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Radioactive Cs transfer to vegetables after the FDNPP accident

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19 ABSTRACT

To evaluate the effectiveness of potassium (K) application in mitigating¹³⁷Cs transfer from soil 20 21 to plants, several vegetable species were cultivated under field and pot experiments. In the field 22 experiment, squash, sweet potato, turnip, potato, and carrot were examined in 2020 and 2021 23 in two different areas of Hamadori (coastal region in Fukushima Prefecture). Transfer factor (TF) was calculated by dividing harvest radioactivity (Bq kg⁻¹ dry or fresh) to soil radioactivity 24 (Bq kg⁻¹ dry), and was negatively correlated with the amount of exchangeable K (ExK) at 25 26 harvest, regardless of the species, year, and location. In the pot experiment, edamame (immature soybean seed), spinach, turnip, and komatsuna were cultivated, and it was confirmed 27 28 that ExK was the most powerful factor in regulating TF. Based on the relationship between ExK and TF for each vegetable species, the amount of ExK required to keep the ¹³⁷Cs 29 concentration lower than a certain level (standard limitation value and one-quarter of that 30 31 value), was calculated.

33 Keywords: ¹³⁷Cs; Fukushima Prefecture; Potassium application; Vegetables

34

35 1. Introduction

After major nuclear accidents, radionuclides can contaminate agricultural land and products. 36 Based on the inventory of released radionuclides and their half-lives, radiocesium (¹³⁴Cs, ¹³⁷Cs) 37 and ⁹⁰Sr have been considered the most problematic for soil contamination after the Chernobyl 38 39 accident (e.g., Ivanov et al. 1997). In the case of the Tokyo Electric Power Company's Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident that occurred in 2011 in Japan, 40 radionuclides with very short half-lives, such as ¹³³Xe (half-life is 5.25 days) (Stohl et al. 2012), 41 ¹³¹I (half-life 8.02 days) (Fesenko et al. 2020), and others (Provinec et al. 2013) were dispersed 42 in the environment. Among them, ¹³¹I dispersed into the air and got deposited on the surface of 43 44 some leafy vegetables (United Nations 2014; Onda et al. 2015). After a few months, the dispersed ¹³¹I in the environment was almost completely diminished owing to its short half-life, 45 and further dispersion from the FDNPP did not occur. Furthermore, as the FDNPP accident 46 47 occurred in March, most of the agricultural activity was not initiated, so direct attachment to the crops was not a major concern. However, during the initial days after the accident, dry 48 deposition of ¹³¹I occurred on some vegetables (Ohse et al. 2015), and secondary contamination 49 50 took place by radiocesium derived from debris removal operations in a few cases (Matsunami 51 et al. 2016). Therefore, the primary concern was food contamination due to the transfer of 52 radiocesium from soil to plants (Hachinohe and Shinano 2020a, b).

As early as 2011, most research focused on rice cultivation, and at first, the cultivation area was chosen based on the radiocesium activity of the soil (lower than 5 kBq kg⁻¹ on a dry weight basis). It was based on the observation of the transfer factor (TF: radioactivity of brown rice to radioactivity of soil) after the global fallout in the 1960s (Shinano 2021). Unfortunately, 57 the estimated TF was not reliable enough to predict brown rice radioactivity, and the 58 exchangeable potassium (ExK) level was found to be critical for mitigating radiocesium 59 transfer from soil to brown rice (Fujimura et al. 2014; Kato et al. 2015, x). Since 2012, the 60 application of a large amount of potassium fertilizer has been practised to decrease the radioactivity of brown rice in contaminated areas. This countermeasure has also been applied 61 62 for soybean (Hirayama et al. 2018; Hatano, Shinjo, and Takata 2021; Matsunami et al. 2021), 63 buckwheat (Kubo et al., 2015), and pastures (Yamamoto et al. 2014; Ministry of Agriculture, 64 Forestry and Fisheries (MAFF) 2020). On the other hand, very limited work has been conducted 65 on vegetables (Kobayashi, Saito and Hara 2014; Tagami et al. 2020), and most studies on 66 vegetables lack information on how plants respond to soil ExK, which is well known as a critical determinant factor to regulate Cs transfer from soil to plants. 67

68 In the area where a substantial amount of radiocesium was dispersed by the FDNPP 69 accident (mainly the southern part of Tohoku and the northern part of Kanto, Japan), in addition 70 to major crops (e.g., rice, soybean, and buckwheat), leafy vegetables are also important crops, 71 especially to farmers who produce vegetables mainly for domestic consumption, and some of 72 the products are sold in a small lot. However, research on vegetables is limited because of their 73 high water content at harvest, which decreases the radiocesium concentration of the product in 74 fresh weight base (water content is more than 90 % in leafy vegetables, e.g., Popkin, D'Anci 75 and Rosenberg 2010) and because they are generally grown with high amounts of fertilizers, 76 both of which decrease the transfer of radiocesium from soil to plants. In 2020, reports on the limited data on vegetables published after the FDNPP were summarized in TECDOC from 77 78 International Atomic Energy Agency (IAEA) (Tagami et al. 2020). The transfer of radionuclides 79 from soil to plants is widely designated as TF, which is the ratio of the concentration of 80 radionuclides in plants (any distinctive part of plants) to that in the soil. However, TF itself 81 cannot be applied directly to the management of soil; the relationship between potassium

82 availability in the soil and TF is highly regulated, and information on potassium availability 83 (e.g., ExK) is essential. Furthermore, it should be mentioned that after fields were decontaminated ExK tended to be decreased because of the low fertile non contaminated soil 84 85 addition, (Kurokawa et al. 2019), so the importance of potassium fertilization becomes high especially under these decontaminated areas. As different levels of potassium are critical for 86 87 regulating radiocesium uptake, field and pot experiments were conducted to demonstrate the 88 effect of ExK levels at different sites and in different years. Finally, we demonstrate that a 89 critical level of potassium in the soil regulates the radioactivity of several vegetables.

90

91 **2.** Materials and methods

92 **2.1. Condition of fields before experiment**

93 In 2015, the field was decontaminated by topsoil stripping and a non-contaminated soil 94 dressing. Before 2011, the field was used as a paddy field, and after the FDNPP accident, the 95 field was not used until 2019. Soil samples collected from five different points were analyzed 96 separately after air-drying and passing through a 2 mm sieve. ExK was extracted by shaking 97 for 1 h with 1 M ammonium acetate at a soil:solution ratio of 1:20. Soil chemical properties, 98 including ExK, were determined using Eurofin Japan (Kanagawa, Japan). The data are presented in Table S1 in the Supplementary Material. The ¹³⁷Cs concentration was 99 approximately 2.9 kBq kg⁻¹ dry soil, and no significant difference was observed between 100 101 different crop fields. However, the heterogeneity of the soil ¹³⁷Cs is well known even after the 102 initiation of agriculture after the accident (e.g., Kubo et al. 2020), and it could not be ignored 103 in this study too. The difference was obvious in the ExK concentration, indicating that the 104 decontamination process was not always constant.

105

106 **2.2. Experiment 1 (Field experiment)**

107 In 2020, squash (Cucurbita moschata Duch.), sweet potato (Ipomoea batatas L.), and turnip 108 (Brassica campestris L. var. glabra) were planted in a field located in the northern Hamadori 109 area of Fukushima Prefecture, designated as Field A. The area of the field was 50m x 20m. The field was divided equally into 5 plots for different K fertilizer application (10m 110 x 20m). Five hills were set in each plot, then each hill was divided into three sections 111 112 as replications. Then turnip was grown in 1 hill. Squash and sweet potato were grown 113 separately in 2 hills. The soil taken from this field was designated Soil A and the type was 114 originally lowland paddy soil. Planting and harvesting dates are listed in Table 1.

115 Nitrogen, phosphorus, and potassium fertilizers were applied before cultivation (Table 116 1). Five different levels of potassium were used to alter the ExK levels in the field. K₂SO₄ 117 fertilizer was applied at the rates of 0, 150 (conventional level), 300, 500, and 1000 kg K₂O ha⁻ 118 ¹, designated as K0, K150, K300, K500, and K1000, respectively, for all vegetable crops, except for sweet potato. For sweet potato, K₂SO₄ fertilizer was applied at rates of 0, 100, 200, 500, and 119 1000 K₂O ha⁻¹, designated as K0, K100, K200, K500, and K1000, respectively. Plants were 120 121 cultivated using conventional farming protocols and four to eight plants were sampled per 122 replication at harvest, with three replications. Tubers, leaves, and fruits were collected from 123 sweet potato, komatsuna, and squash, respectively. In the case of turnip, leaves and roots were 124 harvested (the leaves of turnip are used as leafy vegetables). After measuring the fresh weight, the samples were dried at 80°C for 48-72 h in an oven (VTRL-1000-2T, Isuzu Seisakusyo, 125 126 Niigata, Japan). The dry sample was ground for further analysis after weighing.

127 Soil samples were collected with three replicates after the cultivation of each soil with 128 different K treatments. For the measurement of soil radiocesium concentration and ExK, about 129 100 g of soil sample was taken from beneath each sampled plant (four to eight samples in 2020 130 and two to twelve samples in 2021 depending on the size of the plant) to 0–15 cm depth and pooled for each replication. Exchangeable K was extracted by 1M ammonium acetate andanalyzed using atomic absorption spectrometry (Shimadzu SPCA-6210).

133

134 In 2021, a field in the middle part of the Hamadori area was used for squash, sweet 135 potato, komatsuna (Japanese mustard spinach) (Brassica rapa L. var. perviridis), potato 136 (Solanum tuberosum L.), and carrot (Daucus carrot subs. sativus) and the field was designated 137 Field B, and was originally grey lowland soil and the soil taken from this field was designated 138 Soil B. Soil B was also decontaminated in the same way in Soil A in 2015. The area of the field 139 was 50m x 22m. The field was divided equally into 5 plots for different K fertilizer application 140 (10m x 22m). Fifteen hills were set in each plot and 3 hills were used for one species. Each 141 line was used for the sampling of one replication.

142 Nitrogen, phosphorus, and potassium fertilizers were applied before cultivation, as 143 shown in Table 1. Four different levels of potassium fertilizers were used to alter the ExK level in the field. K₂SO₄ fertilizer was applied at rates of 0, 150, 300, and 500 kg K₂O ha⁻¹, designated 144 145 as K0, K150, K300, and K500, respectively, for all vegetables except for sweet potato. For 146 sweet potato, K₂SO₄ fertilizer was applied at rates of 0, 100, 200, and 400 K₂O ha⁻¹, designated 147 as K0, K100, K200, and K400, respectively. Plants were cultivated using conventional farming 148 protocols and four to eight plants were sampled per replication at harvest, with three 149 replications. Tubers, leaves, and fruits were collected from sweet potato, and squash, 150 respectively. In the case of turnip, leaves and roots were harvested (the leaves of turnip are used 151 as leafy vegetables). Plant and soil sampling and subsequent procedures are same as in 2020.

All crop varieties and their growth conditions are shown in Table 1.

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154 **2.3. Experiment 2 (Pot experiment)**

155 Plants were grown until harvest. Planting and harvesting dates are listed in Table 2. A pot 156 experiment was conducted using soybean (Glycine max (L) Merr.) as edamame (immature 157 soybeans with pods), spinach (Spinacia oleracea L.), and turnip for Soil C (obtained from a 158 decontaminated field in the middle of the Hamadori area; gray lowland soil) in a greenhouse at 159 the Fukushima Agricultural Technology Centre (FATC) (Koriyama, Fukushima). The pot size was 1/2000 a using Wagner pot (AS ONE, Osaka, Japan), containing 12 kg of fresh soil in 2020 160 161 and 10.3 kg of fresh soil in 2021, and three levels of K treatments were used. In pot experiments, nitrogen was applied at 0.22 g urea kg⁻¹ soil for all crops, except for soybean; in the case of 162 soybean, 0.075 g urea kg⁻¹ soil was applied. Phosphorus was applied at 0.47 g superphosphate 163 kg^{-1} soil except for turnip; in the case of turnip, 0.67 g superphosphate kg^{-1} soil was applied. 164 For potassium treatment, potassium sulfate was applied at 0, 0.1, and 0.2 g K_2O kg⁻¹ soil. These 165 application rates were equivalent to 0, 75, and 150 kg K₂O ha⁻¹ in 2020, designated as K0, K75, 166 167 and K150, respectively. The treatment was conducted in triplicate.

168 Three experiments were conducted in 2021 by using edamame, spinach and turnip. One 169 was to observe the effects of repeated cultivation using the same soil used in 2020. K0, K150, 170 and K300 pots were prepared using K0, K75, and K150 soils, respectively, after the experiment 171 in 2020. K500 pots were prepared in 2021 using K150 soils in 2020. The K level was 172 determined after the additional application of K₂SO₄ at concentrations of 0, 150, 300, and 500 173 kg K₂O ha⁻¹. The initial soil ¹³⁷Cs radioactivity (Bq kg⁻¹ DW \pm standard deviation) in Soil C was 2854±135 in 2020, and 2665±203 in 2021. Soil radioactivity was determined in each pot 174 175 prepared for the experiment with three replicates.

The other experiment was to see the effect of repeated cultivation of Komatsuna in a
year by using soil obtained from a field located in the northern part of the Nakadori area (Field
D) as Soil D. The soil was classified as Andosol. No decontamination was conducted on Soil
D before the experiment. Komatsuna was planted between May 6 and June 7 as Komatsuna

180 1st, and second cultivation was carried out between July 2 and July 28 as Komatsuna 2nd. After 181 the 1st cultivation, soil was collected in each treatment and mixed thoroughly then prepared for 182 the 2nd cultivation. As the uptake of nutrient by Komatsuna cultivation was not expected to be 183 large, no fertilization was performed before 2nd cultivation. The soil type was humus gray soil. 184 The initial ¹³⁷Cs radioactivity (Bq kg⁻¹ DW ± standard deviation) in Soil D was 1573±124.

Using the same Soil D, a third experiment was carried out to compare the difference between Soil C and Soil D. For this purpose, turnip was cultivated in Soil D. Soil radioactivity was determined in each pot prepared for the experiment with three replicates.

Soil chemical properties including ExK were determined by FATC. The data are presented in Table S2 in the Supplementary Material. Soil ExK was extracted using 1 M ammonium acetate, and K concentration was determined by atomic absorption spectrometry (280FS AA, Agilent Technology, Santa Clara, CA, USA).

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193 **2.4. Gamma-ray spectrometry**

The radiocesium concentration was determined by FATC, and only ¹³⁷Cs concentration was 194 195 used in this study because the ¹³⁴Cs concentration of the plant sample was too low to determine the precise value. The ¹³⁷Cs concentration was decay-corrected to each sampling time. The 196 ¹³⁷Cs concentration of the soil in the field experiments was determined using a Ge 197 198 semiconductor detector (GCD-40190 (BSI Instruments), and efficiency calibration was performed using a mixed nuclide solution for ²⁴¹Am and ¹⁵²Eu (Nuclear Technology Service, 199 Inc., NIST (ANSI 42.22-195)) and a separate solution for ⁶⁰Co (Japan Radioisotope Association 200 (JRIA), CO401). The ¹³⁷Cs concentration of the soil in the pot experiments was determined 201 202 using an NaI detector (FNF-401, Ohyo Koken Kogyo Co. Ltd., Saitama, Japan), and efficiency calibration was performed using a separate solution for ¹³⁷Cs (JRIA, CS031). The ¹³⁷Cs 203 204 concentrations of the plants in both the field and pot experiments were determined using a Ge

205	semiconductor detectors (GC4020-7500SL-2002CSL, GC3520-7500SL-2002CSL, GC4020-
206	7500SL-iPA-SL, GC3020-7500SL-2002CSL (Canberra Ltd., Boston, MA, UA). Efficiency
207	calibration was performed using a mixed nuclide solution (JRIA, MX033U8PP) and a separate
208	solution for ⁶⁰ Co (JRIA, CO401).

209 The counting time was set to ensure that the counting error for each sample was below 210 10% for soils and 15% for plant samples. Each sample was placed in a cylindrical 211 polypropylene container (U-8 container, 65 mm in height and 50 mm in diameter, RIG, Japan). 212

213 2.5. Statistical analysis

214 All statistical analyses were conducted using a statistical software (JMP Pro 16.1.0; USA). Multiple comparisons were performed using the Tukey-Kramer method. TF was converted to 215 216 reciprocal values, and the relationship between ExK was calculated. Analysis of covariance 217 (ANCOVA) was conducted to determine the difference in years, repetitions, and soil types to evaluate the difference in the relationship between ExK and TF on pot experiments. 218

219

220 3. Results

221 A summary of the experimental design used in this research is shown in Table 3.

222 3.1. Field experiment

223 For the field experiment, two different sites located in the Hamadori area of Fukushima were 224 selected. One was located in the northern part of Hamadori (Field A) and the other was in the 225 middle part of Hamadori (Field B). Both sites were decontaminated by topsoil stripping and 226 non-contaminated mountainous soil was dressed in 2015 and 2016, respectively. Weeds were 227 collected, and after the FDNPP accident, no agricultural activities were conducted until the 228 experiment. The soil mineral content was generally higher in Soil A than in Soil B, except for 229 potassium (Table S1). And the carbon and nitrogen contents were higher in Soil A, it was speculated that the origin of the dressed soil and the original soil characteristics caused thesechanges, although the details are not known.

Harvest weight, soil ExK, and ¹³⁷Cs in the soil and plants after harvest are shown in 232 Table 4. The growth of plant was better in Soil B than in Soil A, though soil physicochemical 233 234 properties did not simply support the yield data (Supplementary Table 1), however as the hill 235 spacing and climate condition were not same, it is not concluded that the productivity between these soils are different. In 2020, a field experiment was conducted in the northern part of the 236 237 Hamadori area (Field A, Soil A). Though there was no significant difference in the productivity of the examined crop species according to K levels. There was a clear tendency for ExK to 238 239 increase with the application level of K even at harvest time, that is 213, 205, and 213 mg K kg⁻¹ at K0 treatment, and increased to 542, 340, and 520 mg K kg⁻¹ at K1000 treatment in 240 squash, sweet potato, and turnip respectively. And at the harvest ¹³⁷Cs content conversely 241 242 decreased with increasing ExK (in case of sweet potato there was no significant difference), that is 104, 83, 94, and 91 Bq kg⁻¹ dry at K0 treatment, and decreased to 13, 24, 24, and 47 Bq 243 kg⁻¹ in squash, sweet potato, turnip root, and turnip leaf, respectively (Table 4). Though the 244 245 significant difference of TF among the K treatments was not observed, there was a decreasing tendency with the higher K level (Table 4). 246

In 2021, although the field changed from Field A to Field B, the effect of K application 247 248 level on the yield was not significant, except for potato where the fresh weight increased with the increase of K application, that is 2863 g m⁻² at K0 treatment to 4733 g m⁻² at K500 treatment 249 250 (Table 4). ExK increased significantly with increasing K application level even at harvest time, that is 84, 59, 95, 56, and 89 mg K kg⁻¹ at K0 treatment and increased to 196, 132, 316, 208, 251 and 124 mg K kg⁻¹ at K500 treatment in squash, sweet potato, komatsuna, potato, and carrot, 252 respectively. And the harvest ¹³⁷Cs content conversely decreased with increasing ExK, that is 253 254 165, 101, 788, 255, and 203 Bq kg⁻¹ dry at K0 treatment, and decreased to 29, 19, 51, 28, and 19 at K500 treatment (Table 4). TF was high in K0 treatment except for carrot, in carrot the
highest average TF was observed in K10 treatment (Table 4). The lowest value of TF was
observed in the highest K treatment regardless of crop species.

Though 137 Cs in the soil was not same within a field of soil A or B, it is considered that the contamination by the 137 Cs by the nuclear accident was not equally occurred to the field, furthermore decontamination process was also considered that it was difficult to remove the contaminated soil equally from a field. Thus, the evaluation of 137 Cs uptake is not simply carried out by the plant 137 Cs, the concept of TF is important and widely used to explain the difference of 137 Cs uptake from the soil to plant.

264

265 **3.2. Pot experiment**

266 **3.2.1 Repeated experiment using Soil C in 2020 and 2021.**

267 Edamame, turnip root and spinach were cultivated on the same soil with different range of K 268 application level for two years. There was no significant difference in the harvest (fresh weight) 269 in all the crop species regardless of years (Table 5). On the other hand, the harvest weight is 270 lower in 2021 than in 2020 in every crop species. This may be due to the lower irradiation and temperature in 2021 but the detail information of the green house was not collected. ExK 271 272 increased significantly with increasing K application level, that is even at harvest time, that is 177, 181, and 94 mg K kg⁻¹ at K0 treatment and increased to 249, 243, and 171 mg K kg⁻¹ at 273 K150 treatment in edamame, spinach, and turnip root, respectively in 2020 (Table 5). 112, and 274 174, and 96 mg K kg⁻¹ at K0 treatment and increased to 354, 318, and 211 mg K kg⁻¹ at K500 275 276 treatment in edamame, spinach, and turnip root, respectively in 2021. When the applied K level increased the ¹³⁷Cs concentration of plant decreased. In 2020, the level was 122, 91, and 1262 277 Bq kg⁻¹ dry at K0 treatment and decreased to 53, 49, and 497 Bq kg⁻¹ dry at K150 treatment in 278 279 edamame, spinach, and turnip root respectively (Table 5). In 2021, it was 376, 60, and 1123 at K0 treatment and decreased to 58, 30, and 84 Bq kg⁻¹ dry at K500 treatment in edamame, spinach, and turnip root respectively. Though ¹³⁷Cs concentration on dry weight basis was high in turnip root compared to other crops, the difference of the concentration on fresh weight basis was rather small. High concentration of water of turnip root dilutes the radioactivity of plant. The decrease in ¹³⁷Cs in spinach was observed but not significantly confirmed.

285

286 **3.2.2 Repeated experiment in a year, using komatsuna in Soil D.**

287 In 2021, komatsuna was cultivated twice in a year by using the same soil (without additional fertilization at the second trial). The yield was not changed by the different K level in the 1st 288 289 trial, while the yield of K0 treatment was significantly lower than other treatments regardless of fresh weight or dry weight basis in 2nd trial (Table 5). ExK level at the harvest of each trial 290 at K0 treatment was 25 and 29 mgK kg⁻¹, in 1st and 2nd trials, respectively, and these low values 291 may affect the productivity of komatsuna, and increased to 268 and 318 mgK kg⁻¹ in 1st and 2nd 292 trials, respectively. However, the as difference of ExK level in 1st and 2nd trial was not 293 294 significant (data not shown), thus the other factor except for ExK may have the effect on the 295 productivity. ¹³⁷Cs concentration decreased with increasing the K application in both trials. At K0 treatment, it was 1013 and 1613 Bq kg⁻¹ in 1st and 2nd trial, respectively, and decreased to 296 300 and 169 Bq kg⁻¹ in 1st and 2nd trial, respectively, at K500 treatment. The decrease of 297 298 radioactivity can be explained by the increase of ExK level by K application, however the 299 difference of radioactivity at K0 level could not be explained simply by ExK level between 300 trials.

301

302 **3.3.** Effect of soil on the relationship between ExK and TF in pot experiment.

In 2021, turnip was grown in soil C and soil D at the same time in the same greenhouse. Turnip
root was used to detect the soil effect. The growth in soil D was smaller than in Soil C. In soil

305 D, EC, Exchangeable Ca, Exchangeable Mg were lower than that of soil C before the cultivation 306 (Table S2). The lower fertility of soil D may reduce the productivity of turnip. ExK level at the harvest at K0 treatment was 96 and 42 mg K kg⁻¹ in soil C and D, respectively and increased to 307 211 and 184 mg K kg⁻¹ at K500 treatment (Table 5). ¹³⁷Cs concentration was decreased with 308 increasing the K application in both soils. It was 1123 and 781 Bq kg⁻¹ in soil C and soil D, 309 respectively at K0 treatment and decreased to 84 and 168 Bq kg⁻¹ in soil C and soil D, 310 respectively at K500 treatment. It seems that the decrease of ¹³⁷Cs concentration with K level 311 312 was steeper in soil C than in soil D.

313

314 **3.4.Relationship between ExK and TF**

315 K is known to have similar chemical properties in the soil solution; therefore, K in the solution 316 competes with Cs at the absorption site of the plant root (Zhu and Smolder 2000; White and 317 Broadely 2000). Furthermore, it is known that the K transporter absorbs Cs due to its high Cs 318 affinity, especially under low K conditions (Fujimura et al. 2014; Rai and Kawabata 2020). The 319 relationships between ExK at harvest and the TF of each crop cultivated under field conditions 320 in 2020 and 2021 are shown in Fig. 1. In all crop species and years (locations), there was a clear 321 trend that the TF increased with the decrease in ExK. This result was also confirmed in pot 322 experiments (Figs. 2 and 3). The fitting curve was produced by changing the TF into a reciprocal 323 value because as K and Cs compete with each other, the higher K application level may decrease 324 the Cs uptake (indicating a low TF) and vice versa.

325

326 **4. Discussion**

327 4.1. Relationship between ExK and TF in field experiment.

The differences among crop species have been demonstrated in IAEA (2010), but the simple comparison of TF among species fluctuated too much and could not be directly applied to 330 agricultural countermeasures. It is important to determine the relationship between a wide range 331 of ExK levels and TF values in the field, as demonstrated in rice, soybean, and buckwheat 332 (IAEA 2020), and this will also be required for vegetables. In the present experiment we have 333 tried to demonstrate the ExK-TF relationship of squash, sweet potato, turnip root, turnip leaf, 334 komatsuna, potato, and carrot by using field condition. And turnip root, turnip leaf, spinach, 335 and edamame in pot experiment. This relationship is the most important factor to decide the 336 actual countermeasure under radioactive cesium contamination after the nuclear accident (e.g., 337 Kato et al. 2015). In all the examined vegetables in field experiment, close relationship between 338 ExK and TF was observed (Fig. 1). However, the relationship among species and between soil 339 type was not equal (Fig. 1). In the examined vegetables, komatsuna seems to have higher TF 340 (dry weight basis) at the same ExK compared to other species, and sweet potato and carrot seem 341 to have lower TF. It should be mentioned that as the water content is high in komatsuna leaf 342 (more than 90%), the TF (fresh weight basis) will be low.

343 Squash and sweet potato were cultivated in both Soil A, 2020 and Soil B, 2021. The 344 relationship between ExK-TF was not same in Soil A and Soil B. It seems that the TF was 345 higher in Soil B in case of squash, but the difference in sweet potato was not clear (Fig. 1). It is 346 required to have similar and wider ExK variation and under similar environmental condition to 347 evaluate the difference but the importance of ExK to regulate TF was consistent. Soil chemical 348 properties were very different between Soil A and B. As CEC, exchangeable Ca, Mg, total 349 carbon, and total nitrogen were higher in Soil A than in Soil B (Table S1). These differences 350 are partly derived by the composition of dressed soil after the decontamination process and may 351 affect the relationship between ExK-TF also. However, the information about the dressed soil 352 after FDNPP accident is limited (Yoshino et al. 2015), it is required to have a large survey of 353 how the dressed soil was obtained and applied to each field to have more precise evaluation of 354 ExK-TF relationship.

355

356 4.2. Effect of repeated cultivation on the relationship between ExK and TF in pot 357 experiment.

358 As the transfer of radiocesium from soil to plants is strongly regulated by the ratio of the 359 amounts of Cs and K in the soil solution (Shaw and Bell 1991, Smolders et al. 1996), other 360 factors that may change this ratio and radiocesium transfer, such as soil type and ongoing 361 fixation in the soil, have been reported (e.g., Yamaguchi et al. 2016). We chose two 362 combinations to examine the effect of other factors on the relationship between ExK and TF by using ANCOVA analysis (Table 6). 1) Turnip root, spinach, and edamame were used to 363 364 evaluate the ongoing fixation by using the same soil in two consecutive years in pot cultivation; 365 and 2) komatsuna in a pot trial was used to determine the ongoing fixation by repeated 366 cultivation using the same soil in a year.

367 In Table 3, two years of cultivation and repeated cultivation in a year were evaluated 368 by conducting an ANCOVA, and the results are shown in Table 6. Radiocesium fixation to the 369 soil clay has been reported to increase annually (Tsukada 2014), and fixation to the field soil 370 was especially obvious in the early stages after the accident (Yamamura et al. 2018). 371 Radiocesium fixation to soil is known as an ongoing fixation, and has been considered that it 372 may decrease the risk of radiocesium transfer from soil to plant (MAFF, 2021). Though from a 373 two-year experiment using the same soil by pot experiments, there was a significant interaction 374 effect, except for spinach (Table 6). However, it is not able to confirm that there is an ongoing 375 fixation in edamame because even at the same ExK level, the TF was higher (Fig. 2). In case 376 of turnip root, it seems that the ExK-TF relationship decreased in 2021, however as the range 377 of ExK between two years are different it is not suitable to conclude that ongoing fixation is 378 confirmed. Other environmental factors should be considered. Besides the effect of repeated

379 cultivation, the effect of soil is clearly demonstrated. It is important to consider the difference380 of soil to determine the precise prediction of required amount of ExK to regulate TF.

381 From the experiment by a repeated cultivation trial within a year using komatsuna in 382 the pot experiment, the interaction effect was positive, and it seems that the TF was lower in 383 the 2nd trial than in the 1st trial at a similar ExK level (demonstrated from the 100 to 200 mg K₂O kg⁻¹ range) (Table 6, Fig. 3). However, it is not simply concluded that there was a fixation 384 progressed in this experiment. As the pot soil was thoroughly mixed before the 2nd trial, and it 385 386 is considered to have similar effect as plowing in the field condition. Plowing may accompany the mechanical increase in the contact of ¹³⁷Cs with the soil, and it is expected that this process 387 388 promotes the fixation rate. On the other side, plant root uptake nutrient from the soil solution 389 and available fraction as a source for nutrient. As observed in ExK level change, plant growth can reduce the available fraction of soil, and it is also expected the decrease in exchangeable 390 ¹³⁷Cs. That is, there is a possibility that repeated cultivation especially during a short time 391 repetition may decrease the exchangeable ¹³⁷Cs then decrease the TF. It is required to check 392 how the exchangeable ¹³⁷Cs level changes in these repetition experiment. Furthermore, as the 393 394 other environmental condition (e.g., temperature) was not controlled, further precise evaluation 395 is needed. Furthermore, fertilization is also known to increase fixation to the soil (Kubo et al. 2017; Wakabayashi et al. 2022), and it is also important to know how the availability of ¹³⁷Cs 396 397 (exchangeable ¹³⁷Cs) changed through these processes. In addition, the growth of K0 treatment only significantly low in 2nd trial, it is speculated that the contribution of other K source (such 398 as non-exchangeable K) in addition to ExK may explain the difference between 1st and 2nd 399 400 trials, but further research is required.

401

402 **4.3. Effect of soil type on the relationship between ExK and TF in pot experiment.**

403 From the observation of more than 400 fields over 6 years in Fukushima Prefecture, to compare 404 different soils, it was suggested that the relationship between ExK and TF was not similar in 405 the Nakadori and Hamadori areas (Yamamura et al., 2018). Two experimental sites were used 406 in this study in different years. An interaction effect was observed in turnip root in the pot 407 experiments (Table 6). Soil D seems to have lower fertility from the data of EC, ExK, Ex Mg 408 and Ex Ca compared to Soil C (Supplementary Table 2). Though we do not have the 409 information about the original soil before the decontamination, it is suggested that contribution 410 of additional soil by decontamination procedure is larger in soil D. It is speculated that the soil 411 characteristics may change the relationship between ExK and TF through the availability of K 412 and ¹³⁷Cs in the soil. Further investigation is required how the soil characteristics change the relationship between ExK and TF. The usage of non contaminated soil after decontamination 413 414 could change the original soil characteristics, and as the detail information of each 415 decontamination process is not open, the effect of decontamination on ExK-TF behavior is required. It is suggested that exchangeable ¹³⁷Cs level is another important factor to explain the 416 417 difference in the behavior of ExK-TF (Yagasaki et al. 2019a, b), we are trying to develop 418 another equation to cancel the different soil characteristics now (Suzuki et al. 2023). However, 419 regardless of these interaction effects, ExK was clearly demonstrated to be the most powerful 420 factor regulating TF.

421

422 **4.4. Countermeasure for the safe production of vegetables**

The application of a sufficient amount of K was confirmed to be a feasible method for mitigating ¹³⁷Cs transfer from soil to plants. However, the effects of fixation and/or cultivation, soil type, and crop species must also be considered for precise estimation of the required level of ExK during plant growth. From the results, the TF was calculated based on the fresh weight of the plant harvest, and the required level of ExK for each site and crop species was estimated. For this calculation, the data for komatsuna, squash, sweet potato, and turnip were obtained from the field, and the data for edamame and spinach were obtained using a pot (Table 3) because we did not have the data for these crops under field conditions. The TF values obtained from the pot experiments were higher than those of the field (Figs. 1, 2, 3); therefore, the data based on pot experiments may be estimated on the safe side.

433

434

Based on the standard value of radioactivity in food, we calculated the required level of ExK using the following equation:

435 TF (wet)⁻¹=b + a*ExK

where TF (wet) was the ratio of ¹³⁷Cs concentration of the wet harvest to that of the dry soil, 436 437 and a and b are coefficients. The estimated coefficients are summarized in Table 7. For this calculation, we set the soil ¹³⁷Cs concentration as 3,000 Bq kg (Dry weight)⁻¹, though the soil 438 radioactivity is not constant even in a small area even after the decontamination this value is 439 440 generally observed in the contaminated fields especially in the Hamadori area where the 441 decontamination is still in progress (data not shown) and furthermore the value is close to the ¹³⁷Cs concentration we have collected for the experiment in this experiment. To evaluate the 442 required amount of ExK, not only the standard value of 100 (Bq kg⁻¹ fresh) but also a quarter 443 of that (25 Bq kg⁻¹ fresh) was set as the target value. Considering for the usage in the actual 444 445 practice for agriculture in the contaminated fields, it is required to treat the product in fresh 446 weight basis, we used the equation for TF estimation based on fresh weight of each data.

The value of 25 Bq kg⁻¹ fresh was close to the detection limit in most food monitoring locations, and this value was sometimes used to indicate exhaustive food safety for consumers. Table 7 shows that the required ExK level needed to produce all the examined vegetables under the standard limit (100 Bq kg⁻¹ fresh) using the same soil. In some cases (sweet potato and carrot in Soil B and turnip leaf in Soil A), no further countermeasures were needed. Additionally, to reduce the value to the detection limit (25 Bq kg⁻¹ fresh) as closely as possible, 453 the ExK level higher than 200 mgK₂O kg⁻¹ was maintained in most cases, and for edamame, it 454 was maintained at more than 300 mgK₂O kg⁻¹. These results indicate that even in the case of 455 vegetables, a sufficient amount of potassium application is required to maintain high ExK levels 456 during growth.

457

458 **5.** Conclusion

459 Several vegetables (komatsuna, squash, sweet potato, turnip, potato, carrot, spinach, and 460 edamame) were investigated to determine the relationship between ExK and TF. Regardless of 461 the crop species or other factors, such as soil type and/or year, TF was strongly negatively 462 regulated by the amount of ExK. The ongoing fixation was not clearly observed especially 463 under field condition, it should be evaluated other soil chemical properties also. The differences 464 among the soil types were demonstrated and must be investigated in the future. Taking into 465 account all the factors, it is strongly supported that maintaining a sufficient amount of ExK is the most reliable method to decrease the uptake of ¹³⁷Cs from the soil. 466

467

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- 632 Legends
- 633 Table 1. Growth condition of field experiment (2020 and 2021).
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- Fig. 1 Relationship between ExK and TF of a field experiment in 2020 and 2021.
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Voor Vogo	Vagatablas	Variaty	Sowing data	Honvooting data	Nitrogon (kg N ho-1)	Phosphorus	Hill spacing
rear	vegetables	variety	Sowing date	Harvesting date	Nillogen (kg N ha ')	(kg P ₂ O ₅ ha ⁻¹)	(cm x cm)
2020	Squash	Kokonoeguri	28-May	11-Aug	150	150	40 x 200
	Sweet potato	Beniazuma	1-Jun	26-Oct	150	150	30 x 200
	Turnip	Natsuhakurei	28-May	21-Jul	150	150	15 x 200
2021	Squash	Kokonoeguri	19-May	2-Aug	150	150	40 x 180
	Sweet potato	Beniazuma	26-May	5-Oct	30	100	30 x 120
	Komatsuna	Rakuten	6-May	7-Jun	150	150	10 x 120
	Potato	Kitaakari	31-Mar	1-Jul	150	150	30 x 120
	Carrot	Koyo 2go	16-Jul	8-Nov	150	150	15 x 120

Table 1. Growth condition of a field experiment (2020 and 2021).

Table 2Growth condition of a pot experiment (2020 and 2021).

Year	Soil	Species	Variety	Sowing date	Harvesting date	Nitrogen (kg N ha ⁻¹)	Phosphorus (kg P ha ⁻¹)	plants pot ⁻¹
2020	Soil C	Edamame	Yuagarimusume	4-Jun	11-Aug	50	65	2
		Spinach	Mirage	8-Sep	5-Nov	150	65	5
		Turnip	CR Mochibana	8-Sep	5-Nov	150	65	3
2021	Soil C	Edamame	Yuagarimusume	24-May	28-Jul	50	65	1
		Spinach	Mirage	30-Aug	8-Nov	150	65	5
		Turnip	CR Mochibana	30-Aug	28-Oct	150	65	3
	Soil D	Komatsuna 1st	Rakuten	6-May	7-Jun	150	65	4
		Komatsuna 2nd	Rakuten	2-Jul	28-Jul	150	65	4
		Turnip	CR Mochibana	30-Aug	27-Oct	150	65	3

Species	Culture						
	Fie	Field Pot					
	Field A	Field B	So	il C	Soil D		
	2020	2021	2020	2021	2021		
Squash	O	\bigcirc					
Sweet potato	\bigcirc	\bigcirc					
Turnip root	\bigcirc		\bigcirc	\bigcirc	\bigcirc		
Turnip leaf	\bigcirc			\bigcirc	\bigcirc		
Komatsuna		\bigcirc			$\bigcirc\bigcirc$		
Potato		\bigcirc					
Carrot		O					
Edamame			\bigcirc	Ô			
Spinach			\bigcirc	\bigcirc			

Table 3. Experimental designs in this study.

Double circle indicates that the obtained relationship was used to estimate the required K level for the estimation of radioactivity of harvest in Table 5.

Table 4. Growth of harvest and soil characteristics after the experiment (field experiment).

Year	Field	Vegetables	Treatment	Number	Yield (g m⁻²)	ExK	Soil ¹³⁷ Cs	plant	¹³⁷ Cs
				of samples	Fresh	Dry	mg K kg⁻¹	kBq kg⁻¹ dry	Bq kg⁻¹ fresh	Bq kg⁻¹ dry
	2020 Soil A	Squash	K0	3	136 ± 25 a	32 ± 4 a	213 ± 13 b	2.56 ± 0.42 a	24.1 ± 6.6 a	104 ± 36 a
			K150	3	134 ± 27 a	28 ± 6 a	241 ± 30 b	2.48 ± 0.54 a	17.5 ± 12 ab	84 ± 59 a
			K300	3	134 ± 15 a	29 ± 6 a	271 ± 83 b	2.44 ± 0.51 a	6.9 ± 3.2 ab	34 ± 20 a
			K500	3	142 ± 34 a	33 ± 14 a	205 ± 21 b	2.20 ± 0.23 a	20.7 ± 11 ab	88 ± 33 a
			K1000	3	149 ± 52 a	35 ± 9 a	542 ± 158 a	3.02 ± 1.5 a	2.8 ± 1.1 b	13 ± 6 a
		Sweet potato	K0	3	414 ± 131a	120 ± 42 a	205 ± 67 a	2.28 ± 1.1 a	23.9 ± 5.4 a	83 ± 16 a
			K100	3	972 ± 440 a	275 ± 115 a	208 ± 46 a	2.29 ± 0.20 a	28.6 ± 12.4 a	100 ± 46 a
			K200	3	1056 ± 1096 a	281 ± 292 a	191 ± 54 a	2.85 ± 0.28 a	14.6 ± 13.6 a	92 ± 49 a
			K500	3	2722 ± 858 a	776 ± 265 a	205 ± 34 a	1.85 ± 0.34 a	14.1 ± 4.5 a	49 ± 15 a
			K1000	3	1989 ± 1549 a	522 ± 414 a	340 ± 174 a	2.34 ± 0.35 a	6.4 ± 4.6 a	24 ± 17 a
		Turnip (Root)	K0	3	307 ± 131 a	16 ± 7.2 a	213 ± 99 b	1.80 ± 0.56 a	4.5 ± 4.0 a	94 ± 93 a
			K150	3	157 ± 61 a	7.2 ± 2.0 a	161 ± 31 b	2.25 ± 1.1 a	3.9 ± 1.1 a	81 ± 22 a
			K300	3	163 ± 102 a	7.4 ± 5.4 a	202 ± 75 b	1.90 ± 0.59 a	2.3 ± 1.3 a	53 ± 36 a
			K500	2	183 ± 76 a	10 ± 4.7 a	315 ± 82 ab	2.89 ± 0.54 a	1.4 ± 0.3 a	26 ± 7 a
			K1000	2	262 ± 105 a	8.1 ± 1.6 a	520 ± 85 a	2.69 ± 0.72 a	0.8 ± 0.4 a	24 ± 3 a
		Turnip (Leaf)	K0	3	71 ± 65 a	7.1 ± 5.7 a	213 ± 99 b	1.80 ± 0.56 a	10.5 ± 7.7 a	91 ± 49 a
			K150	3	18 ± 23 a	2.1 ± 2.5 a	161 ± 31 b	2.25 ± 1.1 a	21.6 ± 22 a	114 ± 26 a
			K300	3	14 ± 11 a	1.4 ± 1.6 a	202 ± 75 b	1.90 ± 0.59 a	8.2 ± 7.4 a	91 ± 77 a
			K500	2	36 ± 26 a	4.1 ± 2.9 a	315 ± 82 ab	2.89 ± 0.54 a	6.1 ± 3.7 a	53 ± 31 a
			K1000	2	61 ± 78a	6.1 ± 4.2 a	520 ± 85 a	2.69 ± 0.72 a	12.0 ± 11 a	47 ± 18 a
	2021 Soil B	Squash	K0	5	1583 ± 1083 a	369 ± 231 a	84 ± 1.5 c	1.96 ± 1.2 a	39.9 ± 14.8 a	165 ± 55 a
			K150	3	1725 ± 936 a	409 ± 230 a	104 ± 25 bc	2.68 ± 0.99 a	44.1 ± 14 a	188 ± 64 a
			K300	3	1327 ± 339a	262 ± 139 a	139 ± 36 ab	3.11 ± 1.1 a	27.4 ± 5.9 ab	149 ± 41 ab
			K500	3	1264 ± 80 a	276 ± 34a	196 ± 31 a	0.77 ± 0.04 a	6.2 ± 0.2 b	29 ± 4 b
		Sweet potato	K0	5	1720 ± 1319 a	635 ± 492 a	59 ± 10 c	2.64 ± 0.63 a	37.0 ± 6.0 a	101 ± 18 a
			K100	3	2257 ± 618 a	804 ± 184 a	75 ± 13 bc	2.97 ± 0.76 a	29.3 ± 8.3 ab	81 ± 23 ab
			K200	3	3474 ± 853 a	1196 ± 282 a	96 ± 28 ab	2.47 ± 0.43 a	40.3 ± 22 a	118 ± 67 a
			K400	3	1905 ± 963 a	651 ± 313 a	132 ± 8 a	0.90 ± 0.20 b	6.7 ± 0.6 b	19 ± 2 b
		Komatsuna	K0	5	2063 ± 401 a	107 ± 16 a	95 ± 37 c	2.76 ± 0.81 a	40.8 ± 6.9 a	788 ± 182 a
			K150	3	2019 ± 455 a	97 ± 19 a	161 ± 32 bc	3.03 ± 1.0 a	12.8 ± 5.0 b	262 ± 94 b
			K300	3	1972 ± 159 a	97 ±10 a	233 ± 85 ab	2.90 ± 0.36 a	9.9 ± 1.7 b	202 ± 33 b
			K500	3	1827 ± 272 a	103 ± 15 a	316 ± 22 a	0.85 ± 0.12 b	2.8 ± 0.4 b	51 ± 8 b
		Potato	K0	5	2863 ± 574 b	719 ± 145 a	56 ± 12 c	2.07 ± 0.36 ab	64.1 ± 9.7 a	255 ± 39 a
			K150	3	3234 ± 985 ab	783 ± 234 a	103 ± 15 b	2.52 ± 0.69 ab	31.8 ± 6.2 b	131 ± 27 b
			K300	3	3371 ± 700 ab	774 ± 139 a	144 ± 23 b	3.13 ± 0.95 a	24.8 ± 10 bc	107 ± 41 bc
			K500	3	4733 ± 551 a	1089 ± 118 a	208 ± 26 a	1.19 ± 0.77 b	6.4 ± 0.9 c	28 ± 4 c
		Carrot	K0	3	1111 ± 446 a	107 ± 43 a	89 ± 26 a	3.22 ± 0.62 a	19.3 ± 5.1 a	203 ± 35 a
			K150	3	1410 ± 176 a	122 ± 19 a	101 ± 42 a	2.96 ± 0.97 ab	15.7 ± 4.7 a	182 ± 58 a
			K300	3	789 ± 272 a	76 ± 23 a	139 ± 23 a	2.78 ± 1.3 ab	12.0 ± 4.0 ab	127 ± 53 ab
			K500	3	835 ± 102 a	85 ± 10 a	124 ± 22 a	0.81 ± 0.21 b	1.7 ± 0.6 b	19 ± 4 b

Numbers after ± denote the standard deviation. Different letters represent significant differences according to the Tukey's HSD test (p < 0.05).

Experimental procedures are same as shown in Table S1.

Table 5. Growth of harvest and soil characteristics after the experiment (Pot experiment).

Year	Field	Vegetables	Treatment	Number	Yield (g	g pot ⁻¹)	ExK	Soil ¹³⁷ Cs	Plant	¹³⁷ Cs
				of samples	Fresh	Dry	mgK kg⁻¹	kBq kg⁻¹ dry	Bq kg ⁻¹ fresh	Bq kg⁻¹ dry
2020	Soil C	Edamame	K0	3	122 ± 7 a	38 ± 1 a	177 ± 23 a	2.81 ± 0.10 a	38 ±7 a	122 ± 19 a
			K75	3	123 ± 10 a	38 ± 2 a	198 ± 33 a	2.62 ± 0.05 a	24 ± 3 b	77 ± 11 b
			K150	3	130 ± 10 a	39 ± 3 a	249 ± 35 a	2.85 ± 0.15 a	16 ± 4 b	53 ± 13 b
		Spinach	K0	3	91 ± 25 a	10 ± 3 a	181 ± 13 a	2.84 ± 0.26 a	11 ± 1.7 a	91 ± 17 a
			K75	3	107 ± 5 a	12 ± 1 a	196 ± 18 a	2.53 ± 0.15 a	7.5 ± 0.4 b	66 ± 8 ab
			K150	3	112 ± 6 a	13 ± 1 a	243 ± 39 a	2.72 ± 0.19 a	5.6 ± 0.4 b	49 ± 2 b
		Turnip (root)	K0	3	512 ± 6 a	31 ± 1 b	94 ± 7 c	2.82 ± 0.05 a	77 ± 13 a	1262 ± 221 a
			K75	3	522 ± 29 a	34 ± 1 a	122 ± 16 b	2.70 ± 0.23 a	67 ± 15 a	1023 ± 250 ab
			K150	3	528 ± 28 a	34 ± 1 a	171 ± 6 a	3.05 ± 0.07 a	32 ± 9 b	497 ± 150 b
2021	Soil C	Edamame	K0	3	90 ± 5 a	20 ± 1 a	112 ± 10 c	2.06 ± 0.18 b	85 ± 8 a	376 ± 36 a
			K150	3	87 ± 11 a	20 ± 3 a	179 ± 22 bc	2.36 ± 0.07 a	39 ± 3 b	173 ± 13 b
			K300	3	78 ± 3 a	18 ± 0 a	283 ± 16 ab	2.35 ± 0.05 a	20 ± 2 c	87 ± 9 c
			K500	3	81 ± 9 a	19 ± 2 a	354 ± 115 a	2.34 ± 0.09 a	13 ± 2 c	58 ± 6 c
		Spinach	K0	3	65 ± 9 a	7.8 ± 0.9 a	174 ± 25 b	2.40 ± 0.05 a	7.2 ± 3.8 a	60 ± 32 a
			K150	3	103 ± 43 a	11 ± 3.7 a	216 ± 8 b	2.43 ± 0.02 a	8.7 ± 2.7 a	79 ± 26 a
			K300	3	60 ± 5 a	7.1 ± 0.8 a	277 ± 21 a	2.25 ± 0.12 a	5.0 ± 3.6 a	42 ± 30 a
			K500	3	78 ± 14 a	8.8 ± 1.3 a	318 ± 13 a	2.44 ± 0.13 a	3.3 ± 1.2 a	30 ± 12 a
		Turnip (root)	K0	3	180 ± 48 a	12 ± 4 a	96 ± 18 c	2.53 ± 0.01 a	75 ± 29 a	1123 ± 375 a
			K150	3	232 ± 12 a	13 ± 1 a	130 ± 15 bc	2.57 ± 0.09 a	30 ± 3.0 b	524 ± 67 b
			K300	3	238 ± 14 a	14 ± 2 a	185 ± 34 ab	2.54 ± 0.02 a	11 ± 2.9 b	178 ± 41 b
			K500	3	241 ± 11 a	15 ± 2 a	211 ± 17 a	2.65 ± 0.16 a	5.3 ± 2.5 b	84 ± 35 b
2021	Soil D	Komatsuna 1	٤ K0	4	79 ± 6 a	5.4 ± 0.5 a	25 ± 6 c	1.61 ± 0.07 a	109 ± 23 a	1013 ± 150 a
			K150	4	83 ± 8 a	6.3 ± 0.8 a	91 ± 34 b	1.61 ± 0.14 a	85 ± 35 ab	793 ± 233 ab
			K300	4	81 ± 5 a	7.1 ± 0.6 a	129 ± 34 b	1.63 ± 0.11 a	62 ± 10 bc	600 ± 84 bc
			K500	4	77 ± 7 a	6.2 ± 1.2 a	268 ± 4 a	1.56 ± 0.12 a	27 ± 6 c	300 ± 39 c
		Komatsuna 2	r K0	4	60 ± 10 c	4.7 ± 0.6 b	29 ± 2 d	1.59 ± 0.02 a	128 ± 15 a	1613 ± 95 a
			K150	4	120 ± 20 ab	9.0 ± 1.8 a	93 ± 12 c	1.49 ± 0.04 b	37 ± 4 b	497 ± 49 b
			K300	4	139 ± 10 ab	11 ± 1.1 a	164 ± 28 b	1.54 ± 0.04 ab	17 ± 1 c	225 ± 12 c
			K500	4	110 ± 9 a	8.3 ± 0.5 a	318 ± 30 a	1.63 ± 0.05 a	13 ± 1 c	169 ± 14 c
		Turnip (root)	K0	4	149 ± 16 a	9.6 ± 1.4 b	42 ± 2 b	1.73 ± 0.05 a	51 ± 13 a	781 ± 163 a
			K150	4	160 ± 16 a	12 ± 1.0 a	71 ± 8 b	1.72 ± 0.07 a	33 ± 4 b	458 ± 54 b
			K300	4	171 ± 4 a	12 ± 0.3 a	101 ± 18 b	1.73 ± 0.09 a	17 ± 2 c	257 ± 34 c
			K500	4	153 ± 4 a	10 ± 0.3 ab	184 ± 65 a	1.84 ± 0.09 a	11 ± 4 c	168 ± 56 c
		Turnip (leaf)	K0	4	88 ± 12 a	7.9 ± 1.4 a	42 ± 2 b	1.73 ± 0.05 a	184 ± 46 a	2053 ± 454 a
			K150	4	86 ± 11 a	8.6 ± 1.0 a	71 ± 8 b	1.72 ± 0.07 a	140 ± 15 a	1390 ± 96 b
			K300	4	83 ± 5 a	7.7 ± 0.3 a	101 ± 18 b	1.73 ± 0.09 a	74 ± 13 b	792 ± 129 c
			K500	4	76 ± 7 a	7.0 ± 0.4 a	184 ± 65 a	1.84 ± 0.09 a	53 ± 14 b	570 ± 164 c

Numbers afeter \pm denote the standard deviation. Different letters represent significant differences according to the Tukey's HSD test (p < 0.05).

Exchangeable K was extracted by 1M ammonium acetate and analyzed by atomic absorption spectrometry (Agilent, 280FS AA)

Table 6. Results of ANCOVA analysis.

Trial	Species	Effect of interaction (p value)		
		ExK	Factor	Interaction effect
Pot trial (repeated in two years using the same soil)			Year	
	Turnip root	0.0025	0.057	0.042
	Spinach	0.015	0.60	0.69
	Edamame	<0.0001	<0.0001	0.0092
Pot trial (repeated in a year)			Order	
	Komatsuna 1st and 2nd	<0.0001	<0.0001	0.0002
Pot trial (different soils in the same year)			Soil	
	Turnip root	<0.0001	0.78	0.0003

Species	Soil condition	Coefficients of the regression equation for fresh harvest*		Required ExK (mg K kg ⁻¹) to keep the harvest radioactivity less than		
		а	b	100 Bq kg ⁻¹ fresh	25 Bq kg⁻¹ fresh	
Squash	Field, Soil A	2.20	-269	136	177	
Squash	Field, Soil B	0.74	-8.66	53	175	
Sweet potato	Field, Soil A	1.87	-228	138	186	
Sweet potato	Field, Soil B	0.67	33.8	<0	129	
Trunip root	Field, Soil A	8.17	-666	85	96	
Turnip leaf	Field, Soil A	0.69	163	<0	<0	
Komatsuna	Field, Soil B	0.98	25	5	97	
Potato	Field, Soil B	0.99	-20.8	51	142	
Carrot	Field, Soil B	1.00	158	<0	<0	
Edamame	Pot, Soil C	0.47	-13.3	92	284	
Spinach	Pot, Soil C	3.46	-321	102	128	

Table 7. Estimation of required ExK level for the harvest radioactivity.

*The equation is as follows: TF(Fresh weight basis)⁻¹=b + a*ExK

**The equation is as follows: $TF(Dry weight basis)^{-1}=d + c*ExK$

Soil radiocesium Cs concentreation is estimated as 3,000 Bq kg⁻¹ dry.



Fig. 1 Relationship between ExK and TF of a field experiment in 2020 and 2021.



Fig. 2 Relationship between ExK and TF of a pot experiment using Soil C in 2020 and 2021.



Fig. 3 Relationship between ExK and TF of a pot experiment using Soil D in 2021.