, standard result" model, which indicated 0.06 and 0.14 mSv for the first year and 10 years after the accident, respectively. In addition, the"100% local, but allowing for imports" model indicated 0.20 and 0.50 mSv for the first year and 10 years after the accident, respectively[19], because the estimated median dose for 2011 to 2019 was 0.29 mSv. Furthermore, the results nearly slightly exceeded a previously estimated dose, such as "The committed effective dose ranged from 0.01–0.06 and 0.01–0.02 mSv in the first and second screening, respectively," using the WBC measurement in 2013 [20] because the estimated median dose was 0.07 mSv in the central part of Fukushima Prefecture. Such results were also consistent with studies using the duplicate diet methods conducted in 2012, which did not exceed 0.1 mSv[21].

Nuclear disasters render the public prone to radiation exposure, which is divided into internal and external exposure. External exposure can be assessed using dosimeters, whereas internal exposure is difficult to estimate. Internal exposure is derived from inhalation and oral intake. Of these routes, inhalation dose can be roughly estimated by the location of residence, whereas oral intake can be estimated through drinking water and food. Estimating internal dose from food consumption is complicated because it reflects the diversity of behaviors toward food consumption, especially in Japan, due to the flourishing food distribution. The contribution of food intake to radiation dose is greater in groups with high doses. Therefore, understanding the actual situation in terms of radiation protection is important.

The methods for estimating internal exposure include external counting, such as WBC and bioassays for human measurements, as well as food-targeted methods, such as the market basket methods and duplicate diet methods, which are conducted on a large scale. However, sampling bias is possible[22]. Among these methods, WBC was implemented in the early phase for a limited number of persons[23]. It is widely used in Fukushima and maintained a high degree of representativeness within a limited area, thus promoting research[24].

To obtain a holistic picture of radiation exposure from food consumption, the study estimated radiation dose distribution from ingestion of radioactive materials due to the TEPCO FDNPP accident by analyzing the food monitoring database for Fukushima Prefecture and six neighboring prefectures from 2011 to 2019.

The study infers that much of the initial internal dose may have been derived from inhalation exposure and drinking water because measures were taken immediately and normal food distribution was disrupted after the earthquake [25]. Doses from food can be controllable given appropriate information dissemination. However, some residents did not comply with the evacuation protocols. In addition, diversity was observed in behavior toward food consumption. These aspects suggested possible exceptions to the rule. However, the estimated median doses were in close agreement with the previous estimates of the WHO [19,26] and other studies [21,24,27-28].

The current study did not consider the contribution of other radionuclides apart from 131I, 134Cs, and 137Cs. In establishing the reference values, the study assumed that the contribution of radiocesium was approximately 10%. For marine products, this value was assumed at 50%. Importantly, however, previous studies have verified these values to be on the safe side [29].

The results of the JNHNS contained sampling bias. In addition, food intake may vary with the seasons due to the limitations of the sample size. However, the JNHNS excluded this factor from analysis.

1. Assessment of collective committed effective dose

The additional collective dose due to ingestion was 853 man·Sv for a population of 2 million (2011) in Fukushima during 2012 to 2019, thus accomplishing a dose reduction of 89 man·Sv. A conservative estimation was compared to the UNSCEAR 2013 report, which indicated that the additional collective dose due to ingestion was 3.5 man·kSv for a population of 128 million (2010) in Japan during 2012 to 2020 [19].

Dose from oral intake was the dominant component in high-dose populations, thus giving a dose larger than that estimated by UNSCEAR. However, when taken on an individual basis, the dose was negligible for the majority of the population.

Therefore, the current measures should be updated to reflect the dose estimation and estimated effect of public health measures given an appropriate representative person in terms of radiation protection to adapt to changing situations.

2. Effect of public health mitigation

The efficiency of protective measures on food radiation safety during June 2011 was assessed at 42.2% for the median dose among Fukushima. The reduction of internal exposure due to ingestion of affected foodstuff was evaluated by assuming food restriction and utilizing the monitoring data of radionuclide concentration in food.

In Fukushima Prefecture, public health measures effectively reduced radiation doses in the early years. Such a dose reduction was particularly effective for high-dose populations. However, this effect worsened over time. Outside Fukushima Prefecture, the effect was poor even during 2011.

Differences in effectiveness were noted between "timing," "region," and "distribution within a population" in the evaluation of public health measures. The effect was greatest in the first year in Fukushima Prefecture, which was greater in the high-dose groups. Furthermore, regional differences were observed even within Fukushima Prefecture. Of the three regions in Fukushima Prefecture, the largest effect in the first year was seen in Hamadori, followed by Nakadori. In the high-dose cohort, specific food categories contributed to the dose.

Moreover, the effectiveness of the countermeasures employed in Fukushima Prefecture decreased over time. After 2014, the 99.99th percentile value of the annual oral intake of committed effective doses have fallen below 1 mSv even in the northern part of the prefecture. In addition, the 2018 regulatory reduction in the 99.99th percentile was greatest in the northern part of the prefecture. However, the size of effectiveness reached only 63%.

One of the major contributors to radiation doses from radionuclides emitted from the nuclear facilities is oral ingestion [19]. Thus, public health mitigations have been taken to successfully reduce the dose to residents.

Conversely, the values for cost per life-year saved should be considered because it was estimated at 6.6–8.0 million yen and 23–51 million yen for vegetables in March and April in 2011, respectively, reflecting the decline in concentrations in a short period of time, even immediately after the accident [30] . Therefore, based on the results of 9 years of monitoring, the measurement of all cattle and rice samples is expected to be streamlined in the future.

3. Concentration of radioactive substances in food

The concentrations of radioactive substances in foodstuff in each prefecture were generally consistent with the fallout. The amount of ^{137}Cs for March 2011 was nearly within 10 kBq/m^2 to 3 MBq/m^2 except for sites near to and far from the damaged power plant, which was estimated at 1.2 Bq/m^2 (Niigata) to 17 kBq/m^2 (Ibaraki) during the same period [31]. The concentrations of radioactive substances in foodstuff tended to decrease over time. However, the percentage of cases that exceeded the concentration standards for several wild vegetables continued to increase for several prefectures. Previous studies reported a new restriction on wild plants, such as that for Nagano Prefecture (however, it is not adjacent to Fukushima Prefecture) as of June 18, 2020 even 9 years after the accident. The reason for the delay in the introduction of shipping restrictions on these foods is that the level of priority for sampling these foodstuffs is low, which reflects the market size of seasonal local foodstuff and small amount of consumption.

The accident at Fukushima was characterized by a substantial emission of radioactive materials to the ocean because the nuclear power plant is located on the coast. In fact, the spillage of radioactive materials continues into the sea through rivers. However, concentrations of radioactive materials in fish were generally low except for fish harvested very close to the accident site or other species of freshwater fish.

4. Impact of past fallouts

Although data on shipment restrictions were excluded from the study, such restrictions were observed (i.e., mushrooms in Aomori and Yamanashi Prefectures), which indicate the impact of past fallouts including the Chernobyl accident.

5. Necessity of long-term monitoring

Long-term monitoring of wild meat, especially wild game, is necessary considering the half-life of ^{137}Cs [32]. However, the intake weight of this group of food is low, and radiation doses that can be obtained from them are limited. Differences in the distribution pattern of food concentration were also observed among municipalities. This scenario may reflect differences in sampling methods. However, risk for consumers was adequately controlled due to concentration distribution.

6. Significance of the study

Responses to the Fukushima nuclear accident are underway. In the aftermath of the Chernobyl nuclear power plant accident, each member state implemented the PDCA mechanisms of safety countermeasures for food radiation to seek optimization given international coordination [11].

7. Characteristics of data used

Sampling is conducted in accordance with the latest plan at each time point, and the sampling method is intended to minimize the risk of missing excess samples. Therefore, sample selection bias, such as the selection of the target food item, is considered to have influenced the dose estimates.

The highest number of samples was found in beef, but the concentrations decreased over time, and most of them were below the detection limit. The mean values detected were lower than the mean of the total samples. The trend was similar to that of a previous study [33]. According to the revised sampling plan, the sample size for beef will be decreased dramatically after 2020.

On the other hand, foods with high concentrations of radioactive materials are not distributed in large quantities in daily food and are more dependent on local culture, which is considered to reflect local culture characteristics. The fact shown from Fukushima Prefectural government that "26 people exceeded 1 mSv" in the WBC indicates the impact of the accident, and the consumption of local foodstuffs is a possible cause. Although the doses for many people who consume distributed products are considered to be small [34], this study also showed that the current regulations could be regulated so that no one would exceed 1 mSv.

8. Limiting feature of the food consumption data used in this study

When assuming food intake by individual, it is necessary to take into account the correlation between the intake of each type of food. Therefore, in order to obtain more detailed results, it is necessary to take into account the correlation structure using individual unit data. In addition, the National Health and Nutrition Survey is based on daily intake so that this study did not use habitual intake. With regard to people with high radiation doses, the former leads to underestimation and the latter to overestimation [35].

9. Limiting feature of a large proportion of data below the detection limit

Even in Fukushima, the detected ratio for vegetables was 31 % in 2011. A large proportion of data were below the detection limit, such that dose estimation is expected to be conservative, which may cause certain discrepancies with the estimates indicated in the UNSCEAER 2013 report.

10. Uncertainty of health effect due to low radiation exposure

This study used the linear no-threshold (LNT) dose response model to estimate the radiation risk reduction effect. Because of the limitations of risk estimates for low-dose exposures, the risk reduction effect estimated in this study is subject to significant uncertainty.

V. Conclusion

The study estimated radiation doses through ingestion due to the nuclear plant accident Fukushima Prefecture and six surrounding prefectures in June during 2011 to 2019. Furthermore, the study evaluated the reduction of internal exposure as a result of public health measures. Results indicated that the effect of food restriction was 42.2% for the median population, which points to the effectiveness of public health mitigations. Such measures to reduce radiation risk led to savings of 14 million US dollars (for every June during 2011 to 2019.).

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＜原著＞

福島での原子力事故後の食品の摂取による内部被ばく線量と食品規制による線量低減の推定

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抄録

目的：食品のモニタリングデータを用いて東京電力福島第一原子力発電所事故後に実施された公衆衛生政策の効果を検証する．

方法：2011年から2019年までの間での国民健康・栄養調査による食品の摂取量と各都道府県が毎年６月にサンプリングした食品中の放射性物質濃度のモニタリングデータを用いて，住民が経口摂取した放射性物質の量を求め，線量に換算した．また，⑴介入を行わない場合の全食品モニタリングデータを用いて算出した線量と⑵制限を適用した場合の線量の差異により公衆衛生政策の効果を検証した．

結果：2011年６月の福島県の成人男性の預託実効線量の中央値は18.3 μSv（規制あり）と推定された．食品の出荷制限の効果は，2011年の福島県では，中央値人口で42.2％であった．

結論：食品の出荷制限による線量低減は，2011年６月でもっとも大きく福島県の人口の中央値で42.2％であり，公衆衛生上のリスク低減効果を示した．

キーワード：内部被ばく，食品摂取，食品規制，福島原子力発電事故，国民健康・栄養調査