

# HOKKAIDO UNIVERSITY

Title	Comparative dynamics of potassium and radiocesium in soybean with different potassium application levels
Author(s)	Matsunami, Hisaya; Uchida, Tomoko; Kobayashi, Hiroyuki; Ota, Takeshi; Shinano, Takuro
Citation	Journal of environmental radioactivity, 233, 106609 https://doi.org/10.1016/j.jenvrad.2021.106609
Issue Date	2021-07
Doc URL	http://hdl.handle.net/2115/90115
Rights	© 2021. This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/
Rights(URL)	http://creativecommons.org/licenses/by-nc-nd/4.0/
Туре	article (author version)
File Information	Journal of environmental radioactivity_233_106609.pdf



Comparative dynamics of potassium and radiocesium in soybean with different potassium application levels

Hisaya Matsunami<sup>a,\*</sup>, Tomoko Uchida<sup>a,b</sup>, Hiroyuki Kobayashi<sup>a,c</sup>, Takeshi Ota<sup>a,d</sup>, Takuro Shinano<sup>a,e</sup>

<sup>a</sup>Agricultural Radiation Research Center, Tohoku Agricultural Research Center, NARO, 50 Harajuku-minami, Arai, Fukushima, Fukushima, 960-2156, Japan

<sup>b</sup>Division of Agro-Environment Research, Tohoku Agricultural Research Center, NARO, 4 Akahira, Shimo-kuriyagawa, Morioka, Iwate, 020-0198, Japan

<sup>c</sup>Center for Weed and Wildlife Management, Utsunomiya University, 350 Minemachi, Utsunomiya, Tochigi, 321-8505, Japan dBio-oriented Technology Research Advancement Institution, NARO, 8 Higashida-cho, Kawasaki, Kanagawa, 210-0005, Japan

<sup>e</sup>Research Faculty of Agriculture, Hokkaido University, Kita 9, Nishi 9, Kita-ku, Sapporo, Hokkaido, 060-8589, Japan

Correspondence and requests for materials should be addressed to H.M. (hisaya@affrc.go.jp).

# 1 ABSTRACT

 $\mathbf{2}$ We conducted a field experiment in soybean with different levels of K application to elucidate the comparative dynamics of <sup>137</sup>Cs and K. The inventory of K in the shoots increased 3 substantially from the fifth trifoliate stage to the full seed stage, and as the absorption of K 4 increased, so too did the absorption of <sup>137</sup>Cs. Overall, the effect of K application was much  $\mathbf{5}$ greater in terms of <sup>137</sup>Cs dynamics than K dynamics or biomass production. K application 6 reduced not only the accumulation of <sup>137</sup>Cs in the shoots, but also the distribution of <sup>137</sup>Cs to  $\overline{7}$ the grains. However, the decrease of <sup>137</sup>Cs distribution to the grain had a much smaller effect 8 on <sup>137</sup>Cs accumulation in the grains than <sup>137</sup>Cs absorption. A positive correlation was also 9 observed between the exchangeable <sup>137</sup>Cs/K ratio in the soil and the <sup>137</sup>Cs/K ratio in the shoots, 10 and the <sup>137</sup>Cs/K ratios in the shoots at the full seed and full maturity stage were much higher 11 than those at the fifth trifoliate and full bloom stage under the same exchangeable <sup>137</sup>Cs/K ratio 12in the soil. These findings suggest a decrease in the discrimination of <sup>137</sup>Cs from K during 13absorption after the full bloom stage. As a result of this and the increase in soil-exchangeable 14<sup>137</sup>Cs/K, radiocesium was more transferable to the shoots after the full bloom stage. Overall, 15these results suggest that lowering the soil-exchangeable radiocesium /potassium ratio after the 1617full bloom stage by increasing K availability could efficiently reduce the transfer of radiocesium 18 to the grains.

19

# 20 Key words: Comparative dynamics, Potassium, Radiocesium, Soybean

- 21
- 23

- 24
- 25

## 1 1. Introduction

 $\mathbf{2}$ The accident at Tokyo Electric Company's Fukushima Dai-ichi Nuclear Power Plant (FDNPP), caused by the Great East Japan Earthquake and subsequent Tsunami in March 2011, 3 resulted in widespread contamination of agricultural land in eastern Japan with radionuclides, 4 particularly in parts of Fukushima Prefecture. Immediately after the accident, the major  $\mathbf{5}$ radionuclides found in plants and environmental resources, such as soil and water, were <sup>131</sup>I and 6 radiocesium (<sup>134</sup>Cs and <sup>137</sup>Cs). Although <sup>131</sup>I (half-life: 8 days) decays within a few months,  $\overline{7}$ radiocesium is retained in the soil for much longer because of the length of the <sup>137</sup>Cs half-life 8 9 (30.2 years), and its transfer to crops is therefore a long-term problem. With some exceptions, 10 the Japanese government commissioned physical decontamination works, which included topsoil (depth of 15 cm) removal and soil inversion for soils exceeding 5 kBq kg dry weight of 11 radiocesium (Yamaguchi et al. 2016). Ten years have passed since the accident and all 12decontamination work has been completed, except in some difficult-to-return zones near the 13FDNPP, where the annual cumulative radiation doses are greater than 50 mSv, and entry and 14lodging are prohibited. 15

Studies on the absorption and accumulation of radiocesium in crops since the accident 16have shown that potassium fertilization is the most effective and practical countermeasure for 1718 reducing radiocesium transfer from the soil to the edible parts of crops. Because cesium has similar chemical and physiological characteristics to potassium, both potassium and cesium are 19expected to have similar behaviors in soil-plant systems, and cesium absorption from the soil 20is competitively decreased by the application of potassium fertilizer (Shaw and Bell 1991; 21Smolders et al. 1997). In paddy rice (Oryza sativa L.), radiocesium transfer to the grains 22decreased with increasing exchangeable potassium (1 mol  $L^{-1}$  ammonium acetate extractable 23potassium) concentrations in the soil (Tsukada et al. 2002a; Kato et al. 2015), with similar 24results obtained in buckwheat (Fagopyrum esculentum Moench) and vegetables (Kobayashi 25

26 2014; Kobayashi et al. 2014; MAFF 2014; Kubo et al. 2015, 2017). Thus, the additional 27 application of potassium fertilizer has been widely implemented in low-contamination areas 28 (<5 kBq kg<sup>-1</sup> dry weight of radiocesium) and decontaminated areas. Information about the 29 various case studies and the countermeasures published on websites and in technical reports in 30 the early stages after the accident has been summarized by Yamaguchi et al. (2016).

Soybean (Glycine max (Merr.) L.) is one of the most important crops in Japan, with almost 31all being used in food processing, notably tofu production, which is made by concentrating soy 32protein. Other important soybean products, such as miso and soy sauce, which are essential 33 seasonings in traditional Japanese cooking, are produced via fermentation. Immediately after 3435 the accident, we conducted a survey of exchangeable potassium concentrations in the soil and 36 radiocesium concentrations in soybean grains to determine the level of soil-exchangeable potassium required to minimize the radiocesium concentrations. Accordingly, a negative 37correlation was observed between the soil-exchangeable potassium concentration and the soil-38 to-grain transfer factor (TF) of radiocesium, which is expressed as a ratio of radioactivity in the 39grains to that in the soil (Bq kg<sup>-1</sup> (Bq kg<sup>-1</sup>)<sup>-1</sup>) (MAFF 2015). Based on these results, an 40 exchangeable potassium concentration of  $\geq 250 \text{ mg kg}^{-1}$  of K<sub>2</sub>O in the soil prior to the use of 41 42basal fertilizer at a conventional rate is now widely recommended in soybean cultivation, except 43during initial cultivation after the accident or in fields with a high TF, where the recommended application level was increased to 500 mg kg<sup>-1</sup> of K<sub>2</sub>O (MAFF 2015). The rate of additional 44 potassium fertilizer application is calculated from the exchangeable potassium concentration of 45the soil before cultivation, assuming a soil bulk density of 1.0 Mg  $m^{-3}$  and soil depth of 15 cm. 46 As a result, the percentage of soybean grains exceeding the present standard limits (100 Bq kg<sup>-1</sup> 4748 fresh weight for radiocesium in food, established by the Japanese Ministry of Health, Labor and Welfare in April 2012) has decreased annually, and the radiocesium concentration in soybean 49grains has not exceeded this limit since 2015 (Japanese Ministry of Agriculture, Forestry and 50

Fisheries). According to the MAFF (2015), the exchangeable potassium concentration of the 5152soil is relatively low in fields where the radiocesium concentration of the soybean grains exceeds the above limit before 2015. Although additional potassium fertilization is a primary 53factor in reducing the percentage of soybean grains exceeding this limit, the decrease in soil-54exchangeable radiocesium concentrations due to physical decay and fixation to clay minerals 55in the soil (Tsumura et al. 1984; Ehlken and Kirchner 2002) has also contributed to the reduction. 56Radiocesium transfer from the soil to the edible parts of a plant has been widely studied, 57but most research has focused on radiocesium, with few reports on the comparative dynamics 58of radiocesium and potassium. Cesium and potassium are expected to have similar behaviors 5960 in soil-plant systems; however, the radiocesium/potassium ratio is not uniform in paddy rice, indicating different behaviors (Tsumura et al. 1984; Tsukada et al. 2002b; Kondo et al. 2015). 61 Soybean and buckwheat show considerably high TF of <sup>134</sup>Cs (Broadley and Willey 1997), and 62 63 monitoring inspections after the accident also indicated that the percentage of soybean grains exceeding the limit was higher compared with other crops (Nihei and Hamamoto 2019). 64 Potassium application is costly and labor-intensive; therefore, it is important to understand the 65 behavior of potassium and radiocesium in soybean soil-plant systems to establish strategies for 66 reducing radiocesium concentrations with minimal labor and cost. In the present study, we 67 therefore examined the comparative dynamics of radiocesium (<sup>137</sup>Cs) and potassium (K) in 68 soybean. To do so, we conducted a field experiment with five levels of soil-exchangeable K and 69 examined the variability in the absorption and distribution of <sup>137</sup>Cs compared with K. 70

- 71
- 72 **2. Materials and Methods**
- 73

# 74 2.1. Field management and experimental design

The field experiment was conducted in the city of Date in Fukushima Prefecture in 2015. The soil type in the field was gray lowland soil based on the classification of cultivated soils in Japan. The soil texture was sandy clay (27.0% clay, 7.5% silt, and 65.5% sand), and the  $^{137}$ Cs concentration from the surface to a depth of 15 cm was 2.74 kBq kg<sup>-1</sup> in mid-May, 2015. The physical and chemical properties of the soil are shown in Table 1.

Although the additional application of K fertilizer had been widely implemented before 80 the conventional rate of basal fertilizer was applied, the additional K fertilizer was applied 81 together with the basal dressing of K fertilizer (80 mg kg<sup>-1</sup> soil of K<sub>2</sub>O, assuming that the soil 82 bulk density was 1.0 Mg m<sup>-3</sup> and soil depth was 15 cm) in this study. One of the following five 83 84 levels of soil-exchangeable K was applied to the plots prior to cultivation: no K fertilization (K0), 230 (K230), 380 (K380), 580 (K580), and 780 mg kg<sup>-1</sup> K<sub>2</sub>O (K780). For all plots, a 85 conventional rate of N and P were applied as follows:  $20 \text{ mg Kg}^{-1}$  of N and  $80 \text{ mg Kg}^{-1}$  of P<sub>2</sub>O<sub>5</sub> 86 as basal dressing on 3 June 2015, followed by 40 mg  $kg^{-1}$  of N as top dressing on 29 July. 87

The experimental design was a randomized complete block with three replications. The area of each plot was  $27.3 \text{ m}^2$ . The soybean cultivar 'Tachinagaha' was sown at a density of 50 kg seed ha<sup>-1</sup> just after the application of basal dressing (3 June). The hill space between planted rows was 0.7 m.

92

# 93 2.2. Sample collection, sample preparation, and chemical analysis

The soybean shoots were sampled at the fifth trifoliate stage (9 July), the full bloom stage (28 July), the full seed stage (17 September), and the full maturity stage (20 October), hereafter referred to as V5, R2, R6, and R8, respectively. After sampling at the R6 growth stage, the shoots were covered with a polyethylene mesh bag (Nandemo-kaisyubukuro, Nihon Matai Co., Ltd., Japan; 6 mm mesh, 100 × 120 cm) to collect fallen leaves. The leaves turned yellow after the R6 growth stage, and most had fallen by the R8 growth stage; thus, the leaves collected at

this late stage all represented fallen leaves. The shoots were divided into three parts (leaf blade, 100101 petiole, and stem) at the V5 and R2 growth stages, and into five parts (leaf blade, petiole, stem, pod, and grain) at the R6 and R8 growth stages. Then, the samples were washed with tap water 102103 and dried for at least 48 h at 80°C in a ventilated oven. After drying, the dry weight of the samples was measured. The dried samples were cut using a cutting mill (SM300, Retsch, 104105Germany) with a 4-mm bottom sieve, after which a portion of the samples was pulverized with 106 a blender (D3V-10, Osaka Chemical Co., Japan) and used for gamma-ray spectrometry. About 107 0.2 mg of the pulverized samples was digested with 2.5 mL of nitric acid and 0.5 mL of hydrogen peroxide using the heat block acid digestion system (DigiPREP LS, SCP SCIENCE, 108 109 Canada). The acid digests were used to determine the K concentrations of the plant samples using inductively coupled plasma-atomic emission spectroscopy (ICP-AES; Vista-MPX, Varian, 110USA). 111

Soil from the surface to a depth of 15 cm was sampled with a round worm scoop (Fujiwara 112Scientific Company Co., Ltd., Japan) at the same time the plants were sampled. Soil samples 113were collected from 10 points in each plot and combined to make a composite sample. After 114visible plant residues and stones were removed, the soil samples were air-dried and passed 115through a 2-mm sieve using a Dust Shield Automatic Mill and Screen for Soil RK4II (DIK-1162610, Daiki Rika Kogyo Co., Ltd., Japan). Exchangeable <sup>137</sup>Cs was extracted at a soil-to-117solution ratio of 1:10 in 1 mol  $L^{-1}$  ammonium acetate (pH 7.0) with shaking for 1 h, according 118 to Tsukada et al. (2008). The sieved soil samples and the ammonium acetate extracts were then 119 used for gamma-ray spectrometry. Exchangeable K was extracted using 1 mol  $L^{-1}$  ammonium 120acetate at a soil-to-solution ratio of 1:20 with 1 h shaking and the concentration of K was 121122determined via ICP-AES.

123

#### 124 2.3. Gamma-ray spectrometry

The <sup>137</sup>Cs concentrations of the plant and soil samples were determined using high-purity 125germanium detectors (GC2520-7500SL and GC4020-7500SL, Canberra, USA). The <sup>137</sup>Cs 126concentrations of the plant samples were measured using a 0.7 L Marinelli beaker or cylindrical 127128 polypropylene container (U-8 container, 65 mm in height and 50 mm in diameter; RIG, Japan). The <sup>137</sup>Cs concentrations of the soil and ammonium acetate extracts (for determining 129exchangeable <sup>137</sup>Cs) were measured directly in a U-8 container and 0.7 L Marinelli beaker, 130 respectively, using gamma lines at 661.6 keV. The counting uncertainties of <sup>137</sup>Cs were kept 131lower than 10% and concentrations were time-corrected on each sampling day. 132

133

# 134 2.4. Statistical analysis

All statistical analyses were conducted using statistical software (BellCurve for Excel ver. 3.00, Social Survey Research Information Co., Ltd., Japan). Analysis of variance (ANOVA) followed by Tukey's multiple comparison test at P < 0.05 was used to determine the significance of differences between treatments.

139

140 **3. Results** 

141

142 **3.1. Plant growth** 

Figure 1 shows the dry weights and distribution patterns of the dry weights of the shoots. The dry weight of the shoots increased dramatically from the R2 to the R6 growth stage (Fig. 1a, Table S1 in supplementary material) and the weight of the grains at the R8 growth stage was 1.7 to 2.2 times higher than that at the R6 growth stage (Fig. 1a, Table S1), with 42% of the 147 total weight of the shoots represented by the grains at the R8 stage (Fig. 1b). K application did 148 not affect the dry weight or distribution patterns of the dry weights of the shoots at any growth 149 stage. 150

# 151 **3.2.** *K* and <sup>137</sup>*C*s inventory and distribution in the shoots

Figures 2 and 3 show the inventory and distribution patterns of K and <sup>137</sup>Cs in the shoots, respectively, while the corresponding numerical data are in Table S2 and S3 in supplementary material, respectively. The inventory of K in the shoots increased greatly from the V5 to the R6 growth stage (Fig. 2a). From the R6 to the R8 growth stages, the inventory of K increased in the grains and decreased in all other parts of the shoot, regardless of the K application level. The decrease in the inventory of K was higher in the leaf blades and stems than in the petioles and pods.

The inventory of K in the shoots increased with K application, and was 1.46 times greater under K780 treatment than under K0 treatment (Fig. 2a). K application did not affect the distribution pattern of K in the shoots until the R2 growth stage (Fig. 3a); however, at the R6 and R8 growth stages, as the application level of K increased, the distribution of K tended to decrease in the grains and increase in all other parts of the shoot. At the R8 growth stage, 47% to 56% of the total inventory of K in the shoots was distributed in the grains.

The inventory of <sup>137</sup>Cs in the shoots increased sharply from the R2 to the R6 growth stage 165(Fig. 2b). Compared with K, <sup>137</sup>Cs was distributed more in the leaf blades and less in the grains 166 at the R6 and R8 growth stages, and the distribution percentage of <sup>137</sup>Cs to the grains was less 167 than 38% of the total inventory (Fig. 3b). At all growth stages, the total inventory of <sup>137</sup>Cs in 168 the shoots decreased with the increase in K application level (Fig. 2b). Although K application 169 reduced the inventories of <sup>137</sup>Cs in each part of the shoot, the sensitivity to K application differed 170 among parts. The rates of decrease in the inventories of <sup>137</sup>Cs at the R6 and R8 growth stages 171were highest in the grains and pods, followed by the petioles and stems, and were lowest in the 172leaf blades (Fig. 2b). Therefore, as the K application level increased, <sup>137</sup>Cs was distributed to 173the leaf blades rather than to the grains and pods (Fig. 3b). 174

175

176 **3.3.** *K* and <sup>137</sup>Cs concentrations in the grains

Table 2 shows the concentrations of K and <sup>137</sup>Cs in the grains. The K concentration in the 177grains was about 20 g kg<sup>-1</sup> dry weight at the R6 and the R8 growth stages, regardless of the K 178application level. In contrast, the <sup>137</sup>Cs concentration in the grains at the R6 and R8 growth 179stages decreased with the increase in K application level, and the effect of K application on the 180<sup>137</sup>Cs concentration in the grain was unclear when the targeted soil-exchangeable K 181 concentration before the cultivation was greater than 380 mg kg<sup>-1</sup> of K<sub>2</sub>O. The TF ranged from 1820.0015 to 0.0237 at the R8 growth stage, and was dependent on the K application level (data 183184 not shown).

185

# 186 **3.4.** $^{137}Cs/K$ ratios in the plants

Table 3 shows the  ${}^{137}$ Cs/K ratio of each plant part. The ratio was highest in the leaf blade throughout cultivation, and although values at the R6 growth stage were similar in all parts of the shoot except the leaf blade, the ratio of the grains tended to be lower than all other parts at the R8 growth stage. The  ${}^{137}$ Cs/K ratio of the grains at the R8 growth stage was slightly lower than that at the R6 growth stage, whereas in all other parts of the shoot, the ratio increased. K application caused a reduction in the  ${}^{137}$ Cs/K ratio in all parts of the shoot.

193

# 194 **3.5.** Exchangeable K and <sup>137</sup>Cs concentrations in the soil

Table 4 shows the concentrations of exchangeable K and <sup>137</sup>Cs in the soil, both of which can be absorbed by crops. As growth progressed, the exchangeable K concentration decreased except under K0 treatment, whereas exchangeable <sup>137</sup>Cs tended to increase. At all growth stages, higher K application levels increased the exchangeable K concentration and decreased the exchangeable <sup>137</sup>Cs concentration. Consequently, the exchangeable <sup>137</sup>Cs/K ratio tended to increase with growth and decrease with increasing K application level at all growth stages.

201

# 3.6. Relationship between the <sup>137</sup>Cs/K ratio in the shoots and exchangeable <sup>137</sup>Cs/K ratio in the soil

The relationship between the <sup>137</sup>Cs/K ratio in the shoots (Table 3) and exchangeable 204205<sup>137</sup>Cs/K ratio in the soil (Table 4) is shown in Fig. 4. A positive correlation was observed between the <sup>137</sup>Cs/K ratio in the shoots and the exchangeable <sup>137</sup>Cs/K ratio in the soil for each 206 growth stage ( $r^2 > 0.98$ ), and the relationship was expressed as a linear regression equation (Y 207and X representing the <sup>137</sup>Cs/K ratio in the shoots and exchangeable <sup>137</sup>Cs/K ratio in the soil, 208respectively) passing through the origin with a specific regression coefficient (slope). Moreover, 209the slope of the regression line for the shoots was almost twice as high at the R6 and R8 growth 210stages than the V5 and R2 growth stages. 211

212

# 213 **4. Discussion**

The dry weight of the shoots increased significantly from the R2 to the R6 growth stage 214(Fig. 1a). The inventories of K and <sup>137</sup>Cs in the shoots increased remarkably with this increase 215216in the dry weight (Figs. 1a and 2). Harper (1971) reported that the maximum rate of nutrient uptake occurred during the R2 and R5 growth stages. Thus, nutrient accumulation in the shoots 217coincides closely with dry matter accumulation. The rapid increase in K demand after the R2 218219growth stage (full bloom stage) reflects the overlap of vegetative growth (the production of leaves and stems) and reproductive growth (production of grains) (Fig. 1a). Both K and Cs 220belong to the same alkali metal group and are absorbed competitively (Shaw and Bell 1991), 221suggesting that Cs is absorbed by the K transport system (Zhu and Smolders 2000; White and 222

Broadley 2000). Thus, as the absorption of K increased, the absorption of <sup>137</sup>Cs may also have increased.

The K concentration in the grains was relatively constant, regardless of the K application 225level (Table 2). In line with this, a previous study showed that the nutrient composition (K, Mg, 226Ca, Na, and P) and nutritional value (proteins, lipids, and total sugars) of soybean grains were 227not affected by K application (Hirayama et al. 2018), with a similar result also reported in paddy 228229rice (Tsukada et al. 2002a). These results suggest that the dynamics of K in soybean is determined by stoichiometric homeostasis, that is, the ability of plants to maintain a relatively 230stable element composition regardless of changes in nutrient availability. The K concentration 231of the soybean grains was approximately 20 g kg<sup>-1</sup> dry weight (Table 2), whereas that of paddy 232rice grain was about 2 g kg<sup>-1</sup> dry weight (Kato et al. 2015). Furthermore, 47% to 56% of the 233total inventory of K in the soybean shoots was distributed to the grains (Fig. 3a), whereas in 234paddy rice, the distribution of K to the grains was less than 13% of the shoots (Ishikawa et al. 2352018). This is probably because paddy rice grains accumulate K in the embryo, which is only a 236small part of the grains, whereas soybean grains accumulate K in the cotyledon, the largest part 237of the grain (Nihei et al. 2017). When grown under identical soil, the radiocesium concentration 238239of the soybean grains is likely to be higher than that of paddy rice given that the localization of 240Cs and K in the soybean grains is similar (Nihei et al. 2017).

The effect of K application was much greater in terms of the <sup>137</sup>Cs dynamics than those of K or biomass production (Figs. 1, 2 and 3). At all growth stages, the total inventory of <sup>137</sup>Cs in the shoots decreased with the increase in K application level (Fig. 2b), and no apparent effect of K application on <sup>137</sup>Cs accumulation in the shoots was observed when the targeted soilexchangeable K concentration before the cultivation was higher than 380 mg kg<sup>-1</sup> of K<sub>2</sub>O (Fig. 2b). Moreover, <sup>137</sup>Cs was distributed to the leaf blades rather than the grains as the application level of K increased (Fig. 3b). In paddy rice, the ratio of Cs in the brown rice to that in the straw was negatively correlated with the soil K level, suggesting that the proportion of Cs accumulation in the brown rice to that in the whole plant increased under low soil K conditions (Ishikawa et al. 2018). The present results suggest that K application decreased not only the accumulation of <sup>137</sup>Cs in the shoots but also the distribution of <sup>137</sup>Cs to the grains. However, the decrease of <sup>137</sup>Cs distribution to the grain had a much smaller effect than that of <sup>137</sup>Cs root absorption (Fig. 2b and 3b). Overall, the main factor affecting the reduction in <sup>137</sup>Cs accumulation in the grains was the reduction in <sup>137</sup>Cs absorption with K application.

At all growth stages, higher K application levels increased the exchangeable K concentration 255and decreased the exchangeable <sup>137</sup>Cs concentration (Table 4). This result suggest that the 256exchangeable <sup>137</sup>Cs concentration increases as the exchangeable K concentration in the soil 257decreases, which is line with previous findings (Kubo et al. 2015; Ishikawa et al. 2018). Cs in 258the soil is selectively fixed at frayed edge sites (FES) (Sawhney 1972; Cremers 1988), and when 259260the exchangeable K concentration in the soil decreases, Cs fixed in the FES should be released (Gommers et al. 2005; Thiry et al. 2005). Here, the exchangeable <sup>137</sup>Cs/K ratio in the soil was 261positively correlated with the <sup>137</sup>Cs/K ratio in the shoots (Fig. 4), similar to results obtained in 262paddy rice (Kondo et al. 2015). These results also suggest that the exchangeable <sup>137</sup>Cs/K ratio 263in the soil is an important factor determining the <sup>137</sup>Cs/K ratio in shoots. The regression line 264265slopes were similar at the V5 and R2 growth stages and the R6 and R8 growth stages (Fig. 4). In contrast, the regression line slopes at the R6 and R8 growth stages were much higher than 266those at the V5 and R2 growth stages. These results suggest that the discrimination of <sup>137</sup>Cs from 267K at the R6 and R8 growth stages was lower than that at the V5 and R2 growth stages, despite 268similar exchangeable <sup>137</sup>Cs/K ratios in the soil, which indicates that the absorption mechanisms 269of K and <sup>137</sup>Cs in soybean differ before and after the R2 growth stage. The absorption of Cs is 270271mediated mainly by K transporters and channels, and the discrimination of Cs from K differs 272among these systems (White and Broadley 2000; Zhu and Smolders 2000; Broadley et al. 2001;

Qi et al. 2008). High-affinity K transporters function in low-K conditions with low 273discrimination of Cs from K, whereas K channels, such as voltage-independent cation channels, 274function in high-K conditions with high discrimination (Zhu and Smolders 2000). Meanwhile, 275K starvation can also upregulate the expression of high-affinity K transporters, which may have 276reduced the discrimination of <sup>137</sup>Cs from K after the R2 growth stage. As a result of the decrease 277in discrimination of <sup>137</sup>Cs from K during absorption (Fig. 4) and the increase in soil-278exchangeable <sup>137</sup>Cs/K (Table 4) with growth, <sup>137</sup>Cs became more transferable to the shoots after 279the R2 growth stage. 280

The chemical behavior of Cs is likely to be similar to that of K given that both are alkali 281282elements with similar physicochemical properties (Shaw and Bell 1991; Smolders et al. 1997). However, they appear to behave differently in soil-plant systems. The exchangeable <sup>137</sup>Cs/K 283ratio in the soil was much higher than the <sup>137</sup>Cs/K ratio in the shoots at all growth stages (Fig. 2844), and the ratio was not uniform in different parts of the shoot (Table 3). In soybean, <sup>137</sup>Cs was 285distributed more in the leaf blades and less in the grains compared with K, regardless of the K 286application level, and this tendency was promoted by K fertilization (Fig. 3). Accordingly, the 287<sup>137</sup>Cs/K ratio was highest in the leaf blades and tended to be lowest in the grains at the R8 288growth stage, and the rates of decrease in the <sup>137</sup>Cs/K ratio with K application were larger in the 289290grains than the leaf blades at the same stage (Table 3). K is a mobile nutrient, translocated from the older to younger parts and from the source (plant parts other than the grains: leaf blade, 291stem, and so on) to the sink (grains). Tsukada et al. (2002b) reported that, in paddy rice, the 292<sup>133</sup>Cs concentration at maturity was higher in older leaf blades, whereas the K concentration 293was higher in younger leaf blades. These results suggest that K is more efficiently absorbed 294from the soil and more translocatable during source-to-sink translocation than Cs. The 295differences in the <sup>137</sup>Cs/K ratio among different parts of the shoot are thought to be related to 296 the discrimination of Cs from K. 297

Physiological processes that increase nutrient accumulation in the grains include direct 298299transport (absorption) from the soil and remobilization from plant parts other than the grains. The increase in the inventory of K in the grains between the R6 and the R8 growth stages was 300 similar to or slightly lower than the total decrease in K in all parts of the shoot except the grains, 301 whereas the inventory of K decreased sharply in the leaf blades and stems (Fig. 2a). In addition, 302 303 the concentration of K in these parts also decreased substantially during this period (data not 304 shown). Thus, these parts are the primary source of K for soybean grains. Bender et al. (2015) suggested that the leaf provides the primary source of remobilized N and P, but the stem seems 305to serve as temporary storage for K in soybean. However, the source of <sup>137</sup>Cs in the grains could 306 307 not be explained fully by translocation from the parts of the shoot other than the grains, except under K0 treatment. This was because the increase in the inventory of <sup>137</sup>Cs in the grains from 308 the R6 to R8 growth stages was greater than the apparent total decrease in all other parts of the 309 shoot (Fig. 2b). Therefore, it is thought that the increase in the inventory of <sup>137</sup>Cs in the grains 310 from the R6 to the R8 growth stages depends on whether the <sup>137</sup>Cs accumulated in the grains 311312was newly absorbed from the soil or had already accumulated in the roots and was translocated. Given that the two were indistinguishable in this study due to the lack of root samples, further 313studies are needed to elucidate the dynamics of <sup>137</sup>Cs in the roots under minimal soil 314315contamination.

It is difficult to remove all radioactivity from fields by decontamination. Furthermore, the decrease in radiocesium concentrations in the soil is slow because of the length of the <sup>137</sup>Cs half-life. Because there is still a high risk of an increased TF when the soil-exchangeable K concentration decreases substantially (NARO and Fukushima Prefecture 2019), continuous countermeasures against radiocesium transfer to crops are required. In soybean, the demand for K increased after the R2 growth stage (Fig. 2a) and the exchangeable <sup>137</sup>Cs/K ratio in the soil tended to increase with growth (Table 4). Moreover, the discrimination of <sup>137</sup>Cs from K was lower at the R6 and R8 growth stages than at the V5 and R2 growth stages under the same exchangeable <sup>137</sup>Cs/K ratio in the soil (Fig. 4). Therefore, lowering the soil-exchangeable radiocesium/potassium ratio after the R2 growth stage by increasing K availability may efficiently reduce the transfer of radiocesium from the soil to the grains. The optimal strategy for increasing K availability after the R2 growth stage in the field remains unclear, and thus further studies are needed.

329

### 330 **5. Conclusions**

We conducted a field experiment in soybean with different levels of K application to elucidate 331the comparative dynamics of <sup>137</sup>Cs and K. The inventory of K in the shoots increased greatly 332from the fifth trifoliate stage to the full seed stage, and as the absorption of K increased, so too 333 did the absorption of <sup>137</sup>Cs. The effect of K application was much greater in terms of the 334 dynamics of <sup>137</sup>Cs than those of K or biomass production. Although K application reduced not 335 only the accumulation of <sup>137</sup>Cs in the shoots but also the distribution of <sup>137</sup>Cs to the grains, the 336 <sup>137</sup>Cs distribution to the grain had a much smaller effect on <sup>137</sup>Cs accumulation in the grains 337 than <sup>137</sup>Cs absorption. Moreover, the exchangeable <sup>137</sup>Cs/K ratio in the soil was positively 338 correlated with the <sup>137</sup>Cs/K ratio in the shoots for each growth stage, and the slope of the 339 regression line at the full seed and full maturity stage was almost twice that at the fifth trifoliate 340 and full bloom stage. These results suggest that the discrimination of <sup>137</sup>Cs from K decreases 341after the full bloom stage. As a result of the decrease in the discrimination of <sup>137</sup>Cs from K 342during absorption and the increase in soil-exchangeable <sup>137</sup>Cs/K with growth, <sup>137</sup>Cs was more 343transferable to the shoots after the full bloom stage. Therefore, as a future strategy, lowering the 344soil-exchangeable radiocesium/potassium ratio after the full bloom stage by increasing 345potassium availability could efficiently reduce the transfer of radiocesium to the grains. 346

## 348 Funding

This work was conducted as a part of the "Development of Decontamination Technologies for Radioactive Substances in Agriculture Land" project funded by the Japanese Ministry of Agriculture, Forestry and Fisheries.

352

# 353 **Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

356

# 357 Acknowledgments

We thank the following staff of the Agricultural Radiation Research Center, NARO Tohoku Agricultural Research Center for their field and laboratory assistance: Ms. Aya Miura, Ms. Etsuko Shibayama, Ms. Yurie Yoshida, Mr. Yoshihiko Takahashi, Mr. Masakatsu Ito, Mr. Takao Sakurai, Mr. Masanori Yoshida, and Mr. Rikio Shishido.

362

# 363 References

- Bender, R.R., Haegele, J.W., Below, F.E., 2015. Nutrient uptake, partitioning, and
  remobilization in modern soybean varieties. Agron. J. 107, 563-573.
  https://doi.org/10.2134/agronj14.0435.
- Broadley, M.R., Willey, N.J., 1997. Differences in root uptake of radiocaesium by 30 plant taxa.
  Enviro. Poll. 97, 11-15. https://doi.org/10.1016/S0269-7491(97)00090-0.
- 369 Broadley, M.R., Escobar Gutiérrez, A.J., Bowen, H.C., Willey, N.J., White, P.J., 2001. Influx
- and accumulation of Cs<sup>+</sup> by the *akt1* mutant of *Arabidopsis thaliana* (L.) Heynh. lacking a
- dominant K<sup>+</sup> transport system. J. Exp. Bot. 52, 839 844.
- 372 https://doi.org/10.1093/jexbot/52.357.839.

- Cremers, A., 1988. Quantitative analysis of radiocaesium retention in soils. Nature. 335, 247–
  249. https://doi.org/10.1038/335247a0.
- Ehlken, S., Kirchner, G., 2002. Environmental processes affecting plant root uptake of
  radioactive trace elements and variability of transfer factor data: a review. J Environ
  Radioact. 58, 97-112. https://doi.org/10.1016/S0265-931X(01)00060-1.
- Gommers, A., Thiry Y., Delvax B., 2005. Rhizospheric mobilization and plant uptake of
   radiocesium from weathered micas: I. Influence of Potassium Depletion. J Environ Qual.
   34https://doi.org/10.2134/jeq2004.0406.
- Harper, J.E., 1971. Seasonal nutrient uptake and accumulation patterns in soybeans. Crop Sci.

382 11, 347-350. https://doi.org/10.2135/cropsci1971.0011183X001100030011x.

- Hirayama, T., Takeuchi, T., Nakayama, H., Nihei, N., 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).
- Ishikawa, J., Fujimura, S., Kondo, M., Murai-Hatano, M., Goto, A., Shinano, T., 2018. Dynamic

388 changes in the Cs distribution throughout rice plants during the ripening period, and effects

389 of the soil-K level. Plant Soil. 429., 503–518. https://doi.org/10.1007/s11104-018-3700-z.

- Japanese Ministry of Agriculture, Forestry and Fisheries, Results of radioactive cesium
   concentration in agricultural products (in Japanese) (accessed 4 March 2021).
   http://www.maff.go.jp/j/kanbo/joho/saigai/s chosa/index.html.
- Japanese Ministry of Health, Labor, and Welfare, 2011. New standard limits for radionuclides in foods (accessed 4 March 2021). http://www.mhlw.go.jp/english/topics/2011eq/dl/food-
- 395 120821\_1.pdf.
- 396 Kato, N., Kihou, N., Fujimura, S., Ikeba, M., Miyazaki, N., Saito, Y., Egichi, T., Itoh, S., 2015.
- 397 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 Sci. Plant Nutr. 61, 179-190.
  https://doi.org/10.1080/00380768.2014.995584.
- Kobayashi, H., 2014. Countermeasure practices for radiocesium contamination control in 401 J. Plant Japanese). 402 upland crops. Jpn. Soil Sci. Nutr. 85. 94-98 (In https://doi.org/10.20710/dojo.85.2 94. 403
- Kobayashi, T., Saito, S., Hara, Y., 2014. The absorption mechanism and the measure against
  absorption control of radiocesium to vegetables. Jpn. J. Soil Sci. Plant Nutr. 85, 99-102 (In
  Japanese). https://doi.org/10.20710/dojo.85.2\_99.
- Kondo, M., Makino, T., Eguchi, T., Goto, A., Nakano, H., Takai, T., Arai-Sanoh, Y., Kimura, T.,
  2015. Comparative analysis of the relationship between Cs and K in soil and plant parts
  toward control of Cs accumulation in rice. Soil Sci. Plant Nutr. 61, 144-151,
  https://doi.org/10.1080/00380768.2014.973348.
- Kubo, K., Nemoto, K., Kobayashi, H., Kuriyama, Y., Harada, H., Matsunami, H., Eguchi, T., 411 Kihou, N., Ota, T., Keitoku, S., Kimura, T., Shinano, T., 2015. Analyses and 412countermeasures for decreasing radioactive cesium in buckwheat in areas affected by the 413414 nuclear accident in 2011. Field Crops Res. 170, 40-46. 415https://doi.org/10.1016/j.fcr.2014.10.001.
- Kubo, K., Fujimura, S., Kobayashi, H., Ota, T., Shinano, T., 2017. Effect of soil exchangeable
  potassium content on cesium absorption and partitioning in buckwheat grown in a
  radioactive cesium-contaminated field. Plant Prod. Sci. 20, 396–405.
  https://doi.org/10.1080/1343943X.2017.1355737.
- MAFF, NARO, NIAES, 2014. Factors and countermeasure of buckwheat with high radioactive
   cesium concentration. Investigation of factors and result of trial examination (Outline, the

422 second edition) (In Japanese) (accessed 4 March 2021).
423 http://www.maff.go.jp/j/kanbo/joho/saigai/pdf/h25soba\_yoin.pdf.

- MAFF, NARO, NIAES, 2015. Factors and countermeasure of soybean with high radioactive
  cesium concentration. Investigation of factors and result of trial examination (Outline, the
  third edition) (In Japanese) (accessed 4 March 2021).
  http://www.maff.go.jp/j/kanbo/joho/saigai/pdf/youin\_daizu\_3.pdf.
- 428NARO, Fukushima Prefecture, 2019. Cultivation guide to reduce radiocesium concentration in429soybean (in Japanese) (accessed 4 March 2021).

430 http://www.naro.affrc.go.jp/publicity\_report/publication/pamphlet/tech-

- 431 pamph/130461.html.
- Nihei, N., Hamamoto, S., 2019. Absorption of radiocaesium in soybean. In agricultural
  implications of the Fukushima nuclear accident (III): after 7 years, eds. Nakanishi, TM.,
  O'Brien, M., Tanoi, K., Springer Japan, pp. 27-33. https://doi.org/10.1007/978-981-13-
- 435 **3218-0\_4**.
- Nihei, N., Sugiyama, A., Ito, Y., Onji, T., Kita, K., Hirose, A., Tanoi, K., Nakanishi, T.M., 2017.
  The concentration distribution of Cs in Soybean Seeds. RADIOISOTOPES. 66, 235-242.
  https://doi.org/10.3769/radioisotopes.66.235.
- 439 Qi, Z., Hampton, C.R., Shin, R., Barkla, B.J., White, P.J., Schachtman, D.P., 2008. The high
- 440 affinity  $K^+$  transporter AtHAK5 plays a physiological role in planta at very low  $K^+$
- 441 concentrations and provides a caesium uptake pathway in Arabidopsis. J. Exp. Bot. 59,
- 442 595–607. https://doi.org/10.1093/jxb/erm330.
- 443 Sawhney., B.L., 1972. Selective sorption and fixation of cations by clay minerals: a review.
- 444 Clay Clay Miner. 20, 93-100. https://doi.org/10.1346/CCMN.1972.0200208.

- Shaw, G., Bell, J.N.B., 1991. Competitive effects pf potassium and ammonium on caesium
  uptake kinetics in wheat. J. Environ. Radioact. 13, 283-296. https://doi.org/10.1016/0265931X(91)90002-W.
- Smolders, E., Van den Brande, K., Merckx, R., 1997. Concentration of <sup>137</sup>Cs and K in soil
  solution predict the plant availability of <sup>137</sup>Cs in soils. Environ. Sci. Technol. 31,3432-3438.
- 450 https://doi.org/10.1021/es970113r.
- Thiry, Y., Gommers, A., Iserentant, A., Delvaux, B., 2005. Rhizospheric mobilization and plant
  uptake of radiocesium from weathered micas: II. Influence of mineral alterability. J Environ
  Qual. 34, 2174-2180. https://doi.org/10.2134/jeq2004.0407.
- Tsukada, H., Hasegawa, H., Hisamatsu, S., Yamasaki, S., 2002a. Transfer of <sup>137</sup>Cs and stable
  Cs from paddy soil to polished rice in Aomori, Japan. J Environ Radioact. 59, 351-63.
  https://doi.org/10.1016/S0265-931X(01)00083-2.
- Tsukada, H., Hasegawa, H., Hisamatsu, S., Yamasaki, S., 2002b. Rice uptake and distributions
  of radioactive <sup>137</sup>Cs, stable <sup>133</sup>Cs and K from soil. Environ Pollut. 117, 403-409.
  https://doi.org/10.1016/S0269-7491(01)00199-3.
- 460 Tsukada, H., Takeda, A., Hisamatsu, S., Inaba, J., 2008. Concentration and specific activity of
- 461 fallout <sup>137</sup>Cs in extracted and particle-size fractions of cultivated soils. J. Environ. Raidoact.
- 462 99, 875-881. https://doi.org/10.1016/j.jenvrad.2007.11.014.
- 463 Tsumura, A., Komamura, M., Kobayashi, H., 1984. Behavior of radioactive Sr and Cs in soils
  464 and soil-plant systems. Bull. Natl. Inst. Agric. Sci. Ser., B. 36, 57–113 (In Japanese).
- White, P.J., Broadley, M.R., 2000. Mechanisms of caesium uptake by plants. New Phytol. 147,
  241–256.
- Yamaguchi, N., Taniyama, I., Kimura, T., Yoshioka, K., Saito, M., 2016. Contamination of
  agricultural products and soils with radiocesium derived from the accident at TEPCO

469 Fukushima Daiichi Nuclear Power Station: monitoring, case studies and countermeasures.
470 Soil Sci. Plant Nutr. 62, 303-314. https://doi.org/10.1080/00380768.2016.1196119.

Zhu, Y.G., Smolders, E., 2000. Plant uptake of radiocaesium: a review of mechanisms,
regulation and application. J. Exp. Bot. 51, 1635-1645.
https://doi.org/10.1093/jexbot/51.351.1635.

474

#### 475 **Figure captions**

Figure 1. Dry weights and distribution patterns of the dry weights of the shoots. (a) Dry weight. (b) Distribution patterns of the dry weights. V5, fifth trifoliate stage; R2, full bloom stage; R6, full seed stage; R8, full maturity stage. No significant differences in the dry weights of the shoot were observed between K treatment levels (Tukey's multiple comparison test at P < 0.05).

480

Figure 2. Inventories of K and <sup>137</sup>Cs in the shoots. (a) K and (b) <sup>137</sup>Cs. V5, fifth trifoliate stage; R2, full bloom stage; R6, full seed stage; R8, full maturity stage. Different letters at the same growth stage indicate significant differences in the total inventories of K and <sup>137</sup>Cs in the shoots (Tukey's multiple comparison test at P < 0.05).

485

Figure 3. Distribution patterns of K and <sup>137</sup>Cs in the shoots. (a) K and (b) <sup>137</sup>Cs. V5, fifth
trifoliate stage; R2, full bloom stage; R6, full seed stage; R8, full maturity stage.

488

Figure 4. Relationship between the <sup>137</sup>Cs/K ratio in the shoots and exchangeable <sup>137</sup>Cs/K ratio in the soil. V5, fifth trifoliate stage; R2, full bloom stage; R6, full seed stage; R8, full maturity stage. \*\* indicates P < 0.01. ANCOVA shows a significant difference of the regression line slopes before and after R2 growth stage (P < 0.01).

 Table 1. Physical and chemical properties of the soil.

Soil texture	Sandy clay	
Major clay minerals		Illite, smectite
Soil texture (%)	Clay	27.0
	Silt	7.5
	Coarse sand	44.2
	21.2	
pH (H <sub>2</sub> O)		5.2
Phosphate absorption c Kg <sup>-1</sup> )	4940	
Cation exchange capac weight)	12.1	
<sup>137</sup> Cs concentration (Be	q kg <sup>-1</sup> )	2,740

**Table 2**. Concentration of K and <sup>137</sup>Cs in the grains.

K treatment	K (g kg <sup>-1</sup> c	lry weight)	<sup>137</sup> Cs (Bq kg <sup>-1</sup> dry weight							
	R6	R8	R6	R8						
K0	18.3	20.0	79.5 <sup>a</sup>	61.8 <sup>a</sup>						
K230	19.0	21.6	27.3 <sup>b</sup>	23.7 <sup>b</sup>						
K380	20.2	20.9	9.9 <sup>bc</sup>	8.7 <sup>c</sup>						
K580	19.1	20.7	4.8 <sup>c</sup>	4.6 <sup>c</sup>						
K780	19.2	20.6	3.6 <sup>c</sup>	4.0 <sup>c</sup>						
ANOVA										
K treatment	ns		**							
Growth stage	**		ns							
K treatment $\times$ Growth stage	ns			ns						

R6, full seed stage; R8, full maturity stage.

Different letters at the same growth stage indicate significant differences (Tukey's multiple comparison test at P < 0.05).

\*\* and \* show significant difference at P < 0.01 and 0.05, respectively. ns indicates not significant.

Growth	Plant part	<sup>137</sup> Cs/K (Bq g <sup>-1</sup> dry weight)														
stage		K0			K2	K	380	K.	580		K					
V5	Shoot	1.60	А		0.49	В		0.32	В		0.28	В		0.21	В	
	Leaf blade	2.29	A	a	0.67	В	a	0.48	В	a	0.32	В		0.32	В	a
	Petiole	0.94	А	b	0.26	В	c	0.13	BC	b	0.18	BC		0.07	С	b
	Stem	1.03	А	b	0.43	В	b	0.22	В	b	0.30	В		0.15	В	b
	Pod								-							
	Grain								-							
	ANOVA															
	K treatment							*	**							
	Plant parts							*	**							
	K treatment $\times$ Plant parts							*	**							
R2	Shoot	2.19	A		0.59	В		0.22	С	•	0.15	С		0.15	С	
	Leaf blade	3.20	А	а	0.89	В	а	0.34	BC	а	0.21	С		0.21	С	
	Petiole	1.68	А	b	0.41	В	b	0.15	В	b	0.06	В		0.08	В	
	Stem	1.73	А	b	0.51	В	b	0.19	В	ab	0.18	В		0.17	В	
	Pod								-							
	Grain								-							
	ANOVA															
	K treatment							k	**							
	Plant parts							k	**							
	K treatment $\times$ Plant parts							×	**							
R6	Shoot	4.74	А	•	1.67	В		0.87	С	•	0.47	С		0.32	С	•
	Leaf blade	5.97	А	а	2.37	В		2.10	BC	a	1.30	BC	а	0.73	С	а
	Petiole	4.50	А	ab	1.55	В		0.81	BC	b	0.38	С	b	0.34	С	ab
	Stem	4.42	А	ab	1.48	В		0.83	BC	b	0.45	С	b	0.28	С	ab
	Pod	4.87	A	ab	1.74	В		0.66	С	b	0.28	С	b	0.26	С	ab
	Grain	4.36	А	b	1.45	В		0.49	С	b	0.25	С	b	0.19	С	b
	ANOVA	·				•		-	•	•						
	K treatment							*	**							
	Plant parts							*	**							
	K treatment $\times$ Plant parts							1	ıs							
R8	Shoot	4.53	A		1.90	В	*	0.96	BC		0.65	С		0.62	С	
	Leaf blade	10.68	A	а	5.57	AB	а	4.14	В	a	4.28	В	а	4.45	В	а
	Petiole	4.91	A	b	2.45	В	b	0.91	BC	bc	0.76	С	b	0.62	С	b
	Stem	5.70	A	b	2.62	В	b	1.88	BC	b	1.05	BC	b	0.80	С	b
	Pod	6.38	А	b	2.50	В	b	0.92	С	bc	0.52	С	b	0.49	С	b
	Grain	3.09	А	b	1.10	В	b	0.42	С	c	0.22	С	b	0.19	С	b
					•	-										

# Table 3. The <sup>137</sup>Cs/K ratio in each plant part.

K treatment	**	
Plant parts	**	
K treatment × Plant parts	ns	

V5, fifth trifoliate stage; R2, full bloom stage; R6, full seed stage; R8, full maturity stage.

Different letters at the same growth stage indicate significant differences between K treatments (uppercase letters) and between plant parts (lowercase letters) (Tukey's multiple comparison test at P < 0.05).

\*\* and \* show significant differences at P < 0.01 and 0.05, respectively. ns indicates not significant. <sup>137</sup>Cs/K ratios in each part of the shoot were significantly different among growth stages (ANOVA at P < 0.01).

As growth progressed, the <sup>137</sup>Cs/K ratios of the leaf blades, petioles, stems, and pods increased, whereas those in the grains decreased (ANOVA at P < 0.05).

**Table 4**. Concentration of exchangeable K and <sup>137</sup>Cs in the soil.

K treatment	K treatment Exchangeable <sup>137</sup> Cs (Bq kg <sup>-1</sup> dry weight)							Exchangeable <sup>137</sup> Cs/K (Bq mg <sup>-1</sup> dry weight)													
	V5	R2	R6	5 R8		V5	V5			R6		R8	V5		R2		R6		R8		
K0	81	85	90	a	96	a	86	d	72	e	73	d	86 <sup>d</sup>	0.96	a	1.21	a	1.24	а	1.16	a
K230	57	64	61	ab	68	ab	174	cd	145	d	116	cd	122 <sup>cd</sup>	0.35	b	0.44	b	0.53	b	0.58	ab
K380	48	56	51	b	55	ab	251	bc	215	c	150	c	184 <sup>c</sup>	0.18	b	0.25	b	0.34	bc	0.30	b
K580	37	40	41	b	41	b	342	b	327	b	260	b	256 <sup>b</sup>	0.11	b	0.12	b	0.16	c	0.16	b
K780	43	43	41	b	46	b	564	a	521	a	334	a	328 <sup>a</sup>	0.08	b	0.08	b	0.12	c	0.14	b
ANOVA																					
K treatment **					**						**										
Growth stage ns					**							ns									
K treatment $\times$ Growth stage			ns ;							**						ns					

V5, fifth trifoliate stage; R2, full bloom stage; R6, full seed stage; R8, full maturity stage.

Different letters at the same growth stage indicate significant differences (Tukey's multiple comparison test at P < 0.05).

\*\* and \* show significant difference at P < 0.01 and 0.05, respectively. ns indicates not significant.



**Figure 1.** Dry weights and distribution patterns of the dry weights of the shoots. (a) Dry weight. (b) Distribution patterns of the dry weights. V5, fifth trifoliate stage; R2, full bloom stage; R6, full seed stage; R8, full maturity stage. No significant differences in the dry weights of the shoot were observed between K treatment levels (Tukey's multiple comparison test at P < 0.05).



**Figure 2.** Inventories of K and <sup>137</sup>Cs in the shoots. (a) K and (b) <sup>137</sup>Cs. V5, fifth trifoliate stage; R2, full bloom stage; R6, full seed stage; R8, full maturity stage. Different letters at the same growth stage indicate significant differences in the total inventories of K and <sup>137</sup>Cs in the shoots (Tukey' s multiple comparison test at P < 0.05).



**Figure 3.** Distribution patterns of K and <sup>137</sup>Cs in the shoots. (a) K and (b) <sup>137</sup>Cs. V5, fifth trifoliate stage; R2, full bloom stage; R6, full seed stage; R8, full maturity stage.



**Figure 4.** Relationship between the <sup>137</sup>Cs/K ratio in the shoots and exchangeable <sup>137</sup>Cs/K ratio in the soil. V5, fifth trifoliate stage; R2, full bloom stage; R6, full seed stage; R8, full maturity stage. \*\* indicates P < 0.01.