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Effect of different Cs concentrations on overall plant growth and Cs distribution in soybean

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ABSTRACT

The absorption and dynamics of Cs in crops can be measured and examined using not only ^{137}Cs but also ^{133}Cs , a stable isotope which can be analyzed in a regular laboratory. When ^{133}Cs is used, however, the concentration of added ^{133}Cs must be set higher than that in the soil solution due to the detection sensitivity of inductively coupled plasma optical emission spectrometry (ICP-OES). There is concern that such high Cs concentrations may adversely affect crops and interfere with Cs dynamics. Using soybean as a test product, we first examined the initial growth of soybean cultivated under exposure to solutions with different ^{133}Cs concentrations. In combination with each ^{133}Cs concentration, two potassium (K) concentrations were tested. Results show that at both K concentrations, growth was inhibited under ^{133}Cs concentrations higher than $1 \times 10^{-3} \text{ mol L}^{-1}$. Soybeans cultivated at ^{133}Cs concentrations higher than $1 \times 10^{-6} \text{ mol L}^{-1}$ can be subject to ICP-OES for measuring ^{133}Cs concentrations in the plant tissue. Next, soybeans cultivated under different ^{133}Cs concentrations throughout growth were examined for Cs distribution in the plants. The distribution patterns of Cs in soybean plants cultivated at ^{133}Cs concentrations equivalent to those found in the soil were almost identical to those in plants cultivated at measurable ^{133}Cs concentrations (1×10^{-6} – $1 \times 10^{-4} \text{ mol L}^{-1}$) as measured with ICP-OES. Therefore, in our investigation, ^{133}Cs distribution in soybean plants treated with up to $1 \times 10^{-4} \text{ mol L}^{-1}$ was considered equivalent to that in plants cultivated in the field.

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Introduction

Large amounts of radioactive substances, particularly radocesium (RCs, $^{134}\text{Cs} + ^{137}\text{Cs}$), were released into the environment as a result of the accident at the Tokyo Electric Power Company Fukushima Daiichi Nuclear Power Plant. Ever since this disaster, there has been concern about the transmission of these radioactive substances from agricultural soils into crops (Yasunari et al., 2011; Zheng et al., 2014). To address these concerns, the dynamics of RCs in the agricultural environment and agricultural crops have been analyzed, and agricultural products have been subjected to monitoring and inspections since the accident (Kinoshita et al., 2011; Nihei et al., 2015). RCs concentrations can be measured with very high accuracy using an NaI (TI) scintillation detector or a germanium semiconductor detector, etc., and the reference value (100 Bq kg^{-1}) for agricultural distribution is equivalent to $3.1 \times 10^{-9} \text{ g kg}^{-1}$ for ^{137}Cs . Using the radioactive nuclide ^{137}Cs as a physiological tracer in plants enables the measurement of the Cs absorption rate and tissue distribution in crops as

well as competitive analysis with potassium (K), an alkali metal (Nobori et al., 2016). However, using ^{137}Cs as a tracer requires special permission for the use of a radionuclide and must be performed in a controlled facility that requires additional restrictions unrelated to radioactivity. ^{133}Cs , in contrast, is a stable isotope that exists in nature. The concentration of ^{133}Cs in polluted soil is approximately $7 \times 10^{-3} \text{ g kg}^{-1}$ (Nakai, 2001). Assuming that the partition coefficient K_d (solid phase Cs concentration/Cs solution concentration) is between 269 and $16,637 \text{ L kg}^{-1}$ (Ishikawa et al., 2007), ^{133}Cs concentrations in the soil solution and in crops are estimated to be 1×10^{-9} – $1 \times 10^{-7} \text{ mol L}^{-1}$, respectively (Willey & Martin, 1995). ^{133}Cs concentrations are measured by means of inductively coupled plasma optical emission spectrometry (ICP-OES), ICP mass spectrometry, and the atomic absorption method. The detection limit of Cs with ICP-OES, which can simultaneously perform multi-element analysis and is widely used for the analysis of inorganic elements, is approximately 1 ppm ($10^{-5} \text{ mol L}^{-1}$). Therefore, these techniques can only measure crop ^{133}Cs concentrations that are greater than concentrations

ordinarily present in nature. Because Cs is not an essential element for crops (Hampton et al., 2004), there is concern that growth may be inhibited in crops treated with high Cs concentrations in hydroponic cultures. In an effort to examine the dynamics of absorbed Cs in crops, we should examine whether Cs distribution in crops cultivated under high Cs concentrations is similar to that in samples cultivated at low Cs concentrations and comparable to that cultivated in the soil solution. In this study, we investigated whether high Cs concentrations affected crop growth and Cs distribution by treating plants with solutions containing varying Cs concentrations. Soybean was used as the test crop. In monitoring tests for RCs in Fukushima Prefecture, soybean plants have been shown to contain higher RCs concentrations than other crops (Nihei et al., 2016). It is thus urgent to clarify the factors responsible for this finding.

Materials and methods

Initial growth of soybean plants cultivated in solutions with varying ^{133}Cs concentrations (test I)

The effect of various ^{133}Cs concentrations in cultivation solutions on the initial growth of soybean plants (*Glycine max* cv. Enrei) was investigated. Soybean was sown in vermiculite. After germination, each sample was transplanted to a test solution (0.3 L) containing a predetermined concentration of ^{133}Cs . The ^{133}Cs concentration in each test solution was set to one of six levels (0 , 1×10^{-6} , 1×10^{-5} , 1×10^{-4} , 1×10^{-3} , and 1×10^{-2} mol L $^{-1}$) by the addition of $^{133}\text{CsCl}$. For each ^{133}Cs concentration, the K concentration was set to either 3×10^{-5} mol L $^{-1}$ (hereinafter referred to as low K condition) or 3×10^{-3} mol L $^{-1}$ (high K condition) by the addition of KCl. Elements other than ^{133}Cs and K were present at concentrations found in a half Hoagland composition (N: 8×10^{-3} mol L $^{-1}$, P: 1×10^{-3} mol L $^{-1}$, K: 3×10^{-3} mol L $^{-1}$, Ca: 2×10^{-3} mol L $^{-1}$, Mg: 0.5×10^{-3} mol L $^{-1}$). After transplanting, plants were cultivated for 14 days in a phytotron (16 h light/8 h dark, 28 °C), and the solution was changed once every three days. At the time of harvest, each soybean plant was divided into underground and aboveground parts (cotyledon leaves were removed), and the dry weight was measured after drying at 60 °C for 48 h. These treatments had four replications. To a sample weighing approximately 0.1 g, 10 mL of 60% nitric acid was added. The mixture was heated at 90 °C for 600 min to induce thermal decomposition. After this mixture was diluted to 20 mL with ultrapure water, filtration was conducted with a 0.2- μm membrane filter (Advantec, Japan), and ^{133}Cs , K, Ca, and Mg concentrations were measured using ICP-OES (Optima 7300, PerkinElmer Japan).

Differences in Cs distribution in soybean plants cultivated in solutions with varying ^{133}Cs concentrations (test II)

In an attempt to investigate whether the distribution of Cs in soybean plants was altered in samples cultivated under higher-than-normal ^{133}Cs concentrations, soybeans were grown to maturity under treatment with test solutions containing different ^{133}Cs concentrations, and the Cs concentration and the amount of Cs contained in soybean plants was measured. The concentration of ^{133}Cs in each test solution was set to one of seven levels (0 , 1×10^{-9} , 1×10^{-8} , 1×10^{-7} , 1×10^{-6} , 1×10^{-5} , and 1×10^{-4} mol L $^{-1}$) by the addition of $^{133}\text{CsCl}$. Because it was assumed that ^{133}Cs levels in soybean plants cultivated at ^{133}Cs concentrations close to those found in the soil solution (1×10^{-9} to 1×10^{-7} mol L $^{-1}$, Willey & Martin, 1995) could not be measured by ICP-OES, 100 Bq L^{-1} (2.3×10^{-13} mol L $^{-1}$) of ^{137}Cs was added to each solution as a tracer to measure the amount of Cs in each part of each soybean plant. Since the added quantity of ^{137}Cs was extremely small with respect to that of ^{133}Cs , the total amount of Cs added can be approximated as the amount of ^{133}Cs . Because the molecular weight of Cs is 130 or higher, ^{137}Cs and ^{133}Cs can be considered to exhibit the same chemical dynamics in the samples (Slat et al., 2004). Elements other than Cs were present in the solution at the concentrations found in a half Hoagland composition (N: 8×10^{-3} mol L $^{-1}$, P: 1×10^{-3} mol L $^{-1}$, K: 3×10^{-3} mol L $^{-1}$, Ca: 2×10^{-3} mol L $^{-1}$, and Mg: 0.5×10^{-3} mol L $^{-1}$). Soybean plants, after germination, were transplanted to a hydroponic solution (2.5 L) containing a predetermined element concentration. The hydroponic liquid was changed once a week. These treatments had three replications. In the latter part of the growing phase, an appropriate quantity of the hydroponic solution was added according to the transpiration rate of each soybean plant. Soybean plants were cultivated for 83 days within the phytotron (8 h light /16 h dark, 28 °C) in a radioisotope-controlled area until harvesting. To equalize conditions inside the phytotron (such as light exposure), the soybean containers were rotated weekly. Each cultivated soybean plant was divided into its parts (stem, leaf, petiole, pod, and seed), and the amount of ^{137}Cs in each part was measured with via NaI scintillation detector (ARC-300, Aloka, Japan). The dry weight was measured after drying at 60 °C for two days, and the ^{137}Cs distribution ratio and concentration in each part were calculated.

Results and discussion

Initial growth of soybean plants cultivated in solutions with varying ^{133}Cs concentrations (test I)

Figure 1 shows the dry weights of the aboveground and underground parts of soybean plants grown in solutions

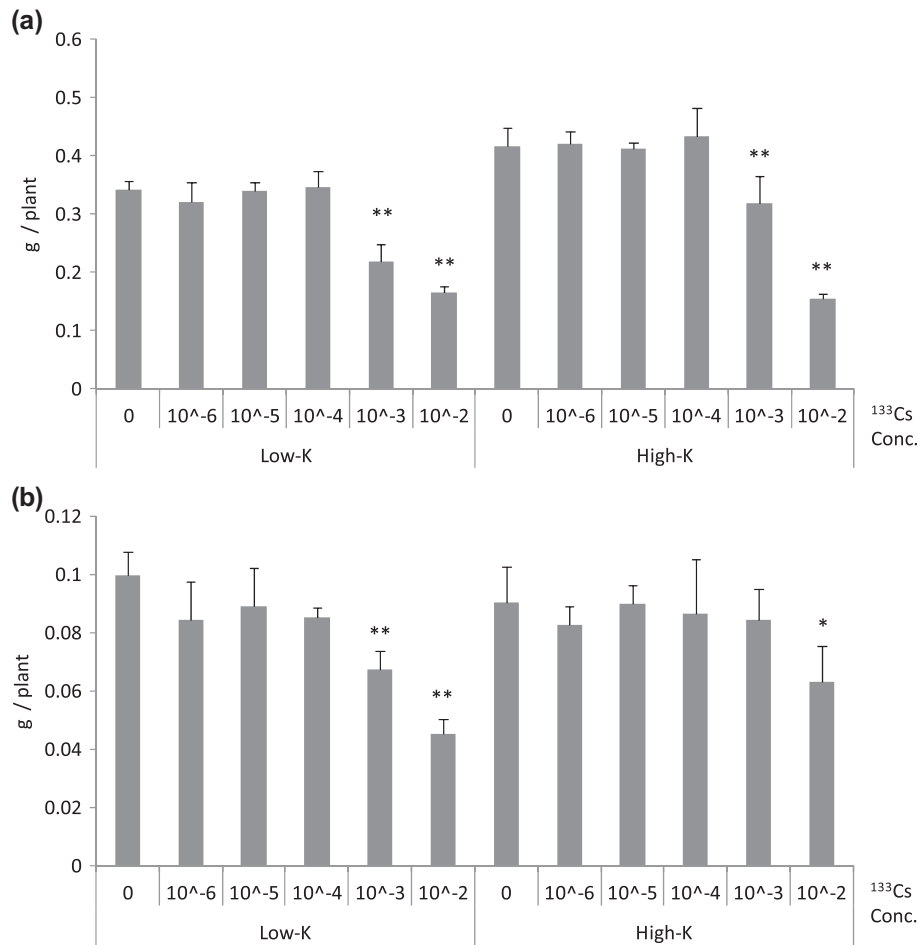


Figure 1. Dry weight of the aboveground and underground parts of soybean plants grown in solutions containing varying ^{133}Cs and K concentrations.

Notes: S and R represent aboveground parts and underground parts, respectively. Data are shown as mean \pm standard deviation. Asterisks (** $p < 0.01$, * $p < 0.05$) indicate a notable difference from $0 \mu\text{M}$ ^{133}Cs based on Dunnett's ANOVA test.

containing different ^{133}Cs concentrations. Soybean plants grown at ^{133}Cs concentrations between 0 and $1 \times 10^{-4} \text{ mol L}^{-1}$ had equivalent dry weights at both K concentrations. In soybean plants grown in ^{133}Cs concentrations higher than $1 \times 10^{-3} \text{ mol L}^{-1}$, the dry weights decreased by 35% under low K conditions and by 21% under high K conditions. Figure 2 shows ^{133}Cs and K concentrations in the aboveground and underground parts of soybean plants. Except for the underground parts grown at $1 \times 10^{-2} \text{ mol L}^{-1}$ of ^{133}Cs under low K conditions, the ^{133}Cs concentration in each plant part increased as the ^{133}Cs concentration increased, regardless of K condition. The K concentration, meanwhile, decreased at $1 \times 10^{-2} \text{ mol L}^{-1}$ of ^{133}Cs in the underground parts under low K conditions, at more than $1 \times 10^{-5} \text{ mol L}^{-1}$ of ^{133}Cs in the aboveground parts under high K conditions, and at more than $1 \times 10^{-3} \text{ mol L}^{-1}$ of ^{133}Cs in the underground parts under high K conditions. The Cs^+ ion has similar chemical properties to the K^+ ion and competes with the K^+ ion for cation binding sites in proteins (Hampton et al., 2004). Unfortunately, the Cs^+

ion does not behave identically to the K^+ ion and inhibits the activity of many K-activated enzymes (Avery, 1995). The Cs^+ ion also inhibits the inward-rectifying K channels in the plasma membranes of plant cells (White, 1997). Excessive Cs in the rhizosphere could therefore induce K starvation in plants (Hampton et al., 2004). Growth inhibition by ^{133}Cs in hydroponic solutions has been reported at concentrations of $1 \times 10^{-5} \text{ mol L}^{-1}$ in rice (Hasegawa, 2012) and $5 \times 10^{-5} \text{ mol L}^{-1}$ in *Arabidopsis thaliana* (Sheahan et al., 1993). In the present study, however, growth inhibition was observed only at concentrations higher than those reported previously ($1 \times 10^{-3} \text{ mol L}^{-1}$). This difference might be a result of difference test crops. In addition, in our study, each test solution contained not only ^{133}Cs but also K and other nutritional elements, whereas those used in previous reports (Hasegawa, 2012; Sheahan et al., 1993) contained only ^{133}Cs as a single salt. We speculate that these differences were among the factors responsible for differing in results. Further, it has been reported that Cs is analogous to K, in that the growth-inhibiting effect of

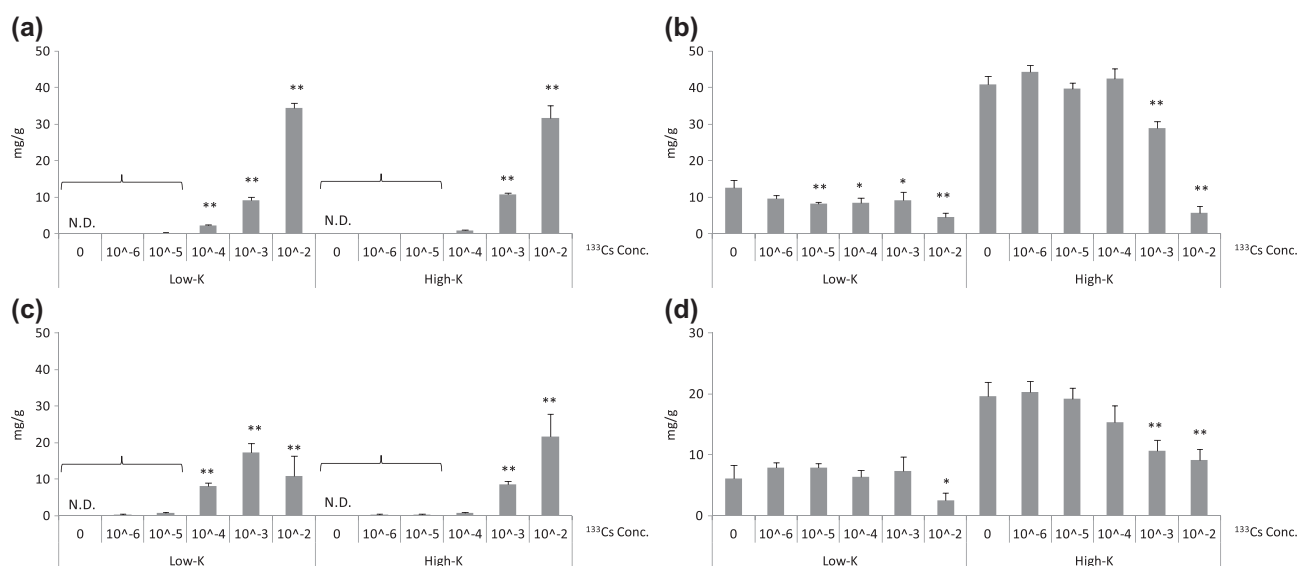


Figure 2. ^{133}Cs and K concentrations in the aboveground and underground parts of soybean plants grown in solutions containing varying ^{133}Cs and K concentrations. Data are shown as mean \pm standard deviation. (a) ^{137}Cs concentrations in aboveground, (b) K concentrations in aboveground, (c) ^{137}Cs concentrations in underground, and (d) K concentrations in underground.

Notes: Asterisks (** $p < 0.01$, * $p < 0.05$) indicate a notable difference from $10^{-6} \mu\text{M } ^{133}\text{Cs}$ in (a) and (c), and $0 \mu\text{M } ^{133}\text{Cs}$ in (b) and (d) based on Dunnett's ANOVA test.

Cs is mitigated by the presence of K and that the K concentration in crops affects Cs dynamics (Zhu & Smolders, 2000). With the exception of $1 \times 10^{-2} \text{ mol L}^{-1}$ of ^{133}Cs , which inhibited growth due to the significant elevation of Cs concentration, ^{133}Cs concentrations in the high K conditions were lower than those in the low K conditions. The growth inhibition that resulted from a ^{133}Cs concentration of $1 \times 10^{-3} \text{ mol L}^{-1}$ was also low in the high K conditions. In the aboveground plant parts, however, there was no difference in Cs concentration between the low and high K conditions. Further study is necessary to investigate detailed Cs dynamics. Moreover, accumulated ^{133}Cs in the aboveground parts of the crop at $1 \times 10^{-6} \text{ mol L}^{-1}$ was approximately $4 \times 10^{-2} \text{ g kg}^{-1}$. Under our decomposition conditions (approximately 0.1 g of soybean plant in 20 mL of decomposition solution), the ^{133}Cs concentration in the decomposition solution was approximately 1 ppm, and this concentration could be measured using ICP-OES. It should be considered that soybeans grown at ^{133}Cs concentrations between $1 \times 10^{-6} \text{ mol L}^{-1}$ and $1 \times 10^{-4} \text{ mol L}^{-1}$ do not experience inhibited growth, and can be measured with ICP-OES.

Differences in Cs distribution in soybean plants cultivated in solutions with varying ^{133}Cs concentrations (test II)

In order to compare Cs concentration of each soybean part, soybeans were cultivated under different ^{133}Cs concentrations ($0-1 \times 10^{-4} \text{ mol L}^{-1}$ solution) and at high K conditions ($3 \times 10^{-3} \text{ mol L}^{-1}$) until harvest. After the

disaster, farmers who cultivated soybeans in Fukushima Prefecture were recommended to fertilize potassium because it became clear that potassium fertilization was effective for reducing radiocesium concentrations in soybeans. As such, there are few potassium-deficient fields in Fukushima Prefecture. We considered that it is important to analyze Cs distribution in soybeans under the K conditions which soybeans are cultivated in Fukushima Prefecture, and test II was conducted under the high K condition. Figure 3 shows the ^{137}Cs concentrations in the various aboveground plant parts. The concentration of ^{137}Cs was $27-37 \text{ Bq kg}^{-1}$ in the stem, $24-33 \text{ Bq kg}^{-1}$ in the leaf, $26-37 \text{ Bq kg}^{-1}$ in the petiole, $13-21 \text{ Bq kg}^{-1}$ in the pod and $13-17 \text{ Bq kg}^{-1}$ in the seed. These concentrations were not significantly affected by increased ^{133}Cs concentrations in the solution. Figure 4 shows the weight and distribution ratio of ^{137}Cs for each part of the soybean plant. The weight distribution for each part in soybean plants grown at various Cs concentrations was 6–8% in the stem, 18–20% in the leaf, 2–3% in the petiole, 18–24% in the pod and 47–54% in the seed. The distribution rate of ^{137}Cs concentration was 9–15% in the stem, 24–32% in the leaf, 3–6% in the petiole, 17–19% in the pod and 36–44% in the seed. These ratios were not significantly affected by increased ^{133}Cs concentrations in the solution. Under our experimental K concentration, absorbed Cs distributions in soybean plant parts grown at high ^{133}Cs concentrations ($1 \times 10^{-6}-1 \times 10^{-4} \text{ mol L}^{-1}$) which can be measured by ICP-MS were similar to that in soybeans grown at low ^{133}Cs concentrations ($1 \times 10^{-9}-1 \times 10^{-7} \text{ mol L}^{-1}$), close to those found in the soil solution.

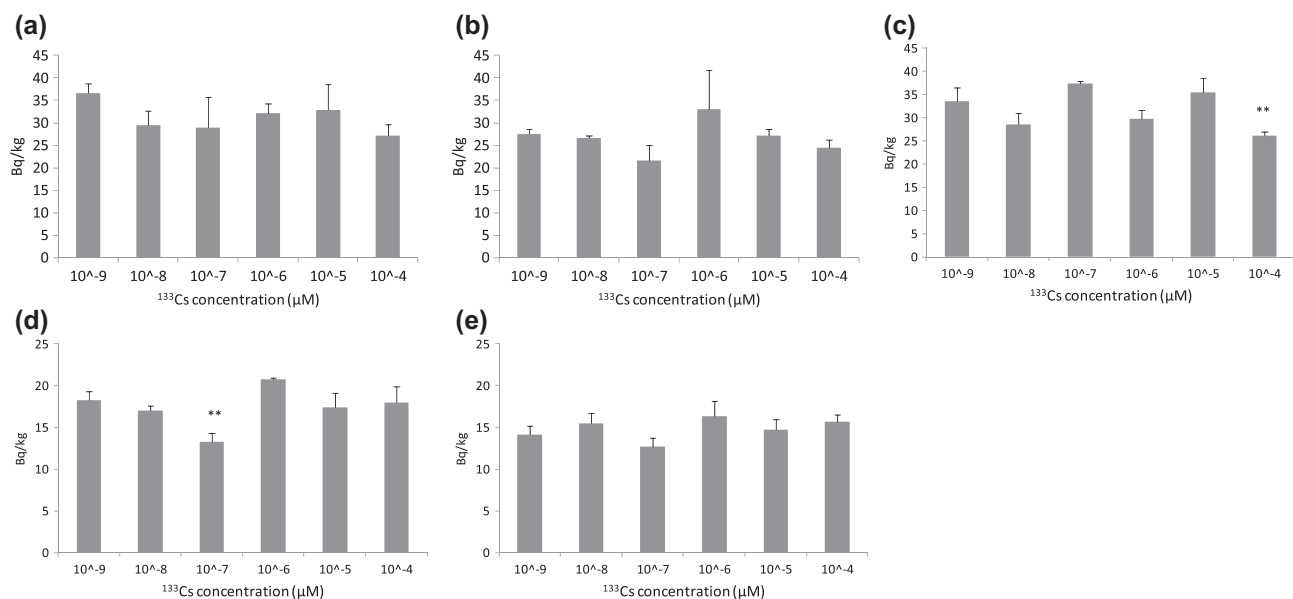


Figure 3. ^{137}Cs concentrations in the various parts of soybean plants treated with various ^{137}Cs concentrations in a hydroponic solution. (a)stem, (b)leaf, (c)petiole, (d)pod, (e)seed.

Notes: Asterisk (** $p < 0.01$) indicates a notable difference from 10^{-9} μM ^{137}Cs based on Dunnett's ANOVA test.

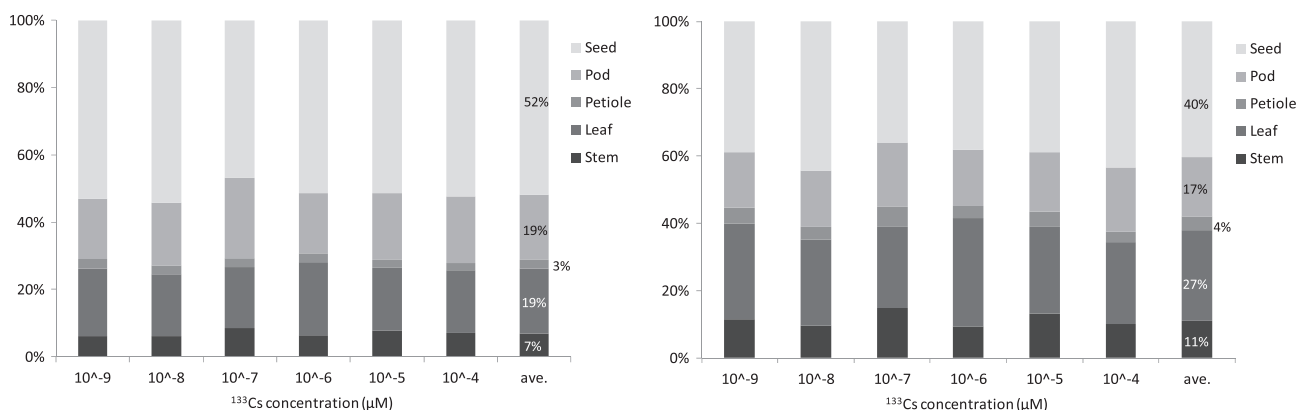


Figure 4. ^{137}Cs distribution rates in the various parts of soybean plants treated with various ^{137}Cs concentrations in a hydroponic solution. Left; distribution of weight, right; distribution of ^{137}Cs concentration.

These results lead to the conclusion that the distribution of Cs in soybean plants can be analyzed without the use of RI-controlled facilities under high ^{137}Cs concentration condition (1×10^{-6} – 1×10^{-4} mol L $^{-1}$) which do not inhibit soybean plant growth and are measurable with ICP-MS.

Disclosure statement

No potential conflict of interest was reported by the authors.

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References

- Avery, S. V. (1995). Caesium accumulation by microorganisms: Uptake mechanisms, cation competition, compartmentalization and toxicity. *Journal of Industrial Microbiology*, 14, 76–84.
- Hampton, C. R., Bowen, H. C., Broadley, M. R., Hammond, J. P., Mead, A., Payne, K. A., ... White, P. J. (2004). Cesium toxicity in arabidopsis. *Plant Physiology*, 136, 3824–3837.
- Hasegawa, H. (2012). Cesium and higher plants. *Journal of Crop Research*, 57, 1–6.
- Ishikawa, N., Uchida, S., & Tagami, K. (2007). Effects of clay minerals on radiocesium sorption behavior onto paddy field soils. *Radioisotopes*, 56(9), 519–528.
- Kinoshita, N., Sueki, K., Sasa, K., Kitagawa, J., Ikarashi, S., Nishimura, T., ... Yamagata, T. (2011). Assessment of

- individual radionuclide distributions from the Fukushima nuclear accident covering central-east Japan. *Proceedings of the National Academy of Sciences*, 108, 19526–19529.
- Nakai, S. (2001). Elemental composition of soils in Japan. *Chishitsu News*, 558, 48–55.
- Nihei, N., Tanoi, K., & Nakanishi, T. M. (2015). Inspections of radiocesium concentration levels in rice from Fukushima prefecture after the Fukushima Dai-ichi nuclear power plant accident. *Scientific Reports*, 5, 8653. doi:10.1038/srep08653
- Nihei, N., Tanoi, K., & Nakanishi, T. M. (2016). Monitoring inspection for radioCs in agricultural, livestock, forestry and fishery products in Fukushima prefecture. *Journal of Radioanalytical and Nuclear Chemistry*, 307, 2217–2220.
- Nobori, T., Kobayashi, N. I., Tanoi, K., & Nakanishi, T. M. (2016). Alteration in caesium behavior in rice caused by the K, phosphorous, and nitrogen deficiency. *Journal of Radioanalytical and Nuclear Chemistry*, 307, 1941–1943.
- Sheahan, J. J., Ribeiro, N. L., & Sussman, M. R. (1993). Cesium-insensitive mutants of *Arabidopsis thaliana*. *Plant Journal*, 3, 647–656.
- Slat, C. A., Kay, J. W., & Jarvis, K. E. (2004). The influence of season and leaf age on concentrations of radiocaesium (^{137}Cs), stable caesium (^{133}Cs) and potassium in *Agrostis capillaries*. *Environmental Pollution*, 130(3), 359–369.
- White, P. J. (1997). Cation channels in the plasma membrane of rye roots. *Journal of Experimental Botany*, 48, 499–514.
- Willey, N. J., & Martin, M. H. (1995). Annual patterns of Cs-133 concentration in british upland vegetation. *Chemosphere*, 30, 717–724.
- Yasunari, T. J., Stohl, A., Hayano, R. S., Burkhart, J. F., Eckhardt, S., & Yasunari, T. (2011). Cs-137 deposition and contamination of Japanese soils due to the Fukushima nuclear accident. *Proceedings of the National Academy of Sciences*, 108, 19530–19534.
- Zheng, J., Tagami, K., Bu, W., Uchida, S., Watanabe, Y., Kubota, Y., ... Ihara, S. (2014). ($^{135}\text{Cs}/^{137}\text{Cs}$) isotopic ratio as a new tracer of radioCs released from the Fukushima nuclear accident. *Environmental Science and Technology*, 48, 5433–5438.
- Zhu, Y. G., & Smolders, E. (2000). Plant uptake of radiocaesium: A review of mechanisms, regulation and application. *Journal of Experimental Botany*, 51, 1635–1645.