Appraisal of the Measures to Avert Health Risks Caused by the Fukushima Nuclear Disaster: from the Perspectives of Costs and Effects of the Policies

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ABSTRACT

In response to the Fukushima Daiichi Nuclear Power Plant accident in March 2011, the Japanese government took actions to prevent people from excess exposure to radiation, including compulsory evacuation and relocation, prohibition of the distribution of contaminated foods, decontamination of residential and agricultural lands, and countermeasures in agriculture to reduce radioactive contamination of agricultural produce. This study assesses the effects and the costs of these policy measures. The effects are measured in terms of loss of life expectancy (LLE), which is calculated from the estimated reductions in cancer mortality caused by radioactive exposure. The costs are measured in monetary terms. The values for cost per life-year saved (CPLYS) are calculated for these policy measures, most of which exceed 100 million yen, some reaching a billion yen. The values are compared to the corresponding values in the case of the Chernobyl nuclear disaster, as well as to the value of the benefit per life-year saved. The policy measures are appraised from the perspectives of effciency and equity.

Keywords: cost-benefit analysis, Fukushima nuclear disaster, loss of life expectancy, effciency, equity, radioactive caesium, evacuation and relocation, food standard, decontamination
JEL Classification Code: D61, Q52, Q58

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1. Introduction

Following the accident of the Fukushima Daiichi Nuclear Power Plant (NPP) of Tokyo Electric Power Company (TEPCO) in March 2011, the Japanese government ordered evacuation of residents from areas located within a 20 km radius of the power plant, and from areas where the annual cumulative dose of radiological exposure could exceed 20 mSv. Moreover, the government immediately began regulating contaminated agricultural products. Various policy actions, including decontamination of the evacuation area, strengthened food monitoring, application of stricter food standards, and countermeasures to reduce food contamination in agriculture, followed these early measures.

These actions were mainly aimed at reducing the health risks of stochastic effects, that is, cancer risks, from radiological exposure. Since stochastic effects are not considered to have a threshold, it is impossible to eliminate such risks completely, unless a society devotes infinite resources toward risk reduction. There is, therefore, a point at which the society ceases to devote further resources to reduce the risk. The aim of this study is to identify the points for various policy measures taken by the Japanese government; I will estimate how much costs the Japanese society has paid for the risk reduction. The risk reduction from these policy measures is assessed in terms of loss of life expectancy (LLE), and the values of cost per life-year saved (CPLYS) are calculated. Thereafter these values are compared with the corresponding values in the Chernobyl case as well as with the values for the benefits of risk reduction based on willingness to pay estimates.

In the next section, the early and late policy measures taken by the Japanese government are described. In section 3, the method for calculating LLE from exposure to radiation is explained, and the values for CPLYS are estimated for the restriction on the distribution of foodstuffs, for the countermeasures taken in agriculture to reduce food contamination, and for the decontamination of the evacuation areas. In section 4, these values are compared with the corresponding values in the Chernobyl case as well as with the value for benefit; thereafter the policy measures in Japan are discussed from the perspectives of efficiency and equity.

2. Policy measures of the Japanese government

2.1. Orders of evacuation and relocation

Unit 1, Unit 2 and Unit 3 of the Fukushima Daiichi NPP lost the core cooling safety function because off-site and on-site electric power was lost due to the great earthquake that occurred on March 11, 2011 and the subsequent tsunami. As those units of the plant were reported to be in a critical condition, the government issued an order at 21:23 on March 11 for the evacuation of people living within a 3 km radius of the NPP. The evacuation zone was expanded to 10 km at 5:44 on March 12, and finally to 20 km at 18:25 on the same day. On March 15, people living in the areas within a 20–30 km radius of the NPP were ordered to go to shelters, and on March 25, a recommendation for voluntary evacuation was issued to them.

On April 22, 2011, a 20 km radius evacuation zone around the Fukushima Daiichi NPP was declared to be a "Restricted Area". The areas outside the Restricted Area where the annual cumulative dose of radiation was expected to exceed 20 mSv, were simultaneously declared as the "Deliberate Evacuation Area", the residents of which were ordered to relocate approximately within a month.

2.2. Foodstuff regulation

Radioactive contamination was detected in vegetables and milk in the area up to 250 km away from the NPP. The Ministry of Health, Labour and Welfare set provisional regulation values (Table 1) for radioactive iodines and caesiums and prohibited the distribution of milk and vegetables produced in the areas where concentrations over the regulation values were found since March 21.

Table 1: Provisional regulation values

($Bq\ kg^{-1}$)

Iodine		Caesium	
Drinking water	300	Drinking water	200
Milk and dairy products	300	Milk and dairy products	200
Vegetables (excluding roots and potatoes)	2000	Vegetables	500
		Crops	500
		Meat, egg, and fishes	500

In July 2011, beef contamination of radioactive caesiums was found and the distribution of all beef from Fukushima Prefecture was stopped for approximately one month. In October 2011, Japanese persimmon from the prefecture was found to include radioactive caesium. Although the concentration was under the regulation value, radioactive caesium was supposed to be concentrated when the persimmon was dried. The Date region of Fukushima Prefecture is famous for producing *anpo-gaki* (a type of dried persimmon). The Fukushima prefectural government requested the anpo-gaki producers to stop production. Rice contamination was detected in November 2011, and rice that had grown in approximately 7000 ha, where rice with a concentration above 100 $Bq\ kg^{-1}$ was found, was excluded from food delivery, with the prospect that the regulation limits would be made stricter.

New standard values for foodstuffs contaminated with radioactive caesium were set in March 2012 and were applicable from April (Table 2). The value for foods in general (100 $Bq\ kg^{-1}$) is based on the criterion that there should be no intake of radioactive caesium with an internal dose of more than 1 $mSv\ y^{-1}$, even if half of the foodstuffs eaten were contaminated with that value. While arriving at the new standard values, no investigation was conducted on the extent of reduction of health risks or costs that would be incurred.

2.3. Countermeasures in agriculture

Although rice planting was restricted to the places where the radioactivity of the harvested rice was likely to exceed the provisional regulation value, rice containing radiocaesium exceeding the provisional standard limit was detected in the autumn, 2011. Responding to this development and to the expected enforcement of stricter standard values that would be applied from April 2012, countermeasures were initiated on rice fields to prevent radiocaesium intake in rice. These countermeasures consisted of supplying sufficient amounts of potassium and zeolite to the soil and deep cultivation. Furthermore, a total inspection of rice produced began in autumn of 2012.

To ensure that none of the fruits contained radiocaesium exceeding the new regulation limits and to resume the production of anpo-gaki (dried persimmon), farmers conducted bark washing in the winter, 2011.

Table 2: New standard values for radioactive caesium for foodstuffs

	(Bq kg^{-1})
Drinking water	10
Milk and dairy products	50
Other foods	100

2.4. Decontamination

The government of Japan announced a policy for remediation of the contaminated areas by enacting the "Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District Off the Pacific Ocean Earthquake that Occurred on March 11, 2011" in August 2011. The Act classified the land to be remediated into two categories: (1) Special Decontamination Area, and (2) Intensive Contamination Survey Area. The former contained the "Restricted Area" and the "Deliberate Evacuation Area", where the national government implemented decontamination. The latter included other areas outside the Special Decontamination Area, where annual individual doses for the first year had been predicted to be between 1 and 20 mSv. In this area, municipalities were responsible for the survey and implementation of the decontamination plans, for which the national government allocated budgets.

The Special Decontamination Area was further classified into three subareas: Subarea 1— preparation areas for lift of evacuation order (1–20 mSv y^{-1}), Subarea 2 —habitation-restricted area (20–50 mSv y^{-1}), and Subarea 3—areas where return would be diffcult (50 mSv y^{-1} and more). The government proposed a plan in March 2012 to complete decontamination by March 2014 in Areas 1 and 2, the target being to reduce the predicted annual dose by 50% for the public and 60% for children in comparison with the dose in August 2011, to achieve 10 mSv y^{-1} or less where the present dose exceeded 10 mSv y^{-1}, and to achieve 1 mSv y^{-1} or less in the long run.

The decontamination activity by the national government began in 2012 and was completed in Tamura city in June 2013 and in Naraha town, Kawauchi village, and Okuma town (except for Area 3) in March 2014, and in all the municipalities in the Special Decontamination Area except for Area 3 by March 2017. The evacuation order was lifted for Tamura city on April 1, 2014, for a part of Kawauchi village on October 1, 2014, for Naraha town on September 5, 2015, and for the residual part of Kawauchi village, Katsurao village, Kawamata town, Iitate village, Tomioka town, Namie town, and Minamisoma city by April 2017 except for Area 3.

3. Cost per life-year saved of the policy measures

3.1. Loss of life expectancy from exposure to radiation

In this study, LLE (Cohen, 1991) was adopted as a measure of the risk from radioactive exposure. According to the 14th report of the Life Span Study (LSS) of atomic bomb survivors (Ozasa et al., 2012), the excess relative risk of death due to solid cancer for the average of men and women is 0.42 when the exposure age is 30 and the attained age is 70, increases by 29% per decade decrease in age at exposure, and is proportional to the attained age to the power of -0.86, that is,

$$R = \alpha d e^{-0.34(x-30)} \left(\frac{a}{70}\right)^{-0.86},$$

where R is the excess relative risk, α is 0.27 for males and 0.57 for females, d is the weighted (with the weights of 1 for γ-ray and 10 for neutron) colon dose (Gy), x is the age at exposure, and a is the attained age. For leukaemia, the LSS reported a model:

$$R = (1.55d + 0.83d^2)e^{-1.06x' - 0.20x't + 0.02x't^2 - 0.0003x't^3 + 0.0007x't'},$$

where d is weighted bone marrow dose (Gy), x' is the minimum of 0 and $(x - 30)/10$, t is the number of years that passed after exposure, and t' is $(t - 30)^3$ if $t > 30$ and 0 if $t \leq 30$ (Richardson et al., 2009).

Assuming that the model for solid cancer is valid from five years after exposure, the model for leukaemia from the next year of exposure, and both models are valid for effective dose, and applying them to the mortalities of solid cancer and leukemia in 2010 for Japanese people, I calculated excess death rates for all the ages at exposure. By combining the results with the life table in 2010, I obtained the values for LLE per mSv, as presented in Table 3.

Table 3: Loss of life expectancy by age at exposure

($y\ mSv^{-1}$)

Age at exposure	Male	Female	Average
0-9	2.7×10^{-3}	4.4×10^{-3}	3.5×10^{-3}
10-19	1.7×10^{-3}	2.9×10^{-3}	2.1×10^{-3}
20-34	1.1×10^{-3}	1.8×10^{-3}	1.5×10^{-3}
35-49	7.3×10^{-4}	1.1×10^{-3}	9.0×10^{-4}
50-	2.6×10^{-4}	3.0×10^{-4}	2.8×10^{-4}
All ages	8.8×10^{-4}	1.3×10^{-3}	1.1×10^{-3}

Calculated on the basis of LSS14 (Ozasa et al., 2012; Richardson et al., 2009), the mortalities of solid cancer and leukemia in 2010 in Japan, and the life table of Japan in 2010.

By using the coefficients for dose from oral intake of radioactive caesiums reported by ICRP (Table 4), we can obtain LLE coefficients from oral intake of radiocaesium for various ages and for various ratios of ^{134}Cs and ^{137}Cs: 1.6×10^{-8} y Bq^{-1} for all ages when the ratio of ^{134}Cs and ^{137}Cs is 1:1, for example.

Table 4: Dose coefficients for oral intake of radiocaesiums

($10^{-5} mSv\ Bq^{-1}$)

Age	0	1	5	10	15	Adult
^{134}Cs	2.6	1.6	1.3	1.4	1.9	1.9
^{137}Cs	2.1	1.2	0.96	1.0	1.3	1.3

ICRP (1996).

3.2. Restriction of food distribution—in the case of vegetables and rice

The Japanese government prohibited the distribution of vegetables polluted by radioactive caesium and iodine for several months from March 21, 2011. Oka (2014) estimated the values for the CPLYS of this regulation. Costs were estimated as net economic values of the produce lost due to regulation. Life-years saved were calculated by using the values in Table 3 and Table 4, age composition of the population in Japan in 2010, estimated average concentration of radioactive caesium in regulated vegetables, and reduction in shipment of vegetables. The results are summarized in Table 5. The CPLYS is 8.0 million yen for March, 51 million yen for April, and 100 million yen for May.

Table 5: Costs and effects of the prohibition of the distribution of contaminated vegetables in Fukushima Prefecture in 2011

	March	April	May
Average concentration of radiocaesium ($Bq\ kg^{-1}$)[a]	4000	720	180
Quantity of vegetables excluded from distribution (t)	740	520	350
Avoided intake of radiocaesium (MBq)[b]	1300 (800 – 1900)	270 (190 – 360)	55 (45 – 66)
Life-year saved (person year)[bc]	21 (12 – 30)	4.3 (3.0 – 5.6)	0.87 (0.70 – 1.0)
Cost (billion yen)	1.9	2.2	0.94
CPLYS (million yen)[b]	8.0 (5.7–13)	51 (39 – 74)	100 (86 – 130)

Oka (2014)

[a]The figures indicate the average concentration over many types of vegetables. The actual calculation was conducted for each type of vegetable.
[b]Figures between parentheses indicate confidence intervals based on a 90% confidence interval of the estimates of average concentration.
[c]The LLE coefficient of 1.6×10^{-8} year/Bq for radioactive caesium for the average person was used, which was calculated from Table 3 and Table 4 on the assumption that the ratio of ^{134}Cs and ^{137}Cs was 1:1 in 2011.

The cost-effectiveness of the ban on the distribution of contaminated rice was also assessed in Oka (2014). The assessment was conducted for three categories of rice according to the extent of the concentration of radioactive caesium: the rice produced in Onami district (most heavily contaminated), the rice from the areas that produced rice with 500 $Bq\ kg^{-1}$ and more, the rice from the areas that produced rice with 100-500 $Bq\ kg^{-1}$. The results are summarized in Table 6.

Table 6: Costs and effects of the prohibition of the distribution of contaminated rice in 2011

	Onami District	Areas 500Bq kg^{-1}	Areas 100-500Bq kg^{-1}
Average concentration of radiocaesium ($Bq\ kg^{-1}$)	52	24	16
Quantity of vegetables excluded from distribution (t)	175	4000	32,000
Avoided intake of radiocaesium (MBq)[a]	9.1 (8.8 – 9.5)	97 (90 – 100)	470 (460 – 470)
The life-year saved (person year)[ab]	0.14 (0.14 – 0.15)	1.5 (1.4 – 1.6)	7.3 (7.2 – 7.5)
Cost (billion yen)	0.045	1.0	7.6
CPLYS (million yen)[a]	3.1 (3.0 – 3.2)	6.6 (6.2 – 7.2)	10 (10 – 10)

Oka (2014)

[a]Figures between parentheses indicate confidence intervals based on 90% confidence interval of the estimates of average concentration.
[b]The LLE coefficient of 1.6×10^{-8} year/Bq for radioactive caesium for the average person was used, which was calculated from Table 3 and Table 4 on the assumption that the ratio of ^{134}Cs and ^{137}Cs was 1:1 in 2011.

3.3. Countermeasures in agriculture

3.3.1. Bark washing of fruit trees

The radiocaesium concentrations in peach, pear, apple, and Japanese persimmon produced in Fukushima Prefecture (the Date area is the major source) did not exceed the then provisional regulation value, 500 Bq kg^{-1}, but many samples of dried persimmon (anpo-gaki) that had been processed as a trial were found to contain radiocaesium exceeding 500 Bq kg^{-1}. The government of Fukushima Prefecture requested the farmers not to process persimmon. The farmers conducted bark washing of fruit trees in the winter, 2011 to ensure that fresh fruits in the following year would not contain radiocaesium greater than the new standard, and that anpo-gaki production could be resumed.

Table 7: Average concentration of radiocaesium in anpo-gaki processed on trial

(Bq kg^{-1})

Year	^{134}Cs	^{137}Cs	Total
2011	-	-	247.7 (SD: 197.9)
2012	50.0 (SD: 34.1)	80.0 (SD: 53.4)	130.0 (SD: 87.1)
2013	22.1 (SD: 13.7)	48.9 (SD: 28.8)	71.0 (SD: 42.0)

Calculated from the data from Fukushima prefecture (2011, 2012, 2013).
For 2011, the division of radiocaesium into ^{134}Cs and ^{137}Cs was not provided.

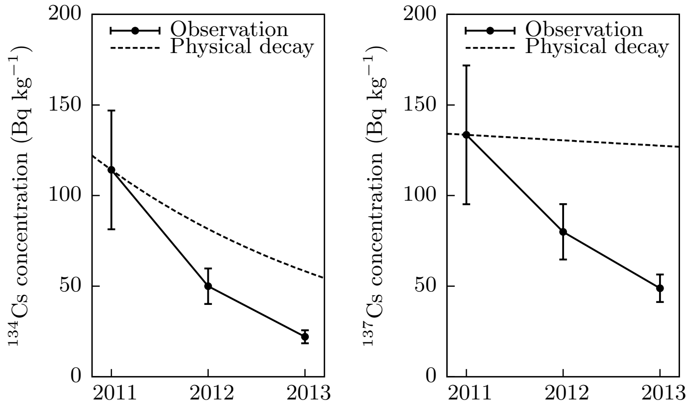
The results of the test processing of anpo-gaki from 2011 to 2013 are shown in Table 7. The data show decreases in concentration. These decreases are not only due to bark washing but also by physical decay and natural biological elimination.

Although Table 7 lacks the data for the division of total radiocaesium into ^{134}Cs and ^{137}Cs in 2011, the relation between the ratio of ^{134}Cs to ^{137}Cs in 2011, α_{2011}, and that in 2012, α_{2012},

$$\alpha_{2011} = \alpha_{2012} e^{R^{134} - R^{137}},$$

and the fact that $\alpha_{2012} = 0.625$ enable us to estimate the division of the radiocaesium into ^{134}Cs and ^{137}Cs in 2011 as $\alpha_{2011} = 0.855$, where $R^{134}(= \log 2/2.06 = 0.337)$ and $R^{137}(= \log 2/30.2 = 0.0230)$ represent the physical decay constants for ^{134}Cs and ^{137}Cs respectively. By using the results, changes in the mean values for the concentration of radiocaesium are shown in Fig. 1, with their confidence intervals, and with the broken lines representing physical decay.

Figure 1: Decrease in the mean values of caesium concentrations in anpo-gaki (Date area). The error bars represent 90% CI for the mean value.



Letting x_t^{134} and x_t^{137} represent the concentrations of ^{134}Cs and ^{137}Cs, respectively, at time t, and D_t represent the decay constant excluding physical decay, which is assumed to be common to ^{134}Cs and ^{137}Cs, we can write

$$x_{t+1}^{134} + x_{t+1}^{137} = x_t^{134} e^{-D_t - R^{134}} + x_t^{137} e^{-D_t - R^{137}},$$

which implies

$$D_t = \log\left(x_t^{134} e^{-R^{134}} + x_t^{137} e^{-R^{137}}\right) - \log\left(x_{t+1}^{134} + x_{t+1}^{137}\right).$$

From the data in Table 7, D_{2011} and D_{2012} were calculated as 0.489 and 0.473, respectively.

D_{2012} and D_{2011} are very close; by and large D_t appears constant. Since bark washing was performed once in the winter, 2011, if its effect remained only until the next harvest, the fact that the decay constant in 2012–2013 is as large as that in 2011–2012 would mean the washing was not effective in reducing radiocaesium in fruits.

Sato (2014) reported, however, that bark washing performed in December 2011 had reduced radiocaesium concentration in fruits of Japanese persimmon not only in 2012 but also in 2013. Sato et al. (2015) presented a model:

$$y = K \exp(-Dx),$$

where y represents the concentration of ^{137}Cs, x the number of years since the nuclear accident, and D the decay constant, which was estimated at:

$$\begin{cases} D = 1.19 \quad (95\%\text{CI} : 1.10, 1.28) & \text{for the case of washing} \\ D = 0.846 \quad (95\%\text{CI} : 0.772, 0.920) & \text{for the case of nonwashing,} \end{cases}$$

indicating that the bark washing raises the decay constant by 0.344 (95%CI: 0.229, 0.459).

Based on this finding, the long-term effect of bark washing on the caesium concentration in anpo-gaki was estimated by the following way; the values for concentration in 2011, 2012, and 2013 with bark washing were those that had been observed, and the concentration values for 2014 and after were assumed to decline with $D_t = D_{2012} = 0.473 (t = 2013, 2014, \cdots, 2029)$ and with the physical decay constants for the case with bark washing, whereas the concentration values for the case without bark washing were estimated by assuming a decay constant excluding physical decay lower by 0.344 than that with bark washing for every year. The results are as presented in Fig. 2. Multiplying these differences by the annual production of anpo-gaki in the Date area, 1737 tons (estimated from the sum of the compensation claim to TEPCO and the average price of anpo-gaki), will produce the reductions in intake of radiocaesium when people eat anpo-gaki. Applying the LLE coefficients of radiocaesium ingestion, 2.0×10^{-8} year/Bq for ^{134}Cs and 1.4×10^{-8} year/Bq for ^{137}Cs, which are calculated from the figures in Table 3 and Table 4, to these intake reductions will give us values for life-years saved by the bark washing. The accumulated life-years saved by the bark washing are shown in Fig. 3.

Figure 2: Difference in caesium concentration in anpo-gaki with and without bark washing

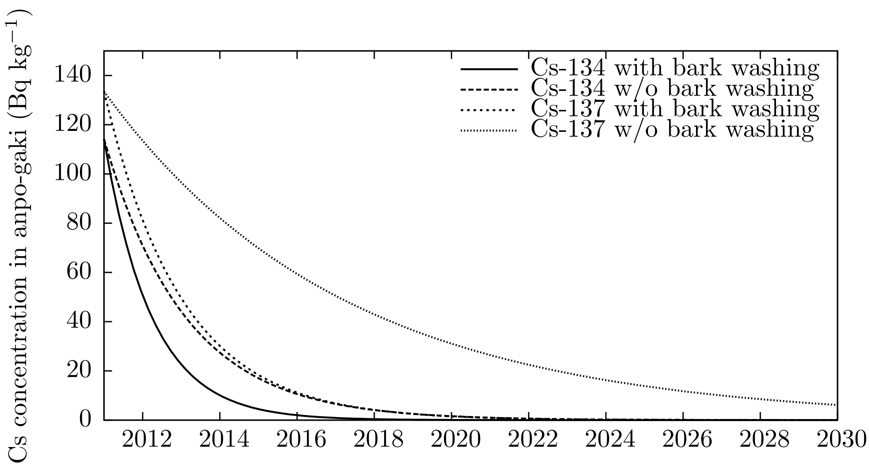
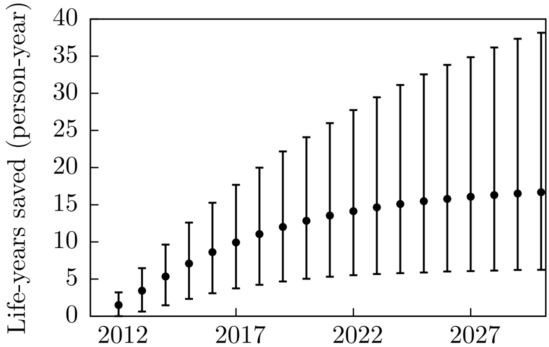


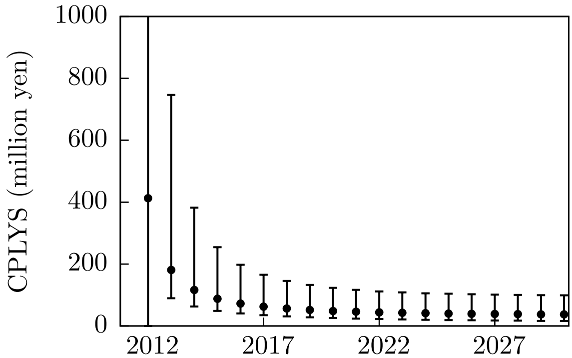
Figure 3: Accumulated life-years saved by the bark washing of Japanese persimmon. The error bars represent 90% CI reflecting the standard errors of the radiocaesium concentration and of the decay constant.



The total cost of bark washing for fruit trees in Date city was 734 million yen (the sum paid by the municipal government of Date to JA Datemirai for entrustment). The number of persimmon trees was 257,517, while the total number of all fruit trees was 549,516. Assuming bark washing takes three times longer time for persimmon trees than other kinds of fruit trees, I estimated that 73% of the total cost was for persimmon trees. Taking into account the fact that the parts of the Date area other than Date city (Kunimi town and Koori town) have 43,187 persimmon trees, I estimated the cost of bark washing for persimmon trees in the Date area as 622 million yen, from which values for CPLYS can be calculated.

CPLYS is 180 million yen taking the effects of washing for the first two years, 2012 and 2013, into account, 72 million yen taking the effects for the first five years into account, 46 million yen taking the effects for the first 10 years into account, and 37 million yen taking the effects for the first 19 years into account (Fig. 4).

Figure 4: CPLYS for bark washing of Japanese persimmon. The error bars represent the same measure as in Fig.3.



3.3.2. Measures to prevent radiocaesium intake in rice

In Date city, where rice with radiocaesium above 100 Bq kg^{-1} had been produced from 14 districts, from six of which rice with radiocaesium above 500 Bq kg^{-1} had been produced, in 2011, potassium and zeolite were applied and deep cultivation was performed to prevent caesium intake in rice during 2012. All the rice bags (each containing 30kg of rice) were inspected (in total 161,632 bags in Date city), none of which turned out to have radiocaesium concentration above 100 Bq kg^{-1} in 2012 (Table 8).

Table 8: Results of the total inspection of rice in 2012 (Date city)

Radiocaesium concentration (Bq kg^{-1})		ND	25–50	51–75	76–100
	Screening	161,155	408	44	-
Freq.	Detailed	4	4	15	2
	Total	161,159	412	59	2
Percentage		99.707%	0.255%	0.037%	0.001%

Data from Fukushima no megumi anzentaisaku-kyogikai (2012).

Farmers in Oguni and Tominari districts and those who had produced rice with radiocaesium exceeding 500 Bq kg^{-1} in 2011 were prohibited from growing rice in 2012. Excluding them, 4.495% of the 2603 farmers within the 14 districts had produced rice with radiocaesium above 100 Bq kg^{-1} in 2011, 18.440% under 100 Bq kg^{-1} (with detection limit of 50 Bq kg^{-1}), and 77.065% of them had produced rice in which radiocaesium had not been detected (Fukushima Prefecture, 2012). This distribution of caesium concentration has been transformed into the distribution presented in Table 8 in 2012.

Of the 4.495% of the rice, which had caesium exceeding 100 Bq kg^{-1} in 2011, 0.293% may have fallen into the group of 25–100 Bq kg^{-1} in 2012, and the residual 4.202% may have fallen into the group of ND. The latter 4.202% should be the category that represents the largest reduction in caesium concentration.

Table 9: Distribution of radiocaesium concentration within 100–500 Bq kg^{-1} for the areas that had produced rice above 500Bq kg^{-1} in Date city in 2011

Concentration (Bq kg^{-1})	ND	≦100	100 < ≦ 200	200 < ≦ 300	300 < ≦ 400	400 < ≦ 500	500 <
Frequency	1267	298	101	25	17	4	8

From the 11th report on the results of the emergency survey of radiocaesium in rice in 2011 by the Fukushima prefectural government (Fukushima Prefecture 2011).

The distribution of radiocaesium concentration in rice that was produced in the area in Date city where rice with radiocaesium exceeding 500 Bq kg^{-1} was detected in 2011 is shown in Table 9. Averaging the values for 100–500 Bq kg^{-1} assuming the central value of each range asrepresenting the range, and using the frequencies for Date city as weights, an average value of 198 Bq kg^{-1} was obtained for the rice within the range 100-500 Bq kg^{-1}. If this concentration was reduced to 12.5 Bq kg^{-1}, one half of the detection limit, the concentration was regarded to be reduced by 186 Bq kg^{-1}. This reduction includes not only that caused by the countermeasures but also that caused by physical decay as well as natural biological decrease. When the concentration of radiocaesium in 2011 was x_{2011}, the concentration in 2012 without any countermeasure would have been

$$x'_{2012} = x_{2011}\gamma_{2011},$$

where

$$\gamma_{2011} = \frac{\alpha_{2011}e^{-0.336-Q} + e^{-0.0230-Q}}{\alpha_{2011}+1},$$

where 0.336 and 0.0230 are the physical decay constants for ^{134}Cs and ^{137}Cs respectively, Q represents the natural biological decay constant, and α_{2011} represents the ratio of the radioactivity of ^{134}Cs to that of ^{137}Cs in 2011, which is given as

$$\alpha_{2011} = 0.634e^{0.336-0.0230}$$

based on the observed ratio in 2012, 0.634. There are several observations by which we can estimate the value for Q, although none of them are decisive.

Niizuma and Fujimura (2014) reported the change from 2011 to 2013 in the concentration of ^{137}Cs in brown rice harvested from seven rice fields, where no countermeasures were taken to prevent radiocaesium intake in rice. Data excluding physical decay were provided. The average of the difference between the logarithm of the value for 2011 and the logarithm of the value for 2012 is 0.424 [95%CI: -0.227, 1.07]. Regarding this value as the natural biological decay constant, i.e. $Q = 0.424$, γ_{2011} would be equal to 0.560, and x'_{2012} would be 111 [Bq kg^{-1}]. Consequently, the reduction by the countermeasures is estimated to be 98.5 Bq kg^{-1}. This is equivalent to 47.8 Bq kg^{-1} for polished rice. When Q is equal to the upper limit of the 95% CI, reduction would be 22.1 Bq kg^{-1}, and when $Q = 0$, reduction would be 76.3 Bq kg^{-1}.

According to the data obtained from Date city, the cost of the countermeasures is 866,000 yen ha^{-1} (Table 10). Since the projected production of rice was 4.44 t ha^{-1}, the cost is equal to 195 yen kg^{-1}. Taking the reduction of radiocaesium, 47.8 (22.1-76.3) Bq kg^{-1}, into account, this is equivalent to 4.1 (2.6-8.8) yen Bq^{-1}. By using the coefficients in Table 3 and Table 4, and the ratio of ^{134}Cs and ^{137}Cs in 2012, 0.634, the LLE coefficient of total radiocaesium is 1.6×10^{-8}. The value for CPLYS is, therefore, 250 (160-540) million yen. The upper limit corresponds to $Q = 1.07$, and the lower limit corresponds to $Q = 0$, which means that the CPLYS cannot be below 160 million yen even if all the reduction in the concentration in rice excluding physical decay were due to the countermeasure. The value for CPLYS here is for the rice for which the concentration of radiocaesium was reduced from 198 Bq kg^{-1} to 12.5 Bq kg^{-1}, which accounts for only 4.202% of the rice produced with the countermeasure in Date city. For the rest, overwhelming majority, the CPLYS must be greater, approaching infinity in the case of ND to ND, which accounts for more than 77%.

Table 10: Costs of the countermeasure for rice

Year	Area (ha)	Cost (million yen)	Unit cost 1000yen ha^{-1}
2011	220	181.33	824
2012	780	674.65	865
	300	269.86	900
Total	1300	1125.84	866

Data obtained from Date city. The countermeasure included application of potassium and zeolite and deep cultivation.

Alternatively, one can estimate the value for CPLYS of the countermeasure on rice fields by using the data from experimental researches. Sakuma and Fujisawa (2013, 2014) conducted experiments to examine the effects of application of potassium and zeolite on the concentration of ^{137}Cs in brown rice. The results are shown in Table 11. Let us estimate CPLYS assuming that these reductions occurred on actual rice fields. The application was conducted in 2012, and its effects continued until 2014, as shown in Table 11. The effects were estimated in terms of LLE taking into account the presence of ^{134}Cs and its ratio that would have declined in 2013 and 2014 (Table 12).

Table 11: Effects of application of potassium on the intake control of radiocaesium by rice

(Bq kg^{-1})

Applied material	^{137}Cs in Brown rice 2012	2013	2014
Potassium silicate	10.7 (SD:2.9)	3.8 (SD:0.6)	7.3
Potassium chloride	3.5 (SD:1.0)	4.2 (SD:0.9)	6.6
No application	18.6 (SD:8.1)	7.5 (SD:0.2)	9.3

Sakuma and Fujisawa (2013, 2014), Sakuma and Sato (2014)

Table 12: Effects of potassium application on the reduction of LLE and CPLYS based on Sakuma and Fujisawa (2013, 2014) study

Applied material	Cs reduction (Bq kg^{-1})[a]			LLE reduction[b]			
	2012	2013	2014	2012	2013	2014	Total
Potassium silicate	12.9	5.4	2.7	2.1×10^{-7}	8.9×10^{-8}	4.1×10^{-8}	3.4×10^{-7}
Potassium chloride	24.7	4.8	3.6	4.0×10^{-7}	7.6×10^{-8}	5.6×10^{-8}	5.3×10^{-7}

	Quantity applied (kg a^{-1})	Cost (yen a^{-1})			Cost[c]	CPLYS
		Material[d]	Application[e]	Total	(yen kg^{-1})	(yen/year-LLE)
Potassium silicate	15.85	1839	4751	6590	148	4.4×10^{8}
Potassium chloride	5.2	504	4751	5256	118	2.2×10^{8}

[a]Including ^{134}Cs and ^{137}Cs. The ratio of 1^{34}Cs to ^{137}Cs is 0.634 in 2012, 0.463 in 2013, and 0.339 in 2014.
[b]LLE coefficient (year/Bq) is 1:6 × 10^{-8} for 2012, 1:6 × 10^{-8} for 2013, and 1:5 × 10^{-8} for 2014.
[c]Based on the predicted production, 44.4 kg a^{-1}.
[d]Based on 116 yen kg^{-1} for potassium silicate and 55 yen kg^{-1} for potassium chloride, both derived from the observations in Fukushima Prefecture (Tohokunoseikyoku 2018).
[e]Based on the observations in Date city.

Cost estimates were obtained from the actual application in Fukushima Prefecture (Tohokunoseikyoku, 2018). The costs for the materials were 116 yen kg^{-1} for potassium silicate and 55 yen kg^{-1} for potassium chloride; both were the averages in Fukushima Prefecture in 2013. The cost of application works was obtained by observation in Date city in 2012. The resulting values of CPLYS are 440 million yen for potassium silicate and 220 million yen for potassium chloride.

Those estimates of CPLYS are for experiments, which represent the cases with low concentrations of caesium. They might represent the values for some cases of ND to ND. It can be said that the value of CPLYS for the case with the greatest reduction, which represents only 4.2% of the rice produced with application of the countermeasures, is 250 [95%CI: 160, 540] million yen, and that for the overwhelming majority the CPLYS may be much greater, approaching infinity, or can be 220 million or 440 million yen if the results of the experimental study are applicable.

3.4. Decontamination

Yasutaka et al. (2013) projected the costs of the decontamination in the Special Decontamination Area to be 1.3 trillion yen for the most plausible scenario (ranging from 0.23 to 3.9 trillion yen depending on the scenario). Now that the decontamination work has been completed except for Area 3, data for several areas on the actual cost are available. Naraha town was the first municipality where the whole region had been designated as Restricted Area, and the order of evacuation was lifted. Data on the air dose rates before and after the decontamination work and on the cost of the work are available for Naraha town. Let us estimate the value of CPLYS for the decontamination in Naraha town.

The whole plan of the decontamination includes storage of removed soil and waste at the Interim Storage Facility and final disposal. The removed soil and waste was stored at temporary storage sites, and transportation of the soil to the Interim Storage Site started in 2016. In total, 8.1 million m^3 of soil has been transported to the Interim Storage Site by July 2020, which is 58% of the whole amount, estimated to be 14 million m^3. The present cost estimation does not include the costs for the transportation to and the storage at the Interim Storage Site or the costs for final disposal.

The area of 20.1 km^2 has been decontaminated in Naraha town, and removed soil and waste amounted to 594,000 bags, each containing about 1 m^3 of soil and waste. Data were obtained on the air dose rate for 239,214 measurement points on decontamination sites in Naraha town from the Ministry of the Environment. I paired the data on the air dose rate at 1 m above the ground before and after the decontamination work for the same measurement points. The number of pairs is 77,911, of which 52,290 are for the measurement points on residential lands and 7854 are for the points on agricultural lands; others include schools, kindergarten, nursery, parks, large-scale buildings, roads, grasslands, and forests.

The measurement dates ranged from November 8, 2012 to December 25, 2013. The values for air dose rates were transformed into the ones on the date of lifting the evacuation order, September 5, 2015, taking physical decay into account, and for each pair of data, calculated the reduction in dose rate by the decontamination work at the time of lifting the evacuation order. The effective dose per year was calculated from the air dose rate for residential lands by considering the ratio of effective dose and air dose, 0.7, and the shielding effect of wooden houses, 0.4, and the hours of staying outdoors, eight in a day. The calculated annual effective doses would be overestimated.

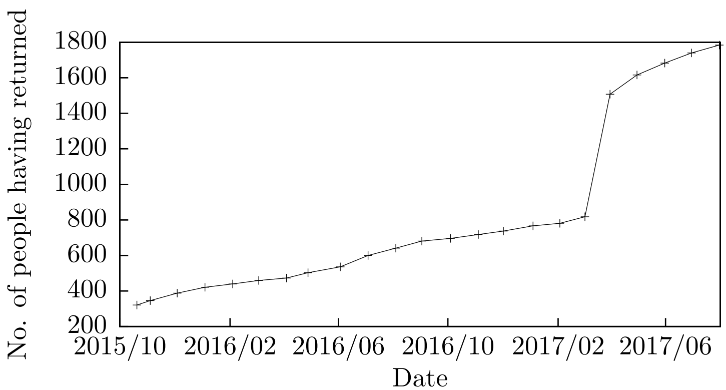
Table 13 shows the reduction in exposure by the decontamination on residential land. The average reduction in the air dose rate is 0.250 μSv h^{-1}, which is equivalent to 0.922 mSv y^{-1} as the effective dose. The accumulated dose for 30 years is calculated on the basis of the annual dose at the time of return of the residents to Naraha town, taking physical decay into account. The timing of the return is, however, diverse. The number of residents who have returned to Naraha town is shown in Fig. 5. The number rose rapidly in March 2017 because the primary school and the junior high school were reopened on April 1, 2017. Since March 31 to July 31, 276 residents newly returned; the pace of return is 828 per annum. Let us assume this pace will continue. However, a survey conducted by the municipal government shows that 25.2% of the people registered as residents of the town have no intention of returning to the town. Since the number of residents registered on July 31, 2017 is 7215, the number of residents who will return will not exceed 5397. If 828 residents return annually, the number of people who have returned will reach this upper limit in 2022.

Table 13: Reduction in effective dose per year on residential land by the decontamination work on the date of lifting the evacuation order

	Before decontamination	After decontamination	Reduction
No. of data	52290	52290	52290
Average air dose rate (μSv h^{-1})	0.543	0.292	0.250
Estimated SD of the population	0.283	0.144	0.211
Maximum	5.82	1.56	5.51
Minimum	0.0896	0.0486	-0.445
Effective dose per annum (mSv)[a]	1.85 (1.83–1.86)	0.929 (0.923–0.935)	0.922 (0.913–0.931)
Cumulative dose for 30 years (mSv)	26.3	13.2	13.1

Calculated from the data provided by the Ministry of the Environment.
[a]The figures in parentheses represent 99% confidence intervals of the means of the populations.

Figure 5: The number of residents having returned to Naraha town



The numbers of residents who have returned broken down by age are shown in Table 14.

Table 14: The numbers of residents who have returned broken down by age

	Age										
	0-4	5–9	10–14	15–19	20–24	25–29	30–34	35–39	40–44	45–49	50–
2016/04/28	3		6		10		15		32		437
2016/06/03	2	0	4	2	6	5	3	7	17	13	477
2016/07/04	2	0	4	5	8	5	3	9	20	15	529
2016/08/04	2	0	5	5	9	7	4	11	20	16	562
2016/09/02	6	4	11	8	11	8	6	14	23	19	571
2016/10/04	6	4	10	9	11	8	6	14	22	21	585
2016/11/04	6	4	10	9	11	9	6	15	24	22	602
2016/12/02	6	4	9	11	13	8	7	15	25	24	615
2017/01/04	6	4	9	11	14	8	9	14	26	25	641
2017/02/03	8	5	9	11	14	9	12	14	25	25	649
2017/03/03	9	7	10	12	14	13	12	18	27	25	671
2017/03/31	32	35	38	38	53	59	60	65	91	74	963
2017/04/30	34	38	41	41	57	63	64	70	98	79	1031
2017/05/31	42	41	45	47	62	75	66	75	101	82	1047
2017/06/30	51	44	45	46	64	83	68	78	103	82	1076
2017/07/31	53	44	45	45	66	84	73	79	106	80	1109

Data from Naraha town.

Accordingly, the population who would newly return to Naraha and would begin to be exposed to radiation broken down by age and by date of beginning of exposure were estimated as shown in Table 15. The total number of people who would have returned by September 5, 2019 was projected to be 3509, while the actual population on August 31, 2019 was 3833, and the projected number of residents was 4337 on September 5, 2020, while the actual population on June 30, 2020 is 4015. The estimation is, therefore, not far from reality.

Table 15: The number of residents who newly return and begin exposure

	Age						
	Total	0–9	10–14	15–19	20–34	35–49	50–
2015/09/05	321	2	3	1	16	20	279
2016/09/05	360	8	8	7	9	36	292
2017/09/05	1172	95	36	39	211	218	575
2018/09/05	828	90	21	21	153	105	438
2019/09/05	828	90	21	21	153	105	438
2020/09/05	828	90	21	21	153	105	438
2021/09/05	828	90	21	21	153	105	438
2022/09/05	232	25	6	6	43	29	123

The figures for 2015 to 2017 are observed. Those for 2018 and after are predicted on the assumption that the pace of return from April to July in 2017 will continue for each age group.

The values for LLE per mSv in Table 3 were obtained by using the corresponding value for each age at exposure and the age composition of the Japanese population in 2010. Based on the value of LLE per mSv for each age at exposure, LLE from a cumulative dose can be calculated for any period beginning at any date, taking the physical decay constants, 9.19×10^{-4} per day for ^{134}Cs and 6.29×10^{-5} per day for ^{137}Cs, into account. For example, if a 30-year-old man lives at a site with a dose rate of 1 mSv per annum for 30 years since September 5, 2015, the LLE from the cumulative exposure would be 1.1×10^{-2} years, which is approximately 10 times as high as the LLE from the exposure by 1 mSv. The contribution of ^{134}Cs to 1 mSv is assumed to be 0.3994 mSv on September 5, 2015. I have calculated this LLE for all the ages of males and females, and for every 5th of September from 2015 to 2022. The averaged results for several ranges of age are shown in Table 16. The later the date of exposure initiation, the larger the value for LLE from a cumulative exposure per mSv in the initial year, because the contribution of ^{137}Cs becomes larger.

Table 16: LLE from 30-year exposure at the site with an initial dose rate of 1 mSv y^{-1}

	Age						
	Total	0–9	10–14	15–19	20–34	35–49	50–
2016/09/05	1.1×10^{-2}	3.6×10^{-2}	2.7×10^{-2}	2.3×10^{-2}	1.6×10^{-2}	8.9×10^{-3}	2.1×10^{-3}
2017/09/05	1.2×10^{-2}	3.9×10^{-2}	2.9×10^{-2}	2.4×10^{-2}	1.7×10^{-2}	9.4×10^{-3}	2.3×10^{-3}
2018/09/05	1.2×10^{-2}	4.1×10^{-2}	3.1×10^{-2}	2.6×10^{-2}	1.8×10^{-2}	9.9×10^{-3}	2.4×10^{-3}
2019/09/05	1.3×10^{-2}	4.2×10^{-2}	3.2×10^{-2}	2.7×10^{-2}	1.9×10^{-2}	1.0×10^{-2}	2.5×10^{-3}
2020/09/05	1.3×10^{-2}	4.4×10^{-2}	3.3×10^{-2}	2.8×10^{-2}	1.9×10^{-2}	1.1×10^{-2}	2.5×10^{-3}
2021/09/05	1.4×10^{-2}	4.5×10^{-2}	3.4×10^{-2}	2.8×10^{-2}	2.0×10^{-2}	1.1×10^{-2}	2.6×10^{-3}
2022/09/05	1.4×10^{-2}	4.6×10^{-2}	3.4×10^{-2}	2.9×10^{-2}	2.0×10^{-2}	1.1×10^{-2}	2.6×10^{-3}

Calculated from Table3 and Table 4.

Table 17: Reduction in LLE for the residents in Naraha town by the decontamination activity

Date of returning	Reduction of exposure in the initial year[b] (mSv)	Reduction in LLE[a]						
			Age					
		Total (year)	0–9 (year)	10–14 (year)	15–19 (year)	20–34 (year)	35–49 (year)	50– (year)
2015/09/05	0.922	1.0	0.059	0.059	0.025	0.22	0.15	0.52
2016/09/05	0.858	1.5	0.25	0.20	0.13	0.12	0.27	0.54
2017/09/05	0.757	9.5	2.8	0.78	0.71	2.7	1.6	0.99
2018/09/05	0.682	6.6	2.5	0.44	0.37	1.9	0.71	0.71
2019/09/05	0.625	6.3	2.4	0.42	0.35	1.8	0.68	0.68
2020/09/05	0.581	6.0	2.3	0.40	0.34	1.7	0.65	0.65
2021/09/05	0.546	5.8	2.2	0.39	0.32	1.7	0.63	0.62
2022/09/05	0.518	1.6	0.60	0.11	0.088	0.45	0.17	0.17
Total		38						

[a]Calculated as reduction in exposure in the initial year [mSv y^{-1}] (the second column of this table) multiplied by the number of people having returned within the preceding year (Table 15), and by the LLE from 30-year exposure per mSv in the initial year (Table 16).

[b]The value for 2015, 0.922, comes from Table 13. The values for the other years were calculated as $0.922[0.399e^{-9.19\times10^{-4}N} + (1-0.399)e^{6.29\times10^{-5}N}]$, where 0.399 is the ratio of ^{134}Cs on September 5, 2015, 9.19×10^{-4} and 6.29×10^{-5} are the physical decay constants per day for ^{134}Cs and ^{137}Cs, respectively, and N is the number of days since September 5, 2015. N for September 5 in the year y ($y \geqq 2016$) is measured as the number of days from September 5, 2015 to the middle day between September 5 in the year y and September 5 in the year $y-1$.

By using the reduction in dose on September 5, 2015, 0.922 mSv y^{-1}, in Table 13 and the values in Table 15 and Table 16, we can calculate the reduction in total LLE suffered by the residents who have returned to Naraha town in 2015 to 2022 for 30 years since the return. The reduction in dose in the initial year is assumed as 0.922 mSv for the residents who returned on September 5, 2015, but it is assumed as 0.858 mSv for the residents who returned by September 5, 2016, assuming they returned on the middle day between September 5, 2015 and September 5, 2016, and it is assumed as 0.757 mSv for the residents who returned by September 5, 2017 on the same assumption, and so on. The results are shown in Table 17. Total reduction in LLE due to the decontamination activity is 38 person-years.

The reduction in the exposure in the places other than residential lands was assumed to be included in the above estimates. The magnitudes of estimates cannot become greater even if we estimate the exposure on those lands separately, because the reductions on those lands do not exceed those on the residential lands, except for agricultural lands. The reduction in the air dose rate on agricultural lands is a little greater, i.e., 0.266 μSv h^{-1} on average, and farmers might spend more time outside than other people. The exposure reduction on agricultural lands was separately estimated, although it might be overestimation if we added the estimates to the one for residential lands estimated above.

Table 18: Reduction in air dose rate on agricultural lands by the decontamination work on the date of the lifting of evacuation order

	Before decontamination	After decontamination	Reduction
No. of data	7854	7854	7854
Average air dose rate (μSv h^{-1})	0.684	0.418	0.267
Estimated SD of the population	0.370	0.187	0.294
Maximum	7.92	2.22	7.55
Minimum	0.149	0.117	-0.481

Calculated from the data provided by the Ministry of the Environment.

Table 19: Working hours and areas of cultivation in Tohoku region

Type of farming	Working hours (h y^{-1})	Area of cultivation				
		Rice paddy (a)	Non-paddy field (a)	Orchard (a)	Pasture (a)	Total (a)
Paddy farming	1047	201.0	10.6	4.0	2.1	217.7
Farming on non-paddy field	3470	136.5	140.9	1.0	-	278.4
Vegetable farming	3533	158.7	56.3	6.6	0.3	221.9
Fruit farming	3496	76.0	5.6	117.1	-	198.7
Flower farming[a]	5344	71.5	39.5	3.7	-	114.7
Dairy farming	4796	189.1	145.4	0.3	842.8	1177.6
Beef production	2701	326.9	48.2	12.7	56.5	444.3

Ministry of Agriculture, Forestry and Fisheries (2012a)
[a]The figures for flowering farming are on the whole country.

Reductions in the exposure on agricultural lands were calculated as the reduction in air dose rate on agricultural lands multiplied by the ratio of effective dose to air dose multiplied by the total working time on agricultural lands. The air dose rates on agricultural lands before and after the decontamination work calculated for the date of lifting the evacuation order are shown in Table 18. From the statistics of agricultural business broken down by farming type (Ministry of Agriculture, Forestry and Fisheries, 2012a), we obtain some figures about the working hours in agriculture and about the areas of cultivation, which are shown in Table 19. The working hours of paddy farming were evidently fewer than those of the other types of farming. The former consisted of more portion of working hours on rice paddy than the latter.

It was, therefore, better to estimate the total working hours on rice paddies and those on the other agricultural lands separately. Of the seven types of farming in Table 19, paddy farming, farming on non-paddy fields, and fruit farming were regarded as the types where working time is closely related to the area; the other four types have much working time inside agricultural houses or other facilities.

Assuming the working time on paddy fields, non-paddy fields, and orchards are *x* hours per 100 m^2, *y* hours per 100 m^2 and *z* hours per 100 m^2 respectively, for these three types, and ignoring the working time on pastures for paddy farming, which is negligible, *x, y* and *z* must satisfy

$$\begin{cases} 1047 = 201.0x + 10.6y + 4.0z \\ 3470 = 136.5x + 140.9y + 1.0z \\ 3496 = 76.0x + 5.6y + 117.1z. \end{cases}$$

We can solve this set of equations as $x = 3.575$, $y = 20.976$, $z = 26.352$. Assuming the values for *x* and *z* are applicable to the other four types of farming, the working hours on non-paddy fields for vegetable farming and for flower farming must be 49.566 hours per 100 m^2 and 126.335 hours per 100 m^2 respectively, and the working hours on pasture for dairy farming and for beef production are 1.260 hours per 100 m^2 and 3.264 hours per 100 m^2 respectively, although these values are overestimates because all the work is assumed to be done outdoors for these types of farming. Using the number of business entities for the types of farming—16,114 for non-paddy farming, 8054 for fruit farming, 17,803 for vegetable farming, 2118 for flower farming, 770 for dairy farming, and 3721 for beef production— in Fukushima Prefecture (Ministry of Agriculture, Forestry and Fisheries, 2012b) as weights, the average working hours for the other agricultural lands than rice fields will be 35 hours per 100 m^2. Assuming the working hours on rice fields as 3.6 hours per 100 m^2 on the basis of the value of *x*, and taking into account the area of agricultural lands before the nuclear accident, 432 ha of rice fields and 100 ha of other fields (Ministry of Agriculture, Forestry and Fisheries, 2012a), the reduction in total exposure on agricultural lands per annum will be

$$0.267[\mu\text{Sv h}^{-1}]\times\{432[\text{ha}]\times 3.6[\text{h a}^{-1}\text{y}^{-1}]+100[\text{ha}]\times 35[\text{h a}^{-1}\text{y}^{-1}]\}\times 100[\text{a ha}^{-1}]\times 10^{-3}[\text{mSv}\mu\text{Sv}^{-1}]\times 0.7,$$

namely, 95 person-mSv for a year from September 5, 2015, if all the agricultural lands were cultivated irrespective of the rate of return. This reduction in exposure will decrease year by year according to physical decay, reaching 52 person-mSv for a year beginning on September 5, 2022 (see the second column of Table 20).

According to the national census in 2010, the number of people engaged in agriculture in Naraha town was 6, 15, and 198 for the ages 20–34, 35–49, and 50 and older, respectively, which implies that the shares of those age groups are 0.041, 0.068, and 0.89, respectively. The annual total exposure from every September 5, is distributed among age groups according to these shares.

Table 20: Estimation of the reduction in exposure on agricultural lands

Date of returning	Population exposure[b] (mSv y^{-1})	Return rate[a]			Reduction						
					Exposure[c] (mSv y^{-1})			LLE			
		Age			Age			Age			
		20–34	35–49	50–	20–34	35–49	50–	20–34	35–49	50–	Total
2015/09/05	95	1.5%	1.6%	7.6%	0.058	0.10	6.4	0.00085	0.00085	0.013	0.015
2016/09/05	83	0.85%	2.8%	8.0%	0.029	0.16	5.9	0.00046	0.0014	0.013	0.015
2017/09/05	74	20%	17%	16%	0.59	0.86	10	0.010	0.0081	0.023	0.042
2018/09/05	67	14%	8.3%	12%	0.39	0.38	7.1	0.0070	0.0037	0.017	0.028
2019/09/05	62	14%	8.3%	12%	0.36	0.35	6.6	0.0068	0.0036	0.016	0.027
2020/09/05	58	14%	8.3%	12%	0.34	0.33	6.2	0.0065	0.0035	0.016	0.026
2021/09/05	55	14%	8.3%	12%	0.32	0.31	5.8	0.0063	0.0034	0.015	0.025
2022/09/05	52	4.0%	2.3%	3.4%	0.085	0.082	1.6	0.0017	0.00092	0.0041	0.0068
Total											0.18

[a]The ratio of those who have returned within a year and begin to be exposed to the entire registered population.
[b]Annual dose for the population when all the farmers return and cultivate the lands.
[c]Population exposure times return rate times age group share of population engaged in agriculture.

Assuming the same age distribution of the population in Naraha town in 2015 as in 2010, when the national census was conducted, the numbers of the registered population were estimated to be 1059, 1259, and 3655 for the age groups of 20–34, 35–49, and 50 and older, respectively, at the date of lifting the evacuation order. The ratio of a number in Table 15 to the corresponding number of the registered population estimated above, namely 1059, 1259, or 3655, gives a return rate, the values of which enters in the second to the fourth column of Table 20.

The figure of "population exposure" in the second column for a date of returning, multiplied by a corresponding figure for "return rate", and by the corresponding share of age groups engaged in agriculture, i.e., 0.041, 0.068, or 0.89, gives a value for exposure reduction, which enters in the 6th to 8th columns. A value for exposure reduction multiplied by the corresponding value for LLE from 30-year exposure at the site with an initial dose rate of 1 mSv y^{-1} in Table 16 produces a total reduction in LLE due to the exposure from agricultural activities, which appears in columns "LLE" in Table 20. The total LLE reduction over all the age groups and all the dates of returning is 0.18 person-years.

The LLE reduction from agricultural exposure is negligible compared to the LLE reduction from residential exposure, but when added to the latter, it raises the total LLE reduction to 39 person-years because of rounding.

Table 21: Costs of the decontamination activity

	Phase 1[a]			Phase 2[b]			Total		
	Area (m^2)	Cost (yen)	Unit cost (yen/m^2)	Area (m^2)	Cost (yen)	Unit cost (yen/m^2)	Area (m^2)	Cost (yen)	Unit cost (yen/m^2)
Paddies, fields, and meadows	5,101,020	880,699,754	173	3,013,700	1,690,209,366	561	8,114,720	2,570,909,120	317
Grasslands	1,719,688	1,013,905,544	590	520,300	226,074,200	435	2,239,988	1,239,979,744	554
Orchards	21,923	6,774,207	309	11,100	3,374,400	304	33,023	10,148,607	307
Agricultural lands	6,842,631	1,901,379,505	278	3,545,100	1,919,657,966	541	10,387,731	3,821,037,471	368
Forests	3,230,004	4,070,453,442	1260	960,400	790,699,780	823	4,190,404	4,861,153,222	1160
Residential lands	1,648,698	3,151,030,854	1911	1,319,900	1,752,766,969	1328	2,968,598	4,903,797,823	1652
Schools	19,282	35,613,889	1847	29,810	29,011,282	973	49,092	64,625,171	1316
Parks	38,618	31,971,667	828	31,711	78,131,422	2464	70,329	110,103,089	1566
Large scale buildings	281,893	334,910,861	1188	142,600	195,343,338	1370	424,493	530,254,199	1249
Lands for buildings	1,988,491	3,553,527,271	1787	1,524,021	2,055,253,011	1349	3,512,512	5,608,780,282	1597
Roads	998,577	573,787,297	575	689,870	568,216,558	824	1,688,447	1,142,003,855	676
Banks	73,112	46,937,678	642	344,200	243,599,800	708	417,312	290,537,478	696
Lands for roads	1,071,689	620,724,975	579	1,034,070	811,816,358	785	2,105,759	1,432,541,333	680
Temporary storage		25,525,670						25,525,670	
Temporary storage sites		4,494,273,899			4,402,552,780			8,896,826,679	
Temporary storage		4,519,799,569			4,402,552,780			8,922,352,349	
Treatment of waste water		15,118,014	(yen/m^3)		33,369,658	(yen/m^3)		48,487,672	
Transportation		3,256,246,216	13615		2,882,634,398	5313		6,138,880,614	
Temporary storage of left waste		382,058,042			330,118,784			712,176,826	
Transportation of left waste		267,676,989			231,913,535			499,590,524	
Cemetery		68,100,764			92,359,424			160,460,188	
Materials					4,817,326,015			4,817,326,015	
Total direct costs	13,132,815	18,655,084,787	1420	7,063,591	18,367,701,709	2600	20,196,406	37,022,786,496	1833
Overhead costs		10,105,205,214			8,674,948,291			18,780,153,505	
Total costs		28,760,290,001			27,042,650,000			55,802,940,001	
Total costs including tax		30,198,304,501			28,777,062,000			58,975,366,501	

Data from the Ministry of the Environment. Based on predetermined prices set by the government.
The actually contracted total sum (including tax) was 60,490,190,000 yen.

[a]Namikura, Shigeoka, Eidan, Shimoshigeoka, Kamishigeoka, Matsudate, Asahigaoka, Onnadaira, Kamikobana, Mominokishita, Shimokobana, and Ooya. From May 2012 to February 2013.
[b]Kitada, Yamadaoka, Yamadahama, Maebara, Kamiide, Shimoide, and Namikura. From February 2013 to November 2014.

The costs of the decontamination activity in Naraha town are summarised in Table 21. The total cost was 55.80 billion yen. These figures are the planned cost based on predetermined prices set by the government, but the total cost including tax, 58.98 billion yen, was very close to the actually contracted total sum (including tax), 60.49 billion yen; the latter was 1.026 times higher. The actual total cost excluding tax is estimated to be 57.24 billion yen. At the expense of this cost, decontamination reduced the health risk by 39 person-years-LLE. The CPLYS was, therefore, 1.5 billion yen.

The direct activity costs, excluding the costs for transportation of soil and waste, temporary storage, waste water treatment, and overhead costs, amount to 15.72 billion yen, of which only 35.7% is for the lands for houses and buildings. The costs for transportation and temporary storage would have been proportional to the amount of soil and waste. Assuming the contribution rates of the lands to the amount of soil and waste are as shown in Table 22, and allocating overhead costs to the land categories proportionally to the direct cost, we have the cost allocation as shown in Table 23.

Table 22: Contribution of the lands to the amount of soil and waste

	Phase 1	Phase 2
Lands for houses and buildings	0.116	0.120
Roads	0.012	0.015
Agricultural lands	0.260	0.622
Forests	0.613	0.244

Table 23: Allocation of total decontamination cost to the land categories

	Phase 1	Phase 2	Total
Lands for houses and buildings	7,002,242,254	5,278,819,353	12,281,061,607
Roads	1,107,937,228	1,475,068,583	2,583,005,811
Agricultural lands	6,335,951,293	14,533,049,387	20,869,000,680
Forests	14,314,159,227	5,755,712,677	20,069,871,904
Total	28,760,290,001	27,042,650,000	55,802,940,001

If the reduction in the health risk can be assumed to be brought about by the decontamination on the lands for houses and buildings, the CPLYS would be 330 million yen. The decontamination of forests is, however, limited to the forests within 20 m from the residential lands, and is performed in order to reduce the dose around houses. Including the costs of forest decontamination, the CPLYS would be 860 million yen.

4. Evaluation of the policy measures

4.1. Comparison with the observations in the Chernobyl case and the cost-benefit comparison

The results on the CPLYS values are summarized in Table 24. The cheapest measure was the regulation of the distribution of contaminated vegetables in the very early stages in March 2011. Most of the policy measures were implemented at the cost per life-year saved above 100 million yen or even above one billion yen. Bark washing of fruit trees could have become a relatively cheap measure, if persimmon fruits were processed to become dried persimmon and eaten by consumers in 2012 and 2013. Actually, processing was not performed because the food standards were made stricter in 2012. Processing was resumed only in 2014, and the quantity of production was two-thirds of the previous amount in 2015. A possible cheaper measure was not realized.

Table 24: The results on the CPLYS values

	CPLYS (million yen/year-LLE)
Restriction of food distribution	
Vegetables in early stages in 2011	8.0–100
Rice in 2011	300–1000
Countermeasures in agriculture	
Bark washing of persimmon trees	37–180
Measures to prevent rice from intaking caesium	250–∞
Decontamination of the evacuation area	330–1500

The Chernobyl NPP released a huge amount of radioactive substances during the reactor accident that occurred in April 1986. The most contaminated areas are in Belarus, Russia, and Ukraine. By the end of September 1986, 115,000 people were evacuated (UNSCEAR, 2008). A uniform criterion of intervention was adopted by the government of the Union of Soviet Socialist Republics (USSR): 350 mSv of forecast effective dose for 70 years. Decontamination activities were conducted based on this criterion.

"Large-scale activities based on standard criteria were undertaken by the military in 1986-87 and by civil defence troops and special brigades under various ministries and organisations in 1988-90. Major activities included removal of the upper layer of untouched soil from squares, pavements, schools, kindergartens, public buildings, sports and recreation facilities, industrial buildings and houses and taking it away from settlements; covering cleaned and uncleaned areas with clean soil, paving squares and streets, replacing roofs" (Antsipov et al., 2000). The cost-effectiveness of these activities in the Bryansk region was estimated to be 4000–12,000 roubles (3200–9600 euro) per 1 manSv of dose averted, and the estimates for Ukraine are 6700–28,000 euro for 1 manSv (*ibid*.).

After the USSR collapsed, the decontamination activities were conducted by the national governments of Russia, Belarus, and Ukraine. In Ukraine, “In the period 1991-96, 44 settlements were decontaminated, 30280 m^2 of roofs were replaced, 87500 m^3 of soil were removed and 72000 m^3 of soil were brought in, and 442 thousand m^2 of land around buildings and houses were paved. Approximately 800 000 euro was spent annually on decontamination and restoration work in the period 1991-95, and 400 000 euro in 1996-97 due to limited funds” (*ibid*.). In Belarus, “Due to the limited resources, the main objects for decontamination are kindergartens and schools” (*ibid*.).

The cost-effectiveness of decontamination at a building of kindergarten and school of the village of Dzerzhinsk (Narovlya district, Gomel region) was reported by Antsipov et al. (2000); the cost was 14,000 euro per 1 manSv. It is said that in this village countermeasures to reduce radiocaesium in foodstuffs had already been implemented, and that the capacity to further reduce internal dose was limited (*ibid*.). Decontamination is, therefore, justified, but it is said “with very high costs (e.g., in Ukraine it is 1-2 times higher than GNP per capita) one should take into account the social and psychological significance of such work” (*ibid*.).

Internal exposure was much more important in Chernobyl than in Fukushima. In general, countermeasures to reduce internal dose are regarded as more cost-effective than decontamination to reduce external dose. Jacob et al. (2000) reported the estimates on the cost-effectiveness of the countermeasures to reduce radiocaesium in foodstuffs, which includes “radical improvement of pastures and meadows (ploughing, fertilising and re-seeding), application of Prussian blue for cows, supply of settlement with uncontaminated milk, restriction of mushroom consumption, application of mineral fertilisers to potato fields, and feeding pigs with uncontaminated fodder before slaughter” (Jacob et al., 2000). They found that annual doses could be reduced to below 1 mSv with a cost of up to 70,000 euro/person-Sv (most countermeasures can be performed at a much lower cost) except for settlements with contamination greater than 555 kBq/m^2 and with an annual internal dose smaller than 0.5 mSv. They concluded that “The results presented underline that very expensive countermeasures (more than 100 kEuro/manSv) have to be taken into account if doses in all settlements shall be reduced below annual total doses of 1 mSv. Under these circumstances, decontamination work to reduce external exposures is certainly an option that needs to be considered”.

Jacob et al. (2009) conducted calculations to identify optimal remediation strategies to reduce internal radioactive dose for 541 settlements in Belarus, Russia, and Ukraine, from six remedial actions: radical improvement of grassland, application of ferrocyn to cows, feeding pigs with uncontaminated fodder before slaughter, application of mineral fertilisers for potato fields, information campaigns on contaminated forest produce, and replacement of contaminated soil in populated areas by uncontaminated soil. They concluded “a considerable collective dose can be averted by quite cost-effective remediation strategies. The costs per averted dose are about 20 kEuro/person-Sv in Russia and Ukraine and about 40 kEuro/person-Sv in Belarus”.

To summarize, there remain many remedial actions that can reduce internal radiation exposure at a low cost of 20 kEuro/person-Sv or 40 kEuro/person-Sv, and it is often said that when the cost per averted dose exceeds 100 kEuro/person-Sv, other measures such as decontamination should be considered. Since 1 person-Sv causes approximately 1.1 years of LLE, these costs per avoided dose can be compared with CPLYS in the Fukushima case. We found that the minimum CPLYS was 8 million yen in Fukushima case, which is equivalent to 620 kEuro under 1 Euro = 130 yen, and that a huge amount of resources had been spent in the decontamination activity with a CPLYS of 1.5 billion yen, which is equivalent to 11 million Euro. This is 110 times as large as 100 kEuro, which is thought to be an upper limit above which remediation activity would be difficult to justify from the perspective of efficiency in the three countries that suffered from the Chernobyl disaster.

From the efficiency perspective, the CPLYS should, theoretically, be compared with the benefit per life-year saved. We can find estimates for the benefit that is based on the concept of willingness to pay from literature. Oka (2014) identified the average value for the benefit of life-year saved as 20 million yen for the Japanese people. Assuming this value for the benefit, only the restriction of the distribution of vegetables in the very early stage of the accident is judged to be efficient in the sense that the cost does not exceed the benefit.

4.2. Efficiency and equity

The International Commission on Radiological Protection (ICRP) has long been proposing "justification" and "optimization" in radiological protection. The two concepts include considerations of efficiency and equity as welfare criteria in the economics of welfare. From the observations in the previous sections, it can be concluded that the Japanese society has been spending much greater amount of resources than the level that can be justified from the criterion of efficiency to reduce the risks from radioactive exposure due to the Fukushima nuclear disaster. However, a decision to reduce risks could be justified from the perspective of equity, even when the risk reduction is not efficient. Are the decisions of risk reductions scrutinized in the previous sections justifiable on the basis of equity?

In the context of radiological protection, equity should be taken into consideration, first, in order not to cause any deterministic health effects, and second, in order not to impose unacceptable levels of cancer risk on any person. No deterministic effect from radiological exposure has been observed in Fukushima. There is no consensus about the unacceptable level of risk that is relevant for any situation, but the dose limit for occupational exposure, 100 mSv per 5 years, which is applicable to planned exposure situations, has been recommended by ICRP as a value exposure above which is inequitable in the sense that the mortality would be greater than 10^{-3} at the age of 65 and the LLE would reach half a year when that level of exposure continued from the age of 18 (ICRP, 1990). With regard to the dose limit for the public, what is the equitable level of risk is not clear. In the case of the reference levels, which was introduced in the 2007 Recommendations of ICRP, the upper limits of the proposed ranges may be regarded as the values exposure above which is inequitable; ICRP (2007) recommended the range 20–100 mSv per annum for the reference level of emergency-exposure situations, and the range 1–20 mSv per annum for that of existing exposure situations.

The Japanese government chose 20 mSv y^{-1} as the criterion for the order of evacuation, which means that it chose the lower limit of the range, 20–100 mSv y^{-1}, proposed by ICRP for the reference levels in emergency-exposure situations. For the existing exposure situations again, the Japanese government adopted the lower limit of the range, 1–20 mSv y^{-1}, proposed by the ICRP, and set 1 mSv y^{-1} as the long-term target of decontamination. It is difficult to regard these decisions to choose the lower limits as being based on equity considerations; rather, the range of the reference levels recommended by ICRP means that an exposure exceeding the upper limit of the range is inequitable, and that each country should select one value within the range taking the principles of justification and optimization into consideration. Efficiency must be an important element in this procedure. Efficiency means the balancing of benefits and costs of the intervention; the most important benefit is the one from the reduction of health risks due to radiological exposure, and the costs include resource costs to implement remediation activities, economic loss from the restriction of activities, and other health risks induced by the radiological protection. The government did not assess such aspects, and simply adopted the lower limit as if intended to satisfy the equity requirement.

In determining the standard limits for foodstuffs, the government based them on the intervention exemption level of 1 mSv y^{-1}, which appeared in the Codex Standard, which in turn was based on ICRP (1999), but the government depended on many arbitrary assumptions in order to obtain the values of the standard, 100 Bq kg^{-1} for general foods. Indeed, the government stated that the median value of the expected dose from foods was 0.051 mSv y^{-1} and the dose would not exceed 1 mSv y^{-1} with a probability of 99.95% even under the provisional regulation value, 500 Bq kg^{-1} for many foods, and that the median dose would be 0.043 mSv y^{-1} under the new standard and the probability of not exceeding 1 mSv y^{-1} would rise to 99.99% and more. It is difficult to claim that the reduction from 0.051 mSv y^{-1} to 0.043 mSv y^{-1} is based on equity, which should be pursued regardless of costs.

In Ukraine, standard values for radiocaesium in foods are different among the types of foods: 20 Bq kg^{-1} for bread, 100 Bq kg^{-1} for milk, but 500 Bq kg^{-1} for wild berries and mushrooms, and 2500 Bq kg^{-1} for dried wild berries and mushrooms. These standard values reflect the difference in the difficulty of reducing caesium content among foods. The Japanese standard values, in contrast, do not take such aspects into account; a uniform value is applied to most foods.

To further reduce radiocaesium content when actual exposure is far below the intervention exemption level would not only be inefficient but also can be inequitable with respect to fair trade. Before the Fukushima disaster, Japan had a standard for radiocaesium in foods targeted at imported foods mainly from contaminated areas by the radiocaesium released from the Chernobyl NPP. The standard value was 370 Bq kg^{-1}. Since April 2012, when the new standard, 100 Bq kg^{-1}, was applied, imported foods also came under this new standard. Many imported foods produced in Europe that had met the previous standard failed the new standard. In 2015 and 2016, 16 cases of standard breaches of the radiocaesium standard were reported, all of which are foods made from berries or mushrooms, and only three of which would have been a breach under the previous standard.

The present standard is not unfair in the sense that it is applied equally to imported and domestic products and conforms to the GATT principle of non-discriminatory treatment. The Codex standards were, however, made to eliminate regulations that comply with the GATT principle, but do not have sufficient scientific basis, and as a result impede fair trade. The “intervention exemption level” implies that trade restrictions under this level may be unfair even when they treat imported products and domestic products indiscriminately. The regulation to ensure exposure under the “intervention exemption level” may be unfair in this respect.

In conclusion, most of the control of radioactive exposure examined above is not efficient or can be justified on the basis of equity.

5. Conclusion

This study estimated the values of CPLYS for policy measures to reduce health risks from radiation exposure from radiocaesium released from the Fukushima Daiichi NPP. It was found that the values are much greater than the comparable estimates from the Chernobyl case, and that, in most cases, the values are greater than the benefit per life-year saved. The observations were discussed from the perspective of efficiency and equity.

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