Chapter 13
Studies on Radiocesium Transfer in Agricultural Plants in Fukushima Prefecture

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Abstract After the Fukushima Daiichi Nuclear Power Plant (Tokyo Electric Power Company) accident occurred in March 2011, the concentration of radiocesium in brown rice produced in several areas of Fukushima Prefecture has exceeded a provisional regulation value. Therefore, we attempted research on decreasing the radiocesium concentration in agricultural plants.

To decrease the concentration of radiocesium in brown rice, we investigated the effect of the application of potassium fertilizer in rice paddy fields on the root uptake of radiocesium. The soil-to-brown-rice transfer factor of radiocesium decreased with an increase in exchangeable K_2O in the soil, suggesting that the application of

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potassium fertilizer is an effective countermeasure to reduce the radiocesium concentration in brown rice.

We examine the possibility of decontamination by means of phytoremediation. Four species of plants were sown. The highest removal percentages of ^{137}Cs were obtained in amaranth (0.093 %) and sunflower (0.038 %) in the light-colored Andosol and gray lowland soils, respectively. This result indicates that it is difficult to remove radiocesium from contaminated soil by means of phytoremediation.

Keywords Brown rice • Exchangeable K_2O • Phytoremediation • Radiocesium • Soil • Soil-to-brown-rice transfer factor

13.1 Objective

The magnitude 9.0 earthquake and the subsequent large tsunami that occurred on March 11, 2011, caused extensive damage to coastal areas in Tohoku, Japan. In particular, the cooling system of the Fukushima Daiichi Nuclear Power Plant [Tokyo Electric Power Company (TEPCO) FNPP] collapsed from the tsunami in excess of 10 m, which resulted in several explosions in the four reactors of the plant. Large amounts of radioactive materials, mainly noble gas, ^{131}I, ^{134}Cs, and ^{137}Cs, were released into the atmosphere, and consequently agricultural land and forests in Eastern Japan were contaminated. Radiocesium (^{134}Cs + ^{137}Cs) is an important radionuclide that can be used for the assessment of radiation exposure to the public because it has a long half-life (^{134}Cs, 2.06 years; ^{137}Cs, 30.2 years), high transferability, and wide distribution in the environment. Because of their long half-lives, there is concern that radiocesium (^{134}Cs + ^{137}Cs) will remain on the surface of agricultural land and persist for a long time [1, 2]. Therefore, we have started monitoring of radiocesium in soil collected from agricultural land in Fukushima Prefecture from March 2011. Based on these data, Nuclear Emergency Response Headquarters showed planting areas of rice in all regions, except a 20-km exclusion zone and the deliberate evacuation zone (DEZ) in Fukushima Prefecture in 2011. However, the brown rice produced in some areas in northern part of Fukushima prefecture exceeded the provisional regulation value for agricultural crops at the times (>500 Bq kg^{-1}). Consequently, the planting of rice crops for the year 2012 had been restricted in that area. The present studies show investigation of radiocesium transfer in the agricultural plants.

13.2 Effect of Potassium Application on Root Uptake of Radiocesium in Rice

To decrease radiocesium uptake in brown rice from the contaminated fields, we examined the effect of using potassium fertilizer on the radiocesium uptake in brown rice.

Rice plants (*Oryza sativa*) were cultivated in the five experimental paddy fields in the northern area in Fukushima Prefecture, which was contaminated with radiocesium, in 2011. Soils and rice plants were collected from five points in each experimental field at harvest time. The mean concentration of radiocesium at soil depths of 0–5, 5–10, and 10–15 cm was 5,800, 3,200 and 1,800 Bq kg^{-1} dry weight (DW), which was not uniformly distributed, even during plowing before cultivation. The concentration of radiocesium in each field at the depth of 0–5 cm showed approximately threefold variation.

The concentration of radiocesium in brown rice from five rice paddy fields was 231 ± 135 (52–485) Bq kg^{-1} fresh weight (FW), and the values were different in each collecting point. The soil-to-plant transfer factor is a simple but important parameter that can be used to estimate the concentrations of radionuclides in plants. The transfer factor generally shows a very wide range of variation. The transfer factor of soil-to-brown rice collected from a pair of soil and brown rice samples at each point was in the range of 0.0075–0.11, which was more than one order of magnitude different. Tsukada et al. and Komamura and Tsumura reported that the geometric mean of the soil-to-plant transfer factor of polished rice in rice paddy fields, which were determined by the fallout depositions derived from the nuclear weapons tests, as 0.0016 and 0.0030, respectively [3, 4]. The observed values, which were determined in the same or nearby fields, were higher than previously reported values. The difference may be attributed to nonuniform distribution of radiocesium in the available fractions because of the early stage of the aging periods after deposition onto the soil.

Potassium is an important essential element in plant physiology, and it is supplemented by the application of fertilizers to agricultural soils. There was a high correlation ($r = 0.88$) between the soil-to-brown-rice transfer factor of radiocesium and the exchangeable K_2O in the soil (Fig. 13.1). Other researchers have reported that the transfer factor of ^{137}Cs decreased with increasing concentrations of potassium in soils [5–7]. Kato [8] also reported that the soil-to-plant transfer factor of radiocesium decreased with increasing concentrations of exchangeable K_2O in soils. Further, the soil-to-brown-rice transfer factor of radiocesium also decreased from 0.074 to 0.024 with the application of potassium fertilizer through top dressing. Hence, it is clear that the application of potassium fertilizer reduces the concentration of radiocesium in brown rice.

13.3 Phytoremediation of Radiocesium in Different Soils Using Cultivated Plants

Following the nuclear power plant disaster, more than 90 % of the radionuclides were distributed in the upper 6 cm of the soil column in wheat fields, and within 4 cm of the surface in rice paddies, orchards, and cedar forests [9]. It is well known that radiocesium is adsorbed into the soil and binds strongly to clay. As a result, it is difficult to reduce the contamination level in the soil. It was reported that phytoremediation using rice plants in a paddy field was also difficult [10]. We examined the

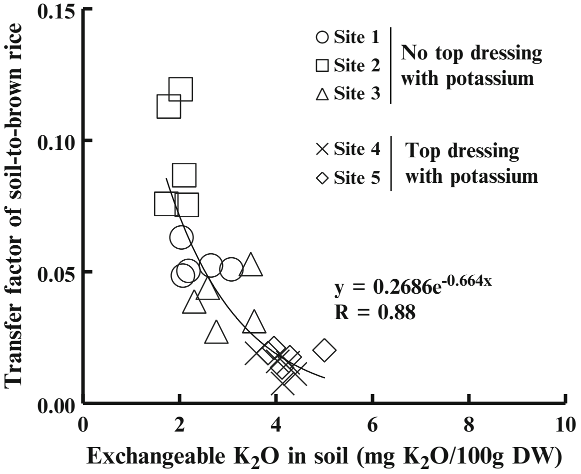

Fig. 13.1 Relationship between transfer factor of soil to brown rice and exchangeable K_2O in the soil

Table 13.1 Yield of four plants cultivated in light-colored andosol and gray lowland soil

Cultivated soil type	Plant	Yield Leaf	Stem	Flower	Root	Whole body	Aboveground of plant
Light-colored andosol	Amaranth	0.15±0.05	0.51±0.02	0.58±0.12	0.18±0.03	1.43±0.19	1.25±0.19
	Buckwheat	0.33±0.04	0.57±0.10	0.79±0.13	0.16±0.06	1.86±0.27	1.69±0.22
	Sorghum	0.55±0.07	1.11±0.18	–	0.24±0.02	1.91±0.20	1.66±0.18
	Sunflower	0.13±0.04	0.28±0.01	0.13±0.01	0.03±0.01	0.57±0.05	0.54±0.05
Gray lowland soil	Amaranth	0.28±0.01	0.30±0.01	0.58±0.02	0.09±0.01	1.24±0.02	1.16±0.02
	Buckwheat	0.16±0.01	0.28±0.01	0.49±0.03	0.04±0.00	0.98±0.03	0.94±0.03
	Sorghum	0.91±0.03	1.58±0.10	–	0.42±0.06	2.91±0.14	2.49±0.13
	Sunflower	0.29±0.05	0.50±0.08	0.05±0.00	0.04±0.00	0.87±0.13	0.84±0.13

Sampling from September 6–13, 2011

possibility of decontamination by means of phytoremediation using four agricultural plants such as sunflower (*Helianthus annuus* L.), amaranth (*Amaranthus* L.), sorghum (*Sorghum bicolor*), and buckwheat (*Fagopyrum esculentum*) in upland fields.

The total yields of biomass cultivated in the light-colored Andosol and gray lowland soil is shown in Table 13.1. The biomass of the sorghum in the gray lowland soil (2.91 kg dry weight m^{-2}) was five times higher than that of buckwheat cultivated in the light-colored Andosol, and the gray lowland soil was within a factor of 2.

Table 13.2 Concentration of ^{137}Cs in plant components (Bq kg^{-1} dry weight)

Cultivated soil type	Plant	Concentration of plant component Leaf	Stem	Flower	Root	Whole body	Aboveground of plant
Light-colored andosol	Amaranth	184 ± 57.7	49 ± 31.6	57 ± 11.0	113 ± 48.4	50 ± 4.9	79 ± 15.8
	Buckwheat	104 ± 26.4	9 ± 0.1	33 ± 10.7	150 ± 9.9	22 ± 1.9	37 ± 5.4
	Sorghum	72 ± 8.4	25 ± 12.5	–	156 ± 9.9	21 ± 4.1	42 ± 9.4
	Sunflower	152 ± 28.7	46 ± 7.4	23 ± 2.5	142 ± 119.1	68 ± 9.1	48 ± 6.4
Gray lowland soil	Amaranth	157 ± 10.9	11 ± 3.8	38 ± 7.5	29 ± 12.6	84 ± 14.2	51 ± 5.6
	Buckwheat	41 ± 3.5	8 ± 1.3	34 ± 3.6	38 ± 2.6	43 ± 5.0	21 ± 2.5
	Sorghum	41 ± 7.4	5 ± 1.4	–	35 ± 8.7	58 ± 7.4	18 ± 4.1
	Sunflower	231 ± 4.7	30 ± 8.7	11 ± 2.3	39 ± 13.9	65 ± 11.6	69 ± 11.6

Decay correction was done at harvest time, 2011; average ± SD ($n = 3$)

Sorghum had the highest biomass in both the light-colored Andosol and the gray lowland soil.

The concentration of ^{137}Cs in the soil among the fields was 1,300–2,000 Bq kg^{-1} dry weight. The concentration of ^{137}Cs in the plant components is indicated in Table 13.1. Among the components, the leaves exhibited the highest concentration of ^{137}Cs, except sorghum cultivated in the light-colored Andosol. The concentration of ^{137}Cs in the roots, including adhered soil particles, was relatively similar among the plants cultivated in each soil. However, the concentration of ^{137}Cs in the stem differed approximately fivefold among the plants. The ^{137}Cs concentration in the aboveground part of the plant was 36.7–78.9 Bq kg^{-1} dry weight in the light-colored Andosol and 18.0–69.1 Bq kg^{-1} dry weight in the gray lowland soil (Table 13.2).

The total content of ^{137}Cs in the biomass among the four plants was 19.8–132 Bq m^{-2} cultivated in the light-colored Andosol and 17.6–79.8 Bq m^{-2} cultivated in the gray lowland soil. The content in amaranth and sunflower was the highest in the light-colored Andosol and the gray lowland soil, respectively.

The removal percentage of ^{137}Cs, which is defined as the ratio of the total content of ^{137}Cs in the plant biomass (20–154 Bq m^{-2}) to that in the cultivated soil of 0–15 cm depth (154,000–247,000 Bq m^{-2}), was 0.015–0.109 % for the light-colored Andosol and 0.008–0.039 % for the gray lowland soil. The removal percentage of ^{137}Cs for aboveground parts, excluding the root part, was 0.013–0.093 % for the light-colored Andosol and 0.007–0.038 % for the gray lowland soil. The highest values of the aboveground parts were obtained in amaranth (0.093 %) and sunflower (0.038 %) in the light-colored Andosol and the gray lowland soil, respectively (Table 13.3). The ratio of the removal of radiocesium from the surface soil to that of the cultivated biomass, that is, sunflower, amaranth, sorghum, and buckwheat, was negligible. This result indicates that it is difficult to remove radiocesium from contaminated soil by means of phytoremediation.

Table 13.3 Removal percentage of ^{137}Cs by cultivated plant

			^{137}Cs content		Removal percentages (%)	
Cultivated soil type	Plant	Soil (Bq m^{-2})	Whole body	Aboveground of plant	Whole body	Aboveground of plant
Light-colored andosol	Amaranth	154,000 ± 61,000	91 ± 12.1	61 ± 15.7	0.109 ± 0.039	0.093 ± 0.032
	Buckwheat	158,000 ± 21,000	154 ± 22.0	132 ± 20.8	0.015 ± 0.001	0.013 ± 0.001
	Sorghum	208,000 ± 11,000	110 ± 10.4	70 ± 21.0	0.056 ± 0.030	0.033 ± 0.023
	Sunflower	175,000 ± 64,000	24 ± 4.2	20 ± 1.2	0.059 ± 0.029	0.036 ± 0.007
Gray lowland soil	Amaranth	209,000 ± 42,000	84 ± 25.8	80 ± 12.2	0.024 ± 0.004	0.023 ± 0.003
	Buckwheat	247,000 ± 18,000	49 ± 10.6	48 ± 5.8	0.008 ± 0.002	0.007 ± 0.002
	Sorghum	201,000 ± 12,000	60 ± 13.6	45 ± 12.2	0.030 ± 0.007	0.022 ± 0.005
	Sunflower	216,000 ± 20,000	20 ± 4.3	18 ± 4.4	0.039 ± 0.009	0.038 ± 0.009

Decay correction was done at harvest time, 2011; average ± SD ($n = 3$)

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