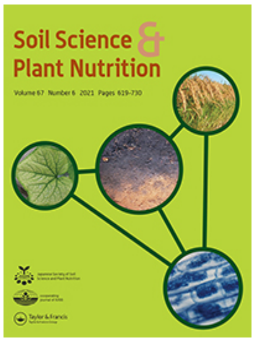

Soil Science and Plant Nutrition

ISSN: 0038-0768 (Print) 1747-0765 (Online) Journal homepage: www.tandfonline.com/journals/tssp20

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To cite this article: Katashi Kubo, Hayato Maruyama, Hisae Fujimoto, Masataka Suzuki, Ayane Kan, Yusuke Unno & Takuro Shinano (2021) Comparative study of radioactive cesium transfer from soil to peanut and soybean, Soil Science and Plant Nutrition, 67:6, 707-715, DOI: 10.1080/00380768.2021.1988829

To link to this article: https://doi.org/10.1080/00380768.2021.1988829

Published online: 17 Oct 2021.

SOIL SCIENCE AND PLANT NUTRITION
2021, VOL. 67, NO. 6, 707–715
https://doi.org/10.1080/00380768.2021.1988829

ORIGINAL ARTICLE

Comparative study of radioactive cesium transfer from soil to peanut and soybean

Katashi Kubo[a], Hayato Maruyama[b], Hisae Fujimoto[b], Masataka Suzuki[b], Ayane Kan[b], Yusuke Unno[c] and Takuro Shinano[a,b]

[a]Agricultural Radiation Research Center, Tohoku Agricultural Research Center, National Agriculture and Food Research Organization (Naro), Fukushima, Japan; [b]Laboratory of Plant Nutrition, Research Faculty of Agriculture, Hokkaido University, Sapporo, Hokkaido, Japan; [c]Department of Radioecology, Institute for Environmental Sciences, Aomori, Japan

ABSTRACT

Low transfer of radioactive cesium (radiocesium) from soil to grains of agricultural crops is desirable to ensure food safety for humans and animals. Although the transfer of radiocesium from soil to grains is higher in upland crops such as soybean (*Glycine max* L.) than in paddy rice (*Oryza sativa* L.), little information related to the specific difference in radiocesium accumulation among leguminous crops is available, or for the relation between soil conditions and radiocesium accumulation in leguminous crops. This study compared the pattern of radiocesium transfer from soil to grains between peanut (*Arachis hypogaea* L.) and soybean to elucidate the diversity of radiocesium accumulation in leguminous crops growing with different potassium levels in soil. Pot and field experiments with radiocesium-contaminated soil showed that the radiocesium concentration in grains was lower in peanut than in soybean plants. For peanut, radiocesium absorption was mainly from roots instead of gynophores and fruits formed in the soil. Radiocesium absorption and translocation from roots to shoots were lower in peanut than in soybean plants. Among shoot parts, radiocesium transfers from stems to leaves, shells, and grains were lower in peanut than in soybean plants. Potassium application to the soil decreased the radiocesium transfer from soil to grains in both crops. The radiocesium accumulation was lower in peanut than in soybean under both potassium applied and non-applied conditions. These results underscored the variation in radiocesium transfer from soil to grains in leguminous crops, and demonstrated that peanut plants had lower potential of radiocesium accumulation than soybean plants.

ARTICLE HISTORY
Received 1 August 2021
Accepted 30 September 2021

KEY WORDS
Exchangeable potassium content; groundnut; legumes; radiocesium; soybean

1. Introduction

Leguminous crops can contribute to the health and nutritional benefits of humans by inclusion in diet because they have an abundance of nutrient ingredients such as protein, fiber, vitamins and minerals (Bouchenak and Lamri-Senhadji 2013; Foyer et al. 2016; FAO 2021a, 2021b). For the cultivation of leguminous crops, the capacity of nitrogen fixation in crops can afford complementarity through natural soil fertilization, and can provide economically sustainable benefits for farming (Peoples et al. 2009; Reeves, Thomas, and Ramsay 2014; Foyer et al. 2016).

Areas affected by the accident at the Tokyo Electric Power Company's Fukushima Dai-ichi nuclear power plant in 2011 have faced difficulties caused by translocation of radioactive cesium (^{134}Cs and ^{137}Cs; radiocesium) from farmland environments to various crops including soybean (*Glycine max* L.) (Shinano 2016). Actually, radiocesium, the major radionuclide released by the accident (Ohara, Morino, and Tanaka 2011), can become a threat to human health (Burger and Lichtscheidl 2018). Because close negative correlation between the soil exchangeable (plant-available) potassium (ExK) content and the radiocesium concentration in crops grown in the soil has been confirmed since the accident (e.g., Kubo et al. 2020), increasing the soil ExK content by the application of potassium (K) fertilizer has been continued to decrease radiocesium absorption in soybean (Hirayama et al. 2018; Hatano, Shinjo, and Takata 2021; Matsunami et al. 2021), as well as rice (*Oryza sativa* L.) (Fujimura et al. 2014; Kato et al. 2015) and buckwheat (*Fagopyrum esculentum* Moench) (Kubo et al. 2015, 2018). Although incidents of radiocesium contamination greater than the regulatory value (100 Bq kg^{-1}) in agricultural products have remained limited (MAFF 2020), the monitoring of radioactivity in agricultural products has continued in affected areas (Hachinohe and Shinano 2020) because of the long half-life (30.2 years) of ^{137}Cs.

Long-term monitoring and various experiments have clarified that soybean grains are prone to having higher concentrations of radiocesium than rice (IAEA 2020). However, the characteristics of radiocesium that are transferred from soil to grains in leguminous crops other than soybean remain poorly understood, although comparisons of radiocesium accumulation among crop species have been conducted arduously (Hirayama and Keitoku 2014; Uchida and Tagami 2018). In this study, we specifically examined a leguminous crop: peanut (*Arachis hypogaea* L.). Because peanuts have lower potassium contents in grains than soybeans have (MEXT 2020), the concentration of radiocesium, which has similar chemical properties to potassium, in grains might also be lower in peanut than in soybean. From the other side, how peanut absorbs

CONTACT Katashi Kubo ktskubo@affrc.go.jp Tohoku Agricultural Research Center, NARO, 50 Harajukuminami, Arai, Fukushima 960-2156, Japan
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radiocesium is still unknown, but peanut has been shown to have a unique nutrient uptake mechanism, absorbing calcium from the soil through the gynophore and fruits rather than roots (Bledsoe, Comar, and Harris 1949). We aimed at elucidating the characteristics of radiocesium absorption and partitioning in peanut plants by comparison with soybean in pot and field experiments.

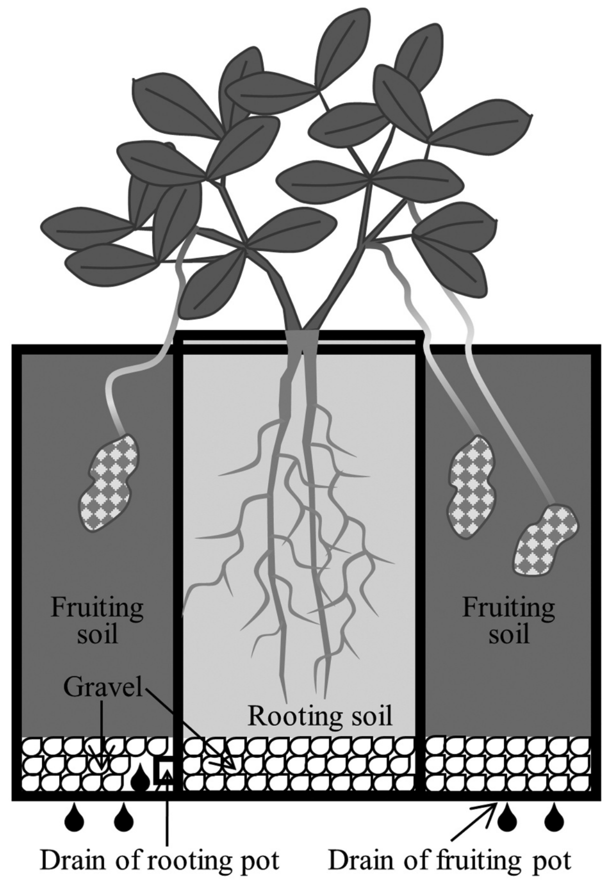
2. Materials and methods

2.1. Plant materials

In all experiments (Experiments 1, 2, and 3), peanut cultivar 'Satonoka' bred in Chiba prefecture, Japan (Suzuki et al. 1997) was used. In soybean, cultivar 'Tachinagaha' bred in Nagano prefecture, Japan (MAFF 2019) was used in Experiments 1 and 2, and cultivar 'Satonohohoemi' bred in NARO Tohoku Agricultural Research Center (Kikuchi et al. 2011) was used in Experiment 3. Hereinafter, 'Satonoka' will be designated as 'peanut,' and 'Tachinagaha' and 'Satonohohoemi' will be designated as 'soybean.'

2.2. Absorption pathway of radiocesium in peanut (Experiment 1)

The peanut plants were grown in pots with the root and fruit zones isolated from each other (Figure 1), as described by Bledsoe, Comar, and Harris (1949). Pot experiments were conducted in a glasshouse at the NARO Tohoku Agricultural Research Center (37.7°N, 140.4°E). The side windows of the glasshouse were always opened, thereby having no temperature control. Plants were grown under natural light as described by Kubo et al. (2016a). Three patterns of the combination of radiocesium-contaminated and non-contaminated soils (abbreviated as Ctm and NCtm soils, respectively) in rooting and fruiting zones were set as depicted in Figure 1. For example, NCtm/Ctm pot had non-contaminated soil in rooting zone and radiocesium-contaminated soil in fruiting zone. After Ctm soil was collected from farmland in Fukushima prefecture, where radiocesium decontamination procedures were conducted in 2014, in 2016, the soil was passed through a 4 mm sieve. The soil ^{137}Cs concentration and ExK content of Ctm soil before the cultivation were, respectively, 3,299 Bq kg^{-1} and 347 mg kg^{-1} (418 mg K_2O kg^{-1}). Culture soil at pH 6.0 containing 31 mg N kg^{-1}, 1,258 mg P_2O_5 kg^{-1}, and 314 mg K_2O kg^{-1} (Sansan seedbed soil; Takii and Co. Ltd.) was used as the NCtm soil (<0.61 Bq kg^{-1}). Rooting soil was filled to Wagner pots (0.02 m^2) after mixing with fertilizer (0.3 g pot^{-1} of N and P_2O_5). Available N and P_2O_5 were applied respectively with ammonium sulfate (21% N) and calcium superphosphate (20.5% P_2O_5). K fertilizer was not applied because higher soil ExK content provides lower transfer of radiocesium from soil to crops as described in the Introduction. The Wagner pot was put in the center of plastic gardening pot (37 cm diameter, 25 cm height). Fruiting soil was filled to the gap of Wagner pot and gardening pot. No fertilizer was applied to the fruiting soil. Sowing was done in 9 June 2016. Five plants were established for each pot. The experimental design was a completely randomized method with four replications. At maturity (November 8),



Pot type	Rooting soil	Fruiting soil
NCtm/Ctm	non-contaminated	contaminated
Ctm/NCtm	contaminated	non-contaminated
Ctm/Ctm	contaminated	contaminated

Figure 1. Schematic diagram and soil layout of a pot isolated root and fruit zones (Experiment 1).

shoots (including shells), roots, and grains were harvested separately for dry weight and ^{137}Cs concentration measurements. The results show that grains grew in both the rooting and fruiting zones. Therefore, grains in the rooting and fruiting zones were sampled separately.

2.3. Root–shoot–grain radiocesium distribution in peanut and soybean (Experiment 2)

For the comparison of radiocesium absorption and translocation between the peanut and the soybean, soybean was cultivated with Wagner pots (0.02 m^2) filled with radiocesium-contaminated soil similarly to the pot experiment of peanut (Experiment 1) in the same glasshouse in 2016. Fertilizer, sowing date, planting density, and replications were the same as those for peanut in 'Experiment 1'. Shoots (including shells), roots, and grains were harvested separately at maturity (October 19). The radiocesium absorption and translocation were compared with peanut grown in pots with radiocesium-contaminated soils (Ctm/Ctm pot).

In 2017, the comparison was repeated using Wagner pots (0.02 m^2) under similar conditions to those of the three replications. To facilitate soil collection after cultivation, a nylon mesh sheet (45 µm aperture) was placed between the pot and the soil. Dates of sowing and sampling were, respectively, 12 June and 28 September 2017. The concentrations of N, K, P, Ca, Mg, and Fe, which were the main nutrients, and stable Cs (^{133}Cs) were also measured as well as ^{137}Cs concentration with samples of roots, shoots, and grains for both crops. In the rhizosphere soil of each pot, ExK content and exchangeable ^{133}Cs ($Ex^{133}Cs$) concentrations were measured.

Field experiments were also conducted in 2020 to elucidate the differences in radiocesium translocation among shoot parts (grain, shell, leaf, and stem) in peanut and soybean. The two crops were cultivated in adjacent fields with Gray Lowland soil in Fukushima prefecture. Experimental plots were set three replications for each crop. The soil ^{137}Cs concentrations of the fields before cultivation were, respectively, 1,884 ± 62 (peanut) and 1,762 ± 48 Bq kg^{-1} (soybean) (average ± standard error, n = 3). The soil ExK contents before cultivation were, respectively, 138 ± 3 and 133 ± 13 mg K_2O kg^{-1} (average ± standard error, n = 3). The N and P_2O_5 were applied at 2.0 and 10.0 kg 10 a^{-1} with ammonium sulfate (21% N) and calcium superphosphate (20.5% P_2O_5), respectively, uniformly across both fields after the application of magnesium lime (100 kg 10 a^{-1}). K fertilizer was not applied. The seeds of the peanut and the soybean were sown with sowing space of 15 cm and row space of 70 cm. Two seeds were sown for each place. The sowing dates were, respectively, 24 and 23 June 2020 in the peanut and the soybean. The areas of the respective plots were 4.5 and 22.5 m^2, respectively, in the peanut and the soybean. Cultivation management such as intertillage and pest control with chemicals was conducted in accordance with custom practice of each crop. The grains, shells, leaves, and stems were harvested separately from each 10 (peanut) or 8 (soybean) plants of respective plot at maturity stage (19 November 2020 in peanut, 28 October 2020 in soybean), and were measured dry weight and ^{137}Cs concentration.

2.4. Effects of potassium application to soil–grain radiocesium transfer in peanut and soybean (Experiment 3)

Field experiments were conducted for two times in a peanut field of 'Experiment 2' in 2019 and 2020 to clarify effects of potassium application to radiocesium accumulation in the peanut and the soybean. The soil ^{137}Cs concentrations and ExK contents before cultivation in 2019 were, respectively, 2,022 ± 21 Bq kg^{-1} and 142 ± 1 mg K_2O kg^{-1} (average ± standard error, n = 6). Two levels of soil ExK content 142 (no-K) and 250 (+K) mg K_2O kg^{-1}, corresponding to applying 0 and 32.4 kg 10 a^{-1} of potassium sulfate (50% K_2O), respectively (calculated as the soil bulk density 1.0 t m^{-3}, soil depth 15 cm) were set in 2019. In 2020, soil ExK contents of no-K and +K plots were set to 136 ± 16 (average ± standard error, n = 3) and 250 mg K_2O kg^{-1}, respectively, as with 2019. Soil ^{137}Cs concentration was 1,944 ± 49 Bq kg^{-1} (average ± standard error, n = 6) before cultivation in 2020. The timing of K application was at the flowering stage of soybean in 2019 and before cultivation in 2020, respectively. The locations of no-K and +K plots were the same during two experiments. The application of N and P_2O_5, sowing density and cultivation management were identical to those of the field experiment of Experiment 2. The sowing dates were, respectively, June 5 and June 24, in 2019 and 2020. The experiments had a split-plot design (main-plot K, sub-plot crop) with three replications. The area of each sub-plot was 4.5 m^2. The grains of the peanut and the soybean were harvested from each of 10 plants of respective plot at the maturity stage (12 November 2019 and 19 November 2020 in peanut, 21 October 2019 and 28 October 2020 in soybean), and were measured ^{137}Cs concentration. ^{137}Cs concentration, exchangeable ^{137}Cs (plant-available ^{137}Cs, $Ex^{137}Cs$) concentration and ExK content of soil collected from the base of each crop at maturity were also measured.

2.5. Soil and plant analyses

Soil samples of field experiments were collected from 15 cm depth around plant roots with a worm scoop (Fujiwara Scientific Co., Ltd.). Rhizosphere soil of pot experiment was brushed off from the surface of roots after removing non-adhering soil particles by hand-shaking roots (Barillot et al. 2013). All soil samples were prepared, from which were determined the ExK content, total ^{137}Cs, $Ex^{137}Cs$, and $Ex^{133}Cs$ concentrations as with Kubo et al. (2017). Soil $Ex^{137}Cs$ ratio (%) was calculated as presented below.

Soil $Ex^{137}Cs$ ratio (%) = soil $Ex^{137}Cs$ concentration/soil total ^{137}Cs concentration × 100

The respective shoot parts and grains of the crops were oven-dried at 80°C for 48 h after washing with running tap water. The grains were separated from shells by hand for both crops. The shells of peanut were oven-dried again after washing with ultrasonic cleaning as described by Kubo et al. (2016b). The roots were also washed with running tap water and ultrasonic cleaning; they were then dried in an oven. Dried plants were ground in a laboratory mill with stainless steel blades (WB-1; Osaka Chemical Co. Ltd.) for ^{137}Cs and other element analyses. Regarding peanut grains, they were crushed with a wooden hammer (the grains would be paste when ground with a laboratory mill). The ^{137}Cs analyses were conducted similarly to those described by Kubo et al. (2019). The transfer factor (TF) of ^{137}Cs from soil to grains was calculated as presented below.

TF = ^{137}Cs concentration (Bq kg^{-1}) in grain (oven-dried) /^{137}Cs concentration (Bq kg^{-1}) in air-dried soil

To evaluate the difference in ^{137}Cs distribution between crops, ^{137}Cs distribution ratio of each tissue (grain, shoot, and root) was calculated as follows (Fujimura et al. 2015).

^{137}Cs distribution ratio = ^{137}Cs content (^{137}Cs concentration × DW) of each tissue (Bq)/^{137}Cs content of whole plant (Bq)

In addition, ^{137}Cs distribution factor (DF) of each tissue was calculated using the ^{137}Cs distribution ratio.

^{137}Cs DF = ^{137}Cs distribution ratio of each tissue/DW of each tissue (kg)

The ^{137}Cs DF of each tissue represents the ease of ^{137}Cs distribution relative to the distribution of dry matter. Using the ^{137}Cs distribution ratio and DF, the ^{137}Cs concentration of each tissue can be ascertained as described below.

The ^{137}Cs concentration of each tissue (Bq kg^{-1}) = (^{137}Cs content of whole plant (Bq) × ^{137}Cs distribution ratio of each tissue)/DW of each tissue (kg)

= ^{137}Cs content of whole plant (Bq) × ^{137}Cs DF of each tissue (kg^{-1}).

The N concentration of plant tissue was measured using an elemental analyzer (FLASH 2000; Thermo Fisher Scientific). To analyze P, K, Ca, Mg, and Fe concentrations of plant tissue, the ground and crushed samples were digested with ultrapure nitric acid. Ion contents were evaluated using an inductive-coupled plasma mass spectrometer (ICP-MS, Agilent 7700; Agilent Technologies Inc.). Also, the DFs of N, P, K, Ca, Mg, and Fe were calculated similarly to ^{137}Cs.

2.6. Statistical analyses

To detect differences among treatments and between crops, data were subjected to the analysis of variance (ANOVA) using the general linear model procedure, and Student's *t*-test. Multiple comparisons after the ANOVA were conducted using the Ryan–Einot–Gabriel–Welsch procedure. For the evaluation of the relation of nutritional elements to Cs accumulation, Pearson's correlation analyses were performed. Analyses were conducted using software (IBM SPSS for Windows, ver. 25; IBM Japan Ltd.).

3. Results and discussion

3.1. Absorption pathway of radiocesium in peanut (Experiment 1)

Experimentation with pots with isolated root and fruit zones in peanut showed that ^{137}Cs of grains grown in NCtm soil of NCtm/Ctm pot, which has NCtm soil in rooting zone and Ctm soil in fruiting zone, were not detected (< 5.0 Bq kg^{-1}) (Table 1). The ^{137}Cs concentration of grains grown in Ctm soil (fruiting zone) of NCtm/Ctm pot was 12.8 Bq kg^{-1}, which was significantly lower than those of either Ctm/NCtm (106.4 Bq kg^{-1}) or Ctm/Ctm (99.9 Bq kg^{-1}) pots. In the Ctm/NCtm pot, grains grown in NCtm soil (fruiting zone) had 23% lower radiocesium concentration than that grown in Ctm soil (rooting zone) (82.7 vs. 106.4 Bq kg^{-1}, $p < 0.05$ according to t-test results). However, grains grown in NCtm soil (fruiting zone) in Ctm/NCtm pot were found to have no significant difference from those grown in Ctm soil (rooting and fruiting zones) of Ctm/Ctm pot (82.7 vs. 99.9 Bq kg^{-1}). Grain and shoot DW showed no significant difference among pot treatments (Table 1). These results suggest that ^{137}Cs was absorbed mainly by roots, and that absorption of ^{137}Cs from gynophores and fruits was slight (13–23% of root absorption). For calcium, Bledsoe, Comar, and Harris (1949) reported that the element is more absorbed from gynophores and fruits than from roots. The result is the opposite of findings obtained from this study evaluating Cs absorption, which indicated that the absorption pattern of peanut (from root or from gynophore and fruit) might differ depending on the element.

Table 1. Grain ^{137}Cs concentration and dry weight of grain and shoot in peanut in pot isolated root and fruit zones (Experiment 1).

	Grain ^{137}Cs in NC (Bq kg^{-1})	Grain ^{137}Cs in C (Bq kg^{-1})	Grain DW (g pot^{-1})	Shoot DW (g pot^{-1})
NC/C	<5.0	12.8 a	47.0	54.3
C/NC	82.7	106.4 b	41.0	46.8
C/C	-	99.9 b	42.1	43.4
		**	ns	ns

**denotes significant differences at $p < 0.01$. ns denotes not significant. Different letters stand for significant differences ($p < 0.05$) according to the Ryan–Einot–Gabriel–Welsch procedure.

3.2. Root–shoot–grain radiocesium distribution in peanut and soybean (Experiment 2)

A comparison of ^{137}Cs concentrations in grains, shoots (stems + leaves + shells) and roots between the peanut and the soybean for 2 years (2016 and 2017) in pot experiment is shown in Table 2. The ^{137}Cs concentrations of grains and shoots in peanut were significantly lower than those in soybean. The ^{137}Cs concentration of root was significantly higher in peanut than in soybean. Moreover, the shoot/root and grain/shoot concentration ratios were both significantly lower in peanut than in soybean. Differences between years (2016 and 2017) in ^{137}Cs concentration in grains, shoots, and roots were significant. The values were high in 2017 than in 2016. Interactions between crops (peanut and soybean) and years in ^{137}Cs concentration in grains and shoots, shoot/root ratios were also significant. These are expected to be affected by the difference of ^{137}Cs concentration between year (2016 < 2017). Especially, peanut had higher ^{137}Cs concentration in grains and shoots in 2017 (grain 359.4 Bq kg^{-1}, shoot 419.2 Bq kg^{-1}) than in 2016 (grain 99.9 Bq kg^{-1}, shoot 131.1 Bq kg^{-1}). Details related to the difference in ^{137}Cs concentrations between the 2 years remain unknown, but might be attributable to the difference in soil water condition (in 2017, the moisture content of the pot soil seemed higher than in 2016 because a nylon mesh sheet was placed between the pot and the soil) and/or because of the fact that timing of the sampling was earlier in 2017 than in 2016. Differences in ^{137}Cs DF of the respective parts are shown in Table 3. Differences between crops were significant in all plant

Table 2. Grain, shoot, and root ^{137}Cs concentrations in peanut and soybean in pot experiment (Experiment 2).

	2016		2017		C	Y	C*Y
	Peanut	Soybean	Peanut	Soybean			
Grain ^{137}Cs (Bq kg^{-1})	99	467	359	463	**	**	**
Shoot ^{137}Cs (Bq kg^{-1})	131	387	419	489	**	**	*
Root ^{137}Cs (Bq kg^{-1})	995	302	1316	731	**	*	ns
Shoot/root ratio	0.135	1.327	0.354	0.874	**	ns	**
Grain/shoot ratio	0.753	1.256	0.862	0.993	*	ns	ns

C, Crop; Y, Year. ** and *, respectively, denote significant differences at $p < 0.01$ and $0.01 \le p < 0.05$. ns stands for not significant.

Table 3. Grain, shoot, and root ^{137}Cs DFs in peanut and soybean in pot experiment (Experiment 2).

	2016		2017		C	Y	C*Y
	Peanut	Soybean	Peanut	Soybean			
Grain	6.37	17.61	7.7	9.81	**	*	**
Shoot	5.56	14.53	8.99	9.92	**	ns	*
Root	66.86	11.72	28.5	14.31	**	*	*

C, Crop; Y, Year. ** and *, respectively, denote significant differences at $p < 0.01$ and $0.01 \le p < 0.05$. ns stands for not significant.

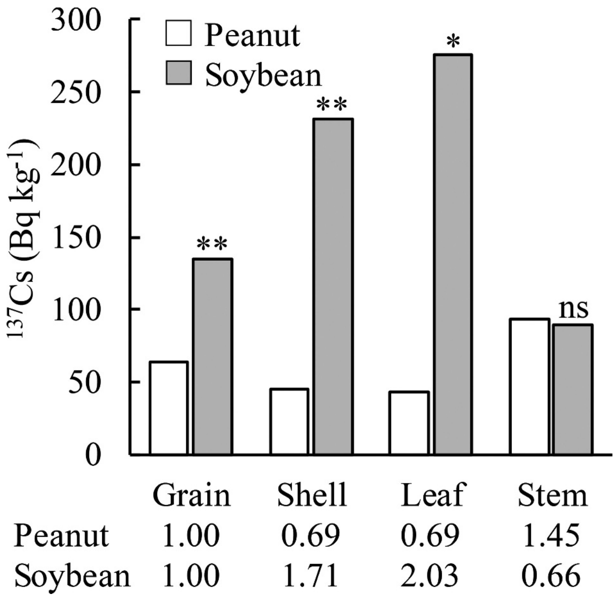
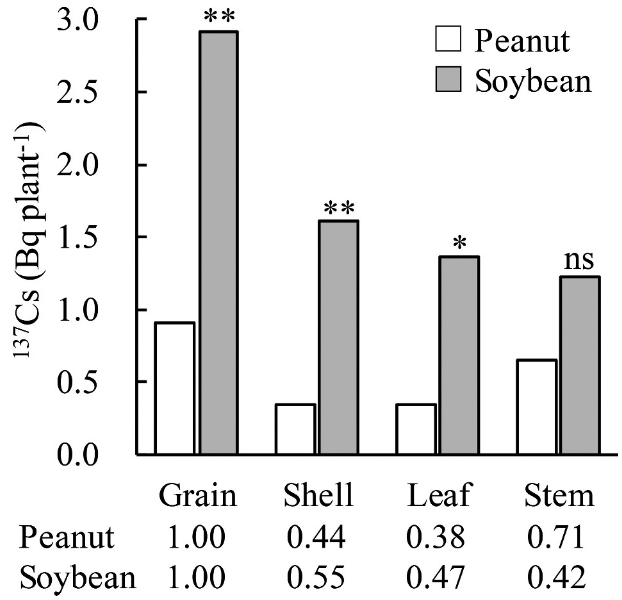


Figure 2. Concentrations and ratios in ^{137}Cs in grain, shell, leaf, and stem in peanut and soybean in field experiment (Experiment 2). Values under the figure are ratios to grain concentration in each crop. ** and *, respectively, stand for significant differences between cops for each plant part at $p < 0.01$ and $0.01 \le p < 0.05$. ns denotes not significant.



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parts. Peanut plants were found to have significantly lower values in grains and shoots and higher values in roots than those of soybean. Based on these results, even considering the difference in dry matter distribution between the peanut and the soybean, the accumulation of ^{137}Cs in the peanut grains was less than in soybean grains. Total (grain + shoot + root) ^{137}Cs contents were 28.9 ± 6.4 and 36.4 ± 5.0 Bq pot^{-1} ($n = 7$, including 2 years of samples), respectively, in the peanut and the soybean. The difference was significant ($p < 0.05$) according to ANOVA (data are not shown in tables and figures). These results indicate that peanut has lower absorption in whole plants and lower translocations from roots to shoots and from shoots to grains of ^{137}Cs than those of soybean. That lower absorption is expected to be one factor affecting lower grain ^{137}Cs concentrations in peanut.

Field experiment evaluated ^{137}Cs partitioning among shoot parts (grains, shells, leaves, and stems) in peanut and soybean (Figure 2). The ^{137}Cs concentrations of grains, shells, and leaves were significantly lower in peanut than in soybean. No significant difference was found in ^{137}Cs concentration of stems between crops. The ^{137}Cs ratios of shells and leaves to the ^{137}Cs concentration of grains were about 60% and 66% lower in peanut than in soybean, respectively. Conversely, ^{137}Cs ratio of stems was about 54% lower in soybean than in peanut. The differences in DF of ^{137}Cs between the two crops were found to have a similar trend to that for ^{137}Cs concentration (Figure 3). These results demonstrate that peanut has lower ^{137}Cs transportability from stems to leaves, shells, and grains than those of soybean, in addition to lower ^{137}Cs absorption and translocation from roots to shoots revealed by pot experiments.

Table 4. Concentrations and DFs of main nutrients in grain, shoots, and roots in peanut and soybean in pot experiment (Experiment 2).

		Grain		Shoot		Root	
		Peanut	Soybean	Peanut	Soybean	Peanut	Soybean
Concentration							
N	(mg g^{-1})	48.7	68.2 **	20.0	14.0 *	21.7	16.0 ns
K	(μg g^{-1})	6513	15,213 **	7905	6454 *	3731	2309 *
P	(μg g^{-1})	3281	3501 ns	999	736 *	1153	939 ns
Ca	(μg g^{-1})	612	2102 **	9775	12,579 **	5479	3692 **
Mg	(μg g^{-1})	2081	2132 ns	5653	5324 ns	3232	920 **
Fe	(μg g^{-1})	15.3	52.7 **	174	104 *	1143	2042 ns
Distribution factor							
N	(kg^{-1})	16.7	20.3 *	6.87	4.19 *	7.40	4.74 **
K	(kg^{-1})	8.19	16.56 **	9.94	7.03 *	4.7	2.5 *
P	(kg^{-1})	19.51	20.13 ns	5.93	4.24 *	6.85	5.38 ns
Ca	(kg^{-1})	0.78	2.69 **	12.41	16.08 **	6.94	4.72 **
Mg	(kg^{-1})	4.17	5.75 *	11.27	14.31 **	6.42	2.45 **
Fe	(kg^{-1})	0.86	2.51 *	9.70	4.62 **	63.8	92.8 ns

** and *, respectively, denote significant differences at $p < 0.01$ and $0.01 \le p < 0.05$. ns stands for not significant.

Table 5. Correlation coefficients between ^{133}Cs and main nutrients in concentrations and DFs in pot experiment (Experiment 2).

	Concentration				Distribution factor			
	Peanut		Soybean		Peanut		Soybean	
N	−0.443		−0.372		−0.439		−0.401	
K	−0.758	*	−0.598		−0.747	*	−0.637	
P	−0.403		−0.340		−0.413		−0.640	
Ca	0.076		−0.275		0.070		−0.300	
Mg	−0.052		−0.517		−0.066		−0.578	
Fe	0.987	**	0.841	**	0.982	**	0.794	*

** and *, respectively, denote significant differences at $p < 0.01$ and $0.01 \le p < 0.05$.

3.3. Relation of food nutrient elements to Cs accumulation (Experiment 2)

Nutrient element concentrations of the peanut and the soybean are shown in Table 4. In the respective grains, N, K, Ca, and Fe were significantly lower in peanut than in soybean. In shoots, peanut was found to have significantly lower Ca concentration and higher N, K, P, and Fe concentrations than soybean. In roots, the K, Ca, and Mg concentrations in peanut were significantly higher than in soybean. Differences in DF between crops for the respective plant tissues were similar to differences in concentrations. In grains, lower concentrations for many elements in peanut compared with soybean are consistent with the Food Composition Database (MEXT 2020). More detailed analysis is needed to determine why the concentrations of many elements including radiocesium are lower in the peanut than in the soybean.

The relation between ^{137}Cs and ^{133}Cs concentrations of all samples (root, shoot and grain) showed significant positive correlation ($r = 0.938$, $p < 0.01$, data are not shown in tables and figures). Correlation analyses between ^{133}Cs concentration and nutritional elements in respective crops are presented in Table 5. Concentrations and DF of K exhibited significant negative correlation with those of ^{133}Cs in peanut. Although the correlation was not significant, coefficients of correlation between K and ^{133}Cs concentrations ($r = -0.598$, $p = 0.089$) and between K and ^{133}Cs DFs ($r = -0.637$, $p = 0.065$) were also high in soybean. The negative correlations between K and ^{133}Cs concentrations in both crops are affected by the high ^{137}Cs DF in roots and the low ^{137}Cs DF in shoot relative to those of K (Table 3, Table 5). Although Cs absorption and translocation into plant bodies is similar and influenced by K ion because Cs and K belong to the same group in the periodic table (Burger and Lichtscheidl 2018), the results indicate that both crops partly discriminate K and Cs at the translocation from roots to shoots. Among shoot parts, the concentration of K was high in the stems of peanut (Table 4). Shimano, Mano, and Furuya (1976) also reported that the concentration of K was higher in stems than in leaves, shells, and grains in peanut. The distribution pattern of K is similar to that for ^{137}Cs evaluated for peanut in this study (Figure 2). The results suggest that Cs and K use similar translocation mechanisms in shoot parts in peanut. For elements other than K, correlation analysis for concentrations and DFs revealed that Fe has significant positive correlation with ^{133}Cs in many combinations for both crops (Table 5). Zhang et al. (2021) reported that family Fabaceae displayed significantly positive correlations among numerous minerals compared to families Rosaceae and Asteraceae in leaf samples. Their results also show significant and positive correlation between ^{133}Cs and Fe concentrations. Although more detailed analyses must be conducted, Cs absorption and translocation among plant parts might be related to the dynamics of other nutritional elements such as Fe in the peanut and the soybean.

3.4. Effects of potassium application on soil-grain radiocesium transfer in peanut and soybean (Experiment 3)

The TF of ^{137}Cs was significantly lower in peanut than in soybean (0.30 and 0.38 times lower in no-K and +K plots, respectively) in field experiments (Table 6). Interactions between the tested years and crops were not significant. From the results obtained for grain ^{137}Cs concentrations in pot and field experiments, this study confirmed that specific differences exist in the ability of radiocesium accumulation in grains of the leguminous crops, and that peanut had lower ability of radiocesium accumulation in grains than in soybean. In farmer fields in Fukushima Prefecture from 2011 to 2020, three municipalities (Date, Shinchi, and Soma) produced both crops, and inspected for radiocesium in 2011 (Fukushima Prefecture 2021). The ^{137}Cs concentration were tended to be lower in peanut than in soybean in all the municipalities, although there was only one data for peanut in every municipality (Table 7). These data acquired from farmer fields would support the findings of the present study.

Table 6. Transfer factor of ^{137}Cs, soil Ex^{137}Cs ratio, and soil ExK content in peanut and soybean at the harvest in field experiment (Experiment 3).

		Transfer factor	Soil Ex^{137}Cs (%)	Soil ExK (mg kg^{-1})
2019				
Peanut	no-K	0.021	13.3	145
Peanut	+K	0.014	8.11	169
Soybean	no-K	0.072	14.5	127
Soybean	+K	0.042	8.99	229
2020				
Peanut	no-K	0.032	10.3	166
Peanut	+K	0.013	9.0	242
Soybean	no-K	0.099	13.8	151
Soybean	+K	0.027	12.3	217
Year (Y)		ns	ns	*
Crop (C)		**	*	ns
Potassium (K)		**	**	**
Y × C		ns	ns	ns
Y × K		*	*	ns
C × K		**	ns	ns
Y × C × K		ns	ns	ns

** and *, respectively, denote significant differences at $p < 0.01$ and $0.01 \le p < 0.05$. ns stands for not significant.

Table 7. ^{137}Cs concentration (Bq kg^{-1}) of grain in peanut and soybean produced in farmer fields in same municipalities and same year.

	Date	Shinchi	Soma
Peanut	15	12	ND (<8.2)
Soybean	28	44	ND (<11)
Soybean	30	32	16
Soybean	23	35	32
Soybean	17	55	
Soybean	ND	20	

Inspected year was 2011. ND shows less than the lower limit of detection. The data were obtained from Fukushima Prefecture Agriculture, Forestry and Fisheries products processed food monitoring information (https://www.new-fukushima.jp/top).

In both crops, K application reduced TF significantly (Table 6) as well as rice, soybean, and buckwheat described in the Introduction. Interaction between the tested year and K application was significant. This is expected to be affected by differences in the timings of K application (at flowering stage in 2019, before cultivation in 2020). TF of +K plot were lower in 2020 (0.020) than 2019 (0.028). Immediately after the nuclear power plant accident, the fixation of radiocesium in the soil increased and TF decreased, but it is unlikely that the fixation of radiocesium in soil occurred in 2019–2020 (IAEA 2020). These results suggest that the effects of K application in decreasing TF were larger in application as basal fertilizer than as additional fertilizer at the flowering stage. The effectivity of K application with the basal fertilization to decrease TF has been demonstrated also for buckwheat (Kubo 2021), and has been consistent with those of current experiment. Interaction between crops and K application was also significant. The interaction is expected to be affected by the greater decrease of TF by K application in soybean than in peanut.

The soil Ex^{137}Cs ratio at maturity was significantly lower in peanut than in soybean (Table 6). Plants are thought to absorb exchangeable radiocesium while solubilizing radiocesium fixed in the soil with organic acids secreted by their roots and with associated microorganisms (Wendling et al. 2005; Chiang et al. 2011), as well as K solubilization from the soil (Meena et al. 2016). Actually, Ex^{133}Cs concentrations of rhizosphere soils tended to be higher (soybean 43.7 ± 0.9 μg kg^{-1}, peanut 40.4 ± 1.2 μg kg^{-1}, $n = 3$ for each crop) than in bulk soil (37.5 μg kg^{-1}, $n = 1$) as shown by the results of a pot experiment (data are not shown in tables and figure), which suggest the solubilization of Cs fixed in the soil. Conversely, ExK content of rhizosphere soils tended to be low (soybean 44.2 ± 1.7 mg kg^{-1}, peanut 60.8 ± 13.1 mg kg^{-1}, $n = 3$ for each crop) compared with bulk soil (86.4 mg kg^{-1}, $n = 1$), which might be related to the intense absorption of K relative to Cs in both crops. Eisenhauer et al. (2017) reported that increased root biomass (increased plant-diversity) brings increased root exudates and increased soil fungal biomass. In pot experiments conducted for this study, root DW was significantly greater in soybean (6.29 ± 0.67 g pot^{-1}) than in peanut (4.71 ± 0.45 g pot^{-1}) at $p < 0.05$ (data are not shown in tables and figures). From the results presented above, the roots of peanut might be less capable of solubilizing radiocesium fixed in the soil than those of soybean. Therefore, soil Ex^{137}Cs ratio around the plant of peanut was lower than that of soybean in the field experiment. The difference in compositions of root exudates between the peanut and the soybean might also be related to the difference in radiocesium solubilization capacity. The soil Ex^{137}Cs ratio also differed between no-K and +K plots. The +K plot was found to have significantly lower values (Table 6). This trend is similar to that reported for the effects of K application to the radiocesium transfer from soil to buckwheat (Kubo et al. 2017). Gommers, Thiry, and Delvaux (2005) and Thiry et al. (2005) have reported that the decreased ExK content can induce the release of Cs fixed at frayed edge sites of weathered mica. The application of K fertilizer promoted radiocesium fixation in soil and reducing the transfer of radiocesium to crops. Interaction between the tested year and K application was significant on soil Ex^{137}Cs ratio. It was affected by the greater reduction of soil Ex^{137}Cs ratio with K application in 2019 than in 2020. Regarding the difference between years, lower soil ExK content in 2019 (167 mg K_2O kg^{-1}) than in 2020 (194 mg K_2O kg^{-1}), and/or the difference of timing in K application might be related.

In conclusion, this study revealed the following three points.

(1) The ^{137}Cs absorption of peanut is mainly from roots, rather than from gynophores or fruits.
(2) Peanut has lower radiocesium absorption and lower radiocesium translocation from roots to shoots and from stems to fruits. The grain radiocesium concentration of peanut is lower than that of soybean.
(3) Potassium application in both crops decreased radiocesium transfer from soil to grains.

Further studies to elucidate differences in absorbability and transportability of ^{137}Cs between peanut and soybean are expected to be necessary. This study tested only one variety of peanut and two varieties of soybean. Although the specific differences in radiocesium accumulation are regarded as being greater than varietal difference in the respective crops, varietal differences in radiocesium accumulation among varieties should be confirmed.

Acknowledgments

We are grateful to the following staff at the NARO Tohoku Agricultural Research Center: Dr. Mitsuru Watanabe, Dr. Shigeto Fujimura, Dr. Hisaya Matsunami, Dr. Kyoko Takagi, Ms. Tomoko Saito, Ms. Yukari Watanabe, Ms. Michie Mimori and Ms. Yurie Yoshida for sample preparation, ^{137}Cs analyses, and critical reading of the manuscript. Mr. Michio Saito, Mr. Yukio Endo, Mr. Osamu Murata, Mr. Rikiya Kimura, Mr. Mitsuhiro Miura, Mr. Katsuya Matsuhashi, Mr. Takashi Shimada, Mr. Akihiro Takahashi, Mr. Junji Tanji, Mr. Masakatsu Ito, Mr. Rikio Shishido, Mr. Takao Sakurai, Mr. Masanori Yoshida, Mr. Tadashi Kan, Ms. Mai Aoto, Mr. Takahiro Oyama, Mr. Takao Ota, Mr. Mizuki Hirae and Taishi Tamauchi of NARO Technical Support Center for Tohoku Region also kindly supported field management.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was partly conducted under the 'Development of Decontamination Technologies for Radioactive Substances in Agricultural Land' and 'A Scheme to Revitalize Agriculture and Fisheries in Disaster Area through Deploying Highly Advanced Technology' projects funded by MAFF and 'Grant-in-Aid for Scientific Research (No. 15H02438 and 15K11961)' from the Japan Society for the Promotion of Science.

References

Barillot, C. D. C., C. O. Sarde, V. Bert, E. Tarnaud, and N. Cochet. 2013. "A Standardized Method for the Sampling of Rhizosphere and Rhizoplan Soil Bacteria Associated to A Herbaceous Root System." *Annals of Microbiology* 63 (2): 471–476. doi:10.1007/s13213-012-0491-y.

Bledsoe, R. W., C. L. Comar, and H. C. Harris. 1949. "Absorption of Radioactive Calcium by the Peanut Fruit." *Science* 109 (2831): 329–330. doi:10.1126/science.109.2831.329.

Bouchenak, M., and M. Lamri-Senhadji. 2013. "Nutritional Quality of Legumes, and Their Role in Cardiometabolic Risk Prevention: A Review." *Journal of Medicinal Food* 16 (3): 185–198. doi:10.1089/jmf.2011.0238.

Burger, A., and I. Lichtscheidl. 2018. "Stable and Radioactive Cesium: A Review about Distribution in the Environment, Uptake and Translocation in Plants, Plant Reactions and Plants' Potential for Bioremediation." *Science of Total Environment* 618: 1459–1485. doi:10.1016/j.scitotenv.2017.09.298.

Chiang, P. N., M. K. Wang, P. M. Huang, and J. J. Wang. 2011. "Effects of Low Molecular Weight Organic Acids on ^{137}Cs Release from Contaminated Soils." *Applied Radiation and Isotopes* 69 (6): 844–851. doi:10.1016/j.apradiso.2011.02.043.

Eisenhauer, N., A. Lanoue, T. Strecker, S. Scheu, K. Steinauer, M. P. Thakue, and L. Mommer. 2017. "Root Biomass and Exudates Link Plant Diversity with Soil Bacterial and Fungal Biomass." *Scientific Reports* 7 (1): 44641. doi:10.1038/srep44641.

FAO 2021a. "Nutritional Benefits of Pulses." Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/3/i5384e/i5384e.pdf

FAO 2021b. "Pulses Contribute to Food Security." Food and Agriculture Organization of the United Nations, Rome, Italy. http://www.fao.org/3/i5387e/I5387E.pdf

Foyer, C., H. M. Lam, H. Nguyen, K. H. M. Siddique, R. K. Varshney, T. D. Colmer, W. Cowling, et al. 2016. "Neglecting Legumes Has Compromised Human Health and Sustainable Food Production." *Nature Plants* 2 (8): 16112. doi:10.1038/nplants.2016.112.

Fujimura, S., J. Ishikawa, Y. Sakuma, T. Saito, M. Sato, and K. Yoshioka. 2014. "Theoretical Model of the Effect of Potassium on the Uptake of Radiocesium by Rice." *Journal of Environmental Radioactivity* 138: 122–131. doi:10.1016/j.jenvrad.2014.08.017.

Fujimura, S., T. Ishikawa, K. Kubo, and T. Ota. 2015. "Comparison of Radiocesium Distribution in Plant among Crops." *Abstract of the 239th Meeting of the CSSJ*. Nihon Univresity, 35. doi: 10.14829/jcsproc.239.0_35. (in Japanese with English title)

Fukushima Prefecture. 2021. "Fukushima Prefecture Agriculture, Forestry and Fisheries Products Processed Food Monitoring Information." https://www.new-fukushima.jp/top

Gommers, A., Y. Thiry, and B. Delvaux. 2005. "Rhizospheric Mobilization and Plant Uptake of Radiocesium from Weathered Micas. I. Influence of Potassium Depletion." *Journal of Environmental Quality* 34 (6): 2167–2173. doi:10.2134/jeq2004.0406.

Hachinohe, M., and T. Shinano. 2020. "Large-scale Agricultural Soil and Food Sampling and Radioactivity Analysis during Nuclear Emergencies in Japan: Development of Technical and Organisational Procedures for Soil and Food Sampling after the Accident." *Journal of Environmental Radioactivity* 220-221: 106265. doi:10.1016/j.jenvrad.2020.106265.

Hatano, R., H. Shinjo, and Y. Takata. 2021. *The Soil of Japan: 6. Tohoku Region, 185-244, World Soils Book Series*. Singapore: Springer Nature Singapore Pte . doi:10.1007/978-981-15-8229-5.

Hirayama, T., M. Takeuchi, H. Nakayama, and N. Nihei. 2018. "Effects of Decreasing Radiocesium Transfer from the Soil to Soybean Plants and Changing the Seed Nutrient Composition by the Increased Application of Potassium Fertilizer." *Bulletin of the Fukushima Agricultural Technology Centre* 9: 1–10. in Japanese with English abstract.

Hirayama, T., and S. Keitoku. 2014. "Differences of Transfer Factors of Radiocesium from Soil to Upland Field Crop." *Bulletin of the Fukushima Agricultural Technology Centre* 41–42. in Japanese with English title

IAEA. 2020. *Environmental Transfer of Radionuclides in Japan following the Accident at the Fukushima Daiichi Nuclear Power Plant. IAEA-TECDOC -1927*. Vienna, Austria: International Atomic Energy Agency.

Kato, N., N. Kihou, S. Fujimura, M. Ikeba, N. Miyazaki, Y. Saito, T. Eguchi, and S. Itoh. 2015. "Potassium Fertilizer and Other Materials as Countermeasures to Reduce Radiocesium Levels in Rice: Results of Urgent Experiments in 2011 Responding to the Fukushima Daiichi Nuclear Power Plant Accident." *Soil Science and Plant Nutrition* 61 (2): 179–190. doi:10.1080/00380768.2014.995584.

Kikuchi, A., Y. Kono, S. Kato, S. Yumoto, Y. Takada, S. Shimada, T. Sakai, et al. 2011. "A New Soybean Cultivar "Satonohohoemi", with High Protein Content, Lodging Resistance, Large Seed Size and Good Quality", *Bulletin of the National Agricultural Research Center for Tohoku Region* 113, 1–15. in Japanese with English abstract.

Kubo, K. 2021. "Decreasing Transfer of Radioactive Cesium and Resumption of Buckwheat Cultivation in Areas Where Evacuation Orders Were Lifted after the Nuclear Power Plant Accident Occurred in 2011." *Journal of NARO Research and Development* 8: 109–116. in Japanese with English summary.

Kubo, K., H. Kobayashi, K. Nemoto, T. Hirayama, H. Matsunami, Y. Ichihashi, T. Ota, S. Keitoku, and T. Shinano. 2016b. "Decreasing Radioactive Cesium in Lodged Buckwheat Grain after Harvest." *Plant Production Science* 19 (1): 91–95. doi:10.1080/1343943X.2015.1128104.

Kubo, K., H. Kobayashi, M. Fujita, T. Ota, Y. Minamiyama, Y. Watanabe, T. Nakajima, and T. Shinano. 2016a. "Varietal Differences in the Absorption and Partitioning of Cadmium in Common Wheat (*Triticum Aestivum* L.)." *Environmental and Experimental Botany* 124: 79–88. doi:10.1016/j.envexpbot.2015.12.007.

Kubo, K., H. Kobayashi, M. Nitta, S. Takenaka, S. Nasuda, S. Fujimura, K. Takagi, O. Nagata, T. Ota, and T. Shinano. 2020. "Variations in Radioactive Cesium Accumulation in Wheat Germplasm from Fields Affected by the 2011 Fukushima Nuclear Power Plant Accident." *Scientific Reports* 10 (1): 3744. doi:10.1038/s41598-020-60716-w.

Kubo, K., H. Kobayashi, R. Fujimoto, T. Ota, and T. Shinano. 2019. "Towards the Partial Resumption of Agriculture with Buckwheat Cultivation in Fields Physically Decontaminated of Radioactive Cesium after the Nuclear Power Plant Accident in 2011: A Case Study in Yamakiya District, Fukushima." *Plant Production Science* 22 (2): 159–167. doi:10.1080/1343943X.2018.1543546.

Kubo, K., K. Nemoto, H. Kobayashi, Y. Kuriyama, H. Harada, H. Matsunami, T. Eguchi, N. Kihou, T. Ota, and T. Shinano. 2015. "Analyses and Countermeasures for Decreasing Radioactive Cesium in Buckwheat in Areas Affected by the Nuclear Accident in 2011." *Field Crops Research* 170: 40–46. doi:10.1016/j.fcr.2014.10.001.

Kubo, K., S. Fujimura, H. Kobayashi, T. Ota, and T. Shinano. 2017. "Effect of Soil Exchangeable Potassium Content on Cesium Absorption and Partitioning in Buckwheat Grown in a Radioactive Cesium-contaminated Field." *Plant Production Science* 20: 396–405. doi:10.1080/1343943X.2017.1355737.

Kubo, K., T. Hirayama, S. Fujimura, T. Eguchi, N. Nihei, S. Hamamoto, M. Takeuchi, T. Saito, T. Ota, and T. Shinano. 2018. "Potassium Behavior and Clay Mineral Composition in the Soil with Low Effectiveness of Potassium Application." *Soil Science and Plant Nutrition* 64 (2): 265–271. doi:10.1080/00380768.2017.1419830.

MAFF. 2019. "Varietal Characteristics of Domestic Soybeans." https://www.maff.go.jp/j/seisan/ryutu/daizu/d_ziten/attach/pdf/index-21.pdf (In Japanese).

MAFF. 2020. "Results of Inspections on Radioactivity Levels in Agricultural Products." https://www.maff.go.jp/e/policies/food_safety/agri_gaiyo.html

Matsunami, H., T. Uchida, H. Kobayashi, T. Ota, and T. Shinano. 2021. "Comparative Dynamics of Potassium and Radiocesium in Soybean with Different Potassium Application Levels." *Journal of Environmental Radioactivity* 233: 106609. doi:10.1016/j.jenvrad.2021.106609.

Meena, V. S., I. Bahadur, B. R. Maurya, A. Kumar, R. K. Meena, S. K. Meena, and J. P. Verma. 2016. "Potassium-solubilizing Microorganism in Evergreen Agriculture: An Overview". In *Potassium Solubilizing Microorganisms for Sustainable Agriculture*. V. S. Meena, B. R. Maurya, J. Prakash Verma and R. S. Meena, edited by. 1–20. India: Springer. doi: 10.1007/978-81-322-2776-2_1.

MEXT. 2020. "Standard Tables of Food Composition in Japan." https://www.mext.go.jp/content/20201225-mxt_kagsei-mext_01110_012.xlsx (in Japanese with English title)

Ohara, T., Y. Morino, and A. Tanaka. 2011. "Atmospheric Behavior of Radioactive Materials from Fukushima Daiichi Nuclear Power Plant." *Journal of the National Institute of Public Health* 60: 292–294. in Japanese with English summary.

Peoples, M. B., J. Brockwell, D. F. Herridge, I. J. Rochester, B. J. R. Alves, S. Urquiaga, R. M. Boddey, et al. 2009. "The Contributions of Nitrogen-fixing Crop Legumes to the Productivity of Agricultural Systems." *Symbiosis* 48 (1–3): 1–17. doi:10.1007/BF03179980.

Reeves, T. G., G. Thomas, and G. Ramsay. 2014. *Save and Grow in Practice: Maize, Rice, Wheat. A Guide to Sustainable Cereal Production*. Rome, Italy: Food and Agriculture Organization of the United Nations.

Shimano, I., M. Mano, and T. Furuya. 1976. "Nutrient Absorption in Peanut." *Report of the Kyushu Branch of the Crop Science Society of Japan* 42: 9–11. in Japanese.

Shinano, T. 2016. "Mitigation of Radioactive Contamination from Farmland Environment and Agricultural Products." *Modern Environmental Science and Engineering* 2 (7): 454–461. doi:10.15341/mese(2333-2581)/07.02.2016/003.

Suzuki, K., T. Nakanishi, Y. Takahashi, T. Matsuda, Y. Iwata, S. Suzuki, R. Ishii, M. Kajiro, H. Matsura, and T. Yashiki. 1997. "On 'Satonoka,' a New Variety of Peanut (*Arachis Hypogaea* L.)." *Bulletin of the Chiba Prefectural Agricultural Experiment Station* 38: 55–66. in Japanese with English summary.

Thiry, Y., A. Gommers, A. Iserentant, and B. Delvaux. 2005. "Rhizospheric Mobilization and Plant Uptake of Radiocesium from Weathered Micas. II. Influence of Mineral Alterability." *Journal of Environmental Quality* 34 (6): 2174–2180. doi:10.2134/jeq2004.0407.

Uchida, S., and K. Tagami. 2018. "Comparison of Radiocesium Concentration Changes in Leguminous and Non-leguminous Herbaceous Plants Observed after the Fukushima Dai-ichi Nuclear Power Plant Accident." *Journal of Environmental Radioactivity* 186: 3–8. doi:10.1016/j.jenvrad.2017.08.016.

Wendling, L. A., J. B. Harsh, C. D. Palmer, M. A. Hamilton, H. M. Dion, J. S. Boyle, and M. Flury. 2005. "Rhizosphere Effects on Cesium Fixation Sites of Soil Containing Micaceous Clays." *Soil Science Society of America Journal* 69 (5): 1652–1657. doi:10.2136/sssaj2004.0286.

Zhang, C., S. Hiradate, Y. Kusumoto, S. Morita, T. F. Koyanagi, Q. Chu, and T. Watanabe. 2021. "Ionomic Responses of Local Plant Species to Natural Edaphic Mineral Variations." *Frontiers in Plant Science* 12: 614613. doi:10.3389/fpls.2021.614613.