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1 **Potassium applications reduced cesium uptake and altered strontium**
2 **translocation in soybean plants**

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13 **Abstract**

14 After the Tokyo Electric Power Company's Fukushima Dai-ichi Nuclear Power Plant accident
15 in 2011, radioactive cesium (RCs) was released in greater concentrations than radioactive
16 strontium (RSr) in the surrounding environment. Most of the countermeasures were developed
17 to mitigate the RCs transfer from the soil to plants. However, to avoid what has happened after
18 the Chernobyl and Mayak accidents, preventing the transfer of RSr from soil to plants should
19 be a priority. Although the application of potassium (K) fertilizers is the most effective method
20 for preventing agricultural crops from absorbing RCs in contaminated fields, this
21 implementation increases the cost and labor requirements. Considering the preparedness for
22 nuclear accidents, it remains unclear how this countermeasure will be affected if RCs and RSr
23 are released simultaneously. We aimed to explore the effect of K applications on cesium (Cs)
24 and strontium (Sr) uptake and their interaction with and correlation to other elements in the
25 soybean plants and soil. The field experiments were conducted in Fukushima Prefecture, Japan,
26 using different K applications (i.e., no, normal, and high K applications). The dry weight and
27 mineral concentrations of K, Cs, Sr, calcium (Ca), magnesium (Mg), and nitrogen (N)
28 concentration in plants and exchangeable K (ExK), exchangeable Cs (ExCs), exchangeable Sr
29 (ExSr), exchangeable Ca (ExCa), exchangeable Mg (ExMg), NH_4^+ (ammonium), and NO_3^-
30 (nitrate) concentrations in the soils were evaluated. This study revealed that K application
31 reduced Cs, Ca, and Mg uptake but did not affect the ExSr, ExCa, and ExMg concentrations in
32 the soil and did not change the uptake of Sr. On the other hand, K concentration of the plant
33 especially at later growth stage, which indicates re-translocation of Sr was negatively regulated
34 by K concentration.

35 **Keywords:** Soybean; cesium; strontium; countermeasure; potassium.
36

1. Introduction

38 The earthquake and subsequent tsunami that occurred at the Tokyo Electric Power Company's
39 Fukushima Dai-ichi Nuclear Power Plant (FDNPP) in 2011 released several radionuclides
40 including radioactive cesium (RCs) and radioactive strontium (RSr) to eastern Japan (Morino
41 et al. 2011). RCs have relatively long half-lives (e.g., 30.2 years for ^{137}Cs and 2.06 years for
42 ^{134}Cs) and high-energy emissions of β and γ radiation. ^{90}Sr is a β -ray emitting radionuclide
43 with a high fission yield, relatively half-life (29 years), and high transferability to plants
44 (Konno and Takagai 2018; Tsukada et al. 2005). RCs has been released in greater
45 concentrations than RSr in the case of the FDNPP accident. However, the transfer of RSr from
46 soil to plants also needs to be prevented to avoid what has happened in the previous Chernobyl
47 and Mayak accidents (Chu et al. 2015).

48 After the FDNPP accident, the application of potassium (K) fertilizers was the most
49 effective method and practical countermeasure for preventing agricultural crops from
50 absorbing RCs in contaminated fields (Fujimura et al. 2014; Kato et al. 2015; Kubo et al. 2015;
51 Matsunami et al. 2021). However, the result of this implementation may also influence
52 strontium (Sr) behavior, even though it is less of an issue in the case of the FDNPP accident.
53 Nuclear accident preparedness must include countermeasures, especially if RCs and RSr will
54 be handled simultaneously. How K application for RCs mitigation alters RSr uptake should be
55 evaluated. This may help support and validate the application of K to reduce the absorption of
56 RCs and RSr in the event of a future incident.

57 The addition of K application to the soil may also change the soil's nutrient balance,
58 which impacts on plant growth. Nitrogen (N) is a determinant element in soybean growth
59 (Osaki et al. 1992). Previous reports have shown that cesium (Cs) uptake can increase with
60 increasing nitrogen (N) concentration and decreasing K concentration in plants (Evans and
61 Dekker 1969; Belli et al. 1995). The uptake of elements such as Cs, Sr, K, and calcium (Ca)
62 are positively correlated with each other (Chu et al. 2015) but their interaction with N remains
63 poorly understood. Thus, a study of the role of these various nutrients in response to the effect
64 of K application to reduce the rate of radionuclide transmission from soil to plants is necessary
65 to ensure a harmonious balance between soil and plants. This nutrient balance is the key to
66 increasing nutrient use efficiency to maintain soil fertility and plant productivity.

67 In this study, we conducted field experiments on soybean plants treated with K
68 applications in Date City, Fukushima Prefecture, for two growing seasons (2019–2020).
69 Despite studies that have found soil K and Ca affect Cs and Sr uptake in lettuce (Roca and

70 Vallejo, 1995), their interrelationship has not been elucidated especially between K and Sr. The
71 K applications have been shown to reduce Cs transport from soil to plants, but it has not been
72 determined if K also reduces Sr transport. And if it occurs, K application for the remediation
73 of agriculture after nuclear accidents can be used not only for radioactive Cs but also for Sr.
74 The purpose of this study is to determine how K application affects the uptake of Cs and Sr
75 simultaneously by soybean plants, one of Fukushima's most important agricultural products.

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78 **2. Material and methods**

79 **2.1. Experimental design**

80 The experiment was conducted at Date City in Fukushima Prefecture, Japan in 2019 and 2020.
81 The soil type is gray lowland soil, based on the classification of cultivated soils in Japan. Each
82 field was fertilized before cultivation with the following nutrients: 20 kg N ha⁻¹ ((NH₄)₂SO₄)
83 before the seedling stage, and 60 kg N ha⁻¹ after the flowering stages, and 100 kg P₂O₅ ha⁻¹
84 (Ca₃(PO₄)₂) with 1000 kg ha⁻¹ magnesium lime applied on the same day. The experimental
85 treatments comprised three application levels of K: no K application, normal K application
86 (increasing the level of exchangeable K (ExK) up to 25 mg K₂O 100 g⁻¹ and applying 100 kg
87 K₂O ha⁻¹), and high K application (increasing the level of ExK up to 45 mg K₂O 100 g⁻¹ and
88 applying 100 kg K₂O ha⁻¹). The amount of K (100 kg K₂O ha⁻¹) was applied as potassium
89 sulfate (K₂SO₄, 50.0% K₂O). In 2019, 132 g/22.5 m² of K was applied to increase the level as
90 normal K application and 551 g/22.5 m² of K was applied to increase the level as high K
91 application. In 2020, 0 mg/22.5 m² of K was applied to increase the level as a normal K
92 application, and 664 mg/22.5 m² to increase the level as a high K application. A randomized
93 block design with three replications in each field was used. Soybeans (*Glycine max* (L.) Merr.
94 var. Tachinagaha) were sown on May 27 and harvested on October 28, 2019; and sown on June
95 23 and harvested on October 26, 2020.

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97 **2.2. Sample collection**

98 Plant and soil samples were collected from each field at each growth stage (vegetative,
99 flowering, pod formation, maturity, and harvest). Plant samples were divided into the stems
100 (including petiole), leaves, pods, and seeds. They were then dried at 80 °C for two days,
101 weighed, and homogenized for subsequent elemental analysis.

102 Soil samples were collected from a depth of 15 cm around the plant roots using a worm
103 scoop (Fujiwara Scientific Co., Ltd.). Soil samples were air-dried at 40 °C for 1 week and then
104 passed through a 2.0 mm sieve, for chemical analysis.

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2.3. *Mineral element measurements*

106 The elemental composition of the plants and soil was determined as previously described
107 (Watanabe et al. 2021). Dried plant samples (stems, leaves, pods, and seeds) were incubated
108 with 2 mL of 61% (w/v) HNO₃ at 110 °C in a DigiPREP apparatus (SCP Science, Quebec,
109 Canada) for 2 h until the solution had almost disappeared. After cooling, 0.5 mL of hydrogen
110 peroxide (H₂O₂) was added, and the samples were incubated at 110 °C for 20 min. Once
111 digestion was complete, the tubes were cooled, and the volume was adjusted to 10 mL by
112 adding 2% (w/v) HNO₃ to ultrapure water. The concentrations of K, Cs, Sr, Ca and Mg in the
113 digests were analyzed using an inductively coupled plasma mass spectrometry (ICP-MS:
114 ELAN DRC-e; PerkinElmer, Waltham, MA, USA). To measure N concentrations in the plants
115 using the Kjeldahl method (Watanabe et al. 2015), the dried plant samples were digested with
116 H₂SO₄ (98%)-H₂O₂.

117 For elemental analysis of the soil, ExK, exchangeable Cs (ExCs), exchangeable Sr
118 (ExSr), exchangeable Ca (ExCa), and exchangeable Mg (ExMg) were extracted from dried soil
119 samples at a soil:solution ratio of 1:10 in 1 M ammonium acetate (NH₄OAc) with shaking for
120 1 h. Soil ExK, ExCs, ExSr, ExCa, and ExMg concentrations were measured using ICP-MS.
121 For the analysis of inorganic N, ammonium (NH₄⁺) and nitrate (NO₃⁻) in the soil, the dried soil
122 samples (4 g) were shaken with 2 M KCl (40 mL) in 50 mL polycarbonate tubes on an end-
123 to-end shaker (150 rpm, 60 min). The soil was filtered using filter paper, and the concentrations
124 in the supernatant were determined by colorimetric assays at 630 and 538 nm with a microplate
125 reader (BioTek EPOCH² Microplate Reader) for ammonium and nitrate, respectively.

126 For measurement of ammonium, we used the Indophenol method according to
127 (Scheiner 1976), with minor modifications. The supernatant was prepared by adding 1 mL of
128 the sample solution, 2 mL of distilled water, and 1 mL of a combination of A and B color-
129 developing liquids (0.4 mL of A and 0.6 mL of B color-developing liquids). The A color-
130 developing liquids are containing 15 g of phenol dissolved in 200 mL buffer solution and
131 adjusted to 250 mL by adding 0.05 g of sodium nitroprusside. The B color-developing liquids
132 are containing 40 mL of 1 M NaOH to 1 mL of sodium hypochlorite solution and adjust to 100
133 mL with distilled water. Before measuring the absorbance, the supernatant was well stirred and
134 left for 60 minutes.

135 For the measurement of nitrate, we used the Ando and Ogata method (Ando and Ogata
136 1980). Prepare for 2.5 M ammonia solution by adjusting 16.7 mL of 28% special grade
137 ammonia to 100 mL with 0.25 M KCl solution. Prepare for reduction auxiliary stock solution

138 by dissolving 186.4 g of KCl in 0.8 L of distilled water, add 167 mL of special grade ammonia
139 water (28%), then adjusts to 1 L with distilled water. The first color former solution was
140 prepared by adding 100 mL of distilled water and 100 mL of concentrated HCl to 500 mg of
141 sulfanilamide to dissolve and then adjust to 1 L with distilled water. The second color former
142 solution was prepared by dissolving 50 mg of N-1-Naphthylethylenediamine dihydrochloride
143 ($C_{12}H_{16}Cl_2N_2$) with distilled water and adjusting to 1 L. The reduction auxiliary stock solution
144 was diluted 10-fold and took 4 mL then placed in a test tube with adding 1 mL of sample
145 solution, 0.75 g of metallic zinc, and plugged. The test tubes were immediately shaken for 15
146 minutes and took 2 mL of the supernatant into another test tube. The supernatant was left for
147 20 minutes and add 2 mL of each of the first and second color former solutions. The supernatant
148 was well stirred and left for 10 minutes before measuring the absorbance.

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2.4. Statistical analyses

151 Data were statistically analyzed using SPSS Statistics 25 (SPSS Inc., Chicago, IL, USA). One-
152 way analysis of variance (ANOVA) was used to evaluate the results at $p < 0.05$ probability
153 level. Tukey's test was calculated only when the ANOVA F-test indicated significant treatment
154 effects at the significant level ($p < 0.05$). Values are reported as mean \pm SE of three replicates.
155 Pearson's correlation analysis was conducted to evaluate the relationship between the mineral
156 elements in the plant and soil. The figures were visualized using R Studio.

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3. Results

159

3.1. Dry Weight

160 The effect of K applications on the dry weight of the stems, leaves, pods, and seeds of soybean
161 plants is shown in Figure S1. The dry weight did not differ in all growth stages during the two
162 years with increasing K application, except for the stems and leaves at the vegetative stage,
163 stems, and pods at harvest in 2019, and stems and leaves at maturity and stems at harvest in
164 2020. The dry weight was relatively lower without the application of K.

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3.2. Effect of K application on mineral elements in plant

167 The concentrations of K, Cs, Sr, Ca, Mg, and N in various parts of the soybean plants in
168 response to K applications are shown in Figures 1 and 2 for 2019 and 2020, respectively. The
169 K concentration in all plant organs (stems, leaves, pods, and seeds) differed significantly
170 among K applications in both years, except for pods and seeds at maturity, and stems, leaves,
171 and seeds at harvest in 2019. The K concentration in the plant organs was relatively higher in

172 applications with higher K levels. For example, the K concentration in pods was ten times
173 higher in the high K application than in the no K application at the harvest stage in 2020.
174 However, the stable Cs in all plant parts differed significantly among K applications in both
175 years, except for stems and leaves at vegetative and harvest stages in 2019. Increased K
176 application has generally led to decreased stable Cs concentrations in the plant parts. For
177 example, the stable Cs concentration of seeds at the harvest stage in 2020 was 46 times lower
178 with high K application than without K application.

179 Except for the leaves at the pod formation and maturity stages in 2019 and the flowering
180 to harvest stages in 2020, the Sr concentration did not differ among K applications. Increased
181 K application has generally led to decreased Sr concentrations in the leaves. For example, the
182 largest decrease in the Sr concentration of leaves was observed in high-K applications at the
183 maturation stage in 2020. However, the Ca concentration in leaves and stems relatively
184 decreased with increasing K application levels at all growth stages in both years, except for the
185 vegetative and harvest stages in 2019, and the vegetative stage in 2020. The largest decrease in
186 Ca concentration was observed in pods at the harvest stage in 2020. In contrast, the Ca
187 concentration of the stems increased with increasing K application level at the harvest stage in
188 2019. Moreover, Mg concentration in all plant organs differed significantly among K
189 applications in both years, except for stems at vegetative, leaves at flowering, and seeds at
190 harvest in 2019, and pods at pod formation and seeds at maturity in 2020. Increased K
191 application has generally led to decreased Mg concentrations in the plant parts. For example,
192 the Mg concentration of leaves at the maturation stage in 2020 was 76 times lower with high
193 K application than without K application.

194 The N concentration of stems and leaves generally increased with increasing the K
195 application levels from pod formation to harvest stages in 2019 and flowering to harvest stages
196 in 2020. The largest differences in N concentration of soybean plants were between the high K
197 application and the no K applications. For example, at the harvest stage in 2019, the leaf N
198 concentration was seven times higher with the high K application than with no K application.
199 Conversely, the differences were smaller at early stages in both years, such as during vegetative
200 growth and flowering in 2019 and vegetative growth in 2020.

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3.3. Effect of K application on mineral elements in soil

203 The ExK, ExCs, ExSr, ExCa, ExMg, ammonium, and nitrate concentrations of the soil in
204 response to K applications are shown in Figure 3. The ExK concentration in the soil differed
205 significantly among K applications in both years, except for the harvest stage in 2020. The ExK

206 concentrations in the soil was relatively higher in applications with higher K levels. For
207 example, ExK concentrations at the pod formation stage in 2019 were four times higher with
208 high K application than without K application.

209 However, the ExCs concentrations at all stages differed significantly among K
210 applications in both years. Moreover, increased K application has generally led to decreased
211 ExCs concentrations in the soil. For example, the highest reduction in ExCs concentrations in
212 the soil was at the flowering stage in 2020, which decreased six -fold with high K application.
213 However, the ExSr, ExCa and ExMg concentrations in all stages did not differ among the K
214 applications at any growth stages in either year, except at vegetative and harvest in 2020 of
215 ExMg concentrations.

216 The ammonium concentration in the soil generally decreased with increasing the K
217 application levels at the harvest stage in 2019 and from flowering to harvest stages in 2020.
218 The largest decrease in ammonium concentration in the soil was observed in the harvest stage
219 with high K application in 2019. On the other hand, the difference was small during the
220 vegetative to maturity stages in 2019 and the vegetative stage in 2020. However, the nitrate
221 concentration in the soil was reduced by increasing the K application from pod formation to
222 harvest in 2019 and from flowering to harvest in 2020. A large decrease in nitrate concentration
223 in the soil was observed during the pod formation stage in 2019 with high K application. The
224 reduction in nitrate in the soil was two times higher with K application than without K
225 application at the pod formation stage in 2019. In contrast, the difference in nitrate
226 concentration was relatively small during the vegetative and flowering stages in 2019 and the
227 vegetative stage in 2020. Moreover, the nitrate concentration in 2020 increases from flowering
228 to pod formation.

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3.4. Correlations among mineral elements in plant and soil

231 The Pearson correlation analysis was performed to establish the correlation between the
232 concentration of each pair of elements in plants (K-Cs, K-Sr, K-Mg, Sr-Ca, Sr-N, and Sr-Mg)
233 and soil (ExK-ExCs, ExK-ExSr, ExK-ExMg, ExSr-ExCa, ExSr-ExMg, ExSr-ammonium, and
234 ExSr-nitrate) under K application (Table 1). The Pearson correlation analysis of mineral
235 elements in plants showed that K concentration was significantly negatively correlated with Cs
236 and Sr concentrations in both years, and but only with Mg concentrations in 2020 (Figure S2).
237 The Sr concentration was significantly positively correlated with Ca and Mg concentration in
238 both years and significantly inversely correlated with N concentration in 2020 (Figure S3). In
239 order to further elucidate the relationship between K and Sr, we explored its relationship in

240 growth stages and plant organs. The K concentration was significantly negatively correlated
241 with Sr concentration in all growth stages except vegetative and in all plant organs except seed
242 (Figure 4).

243 The Pearson correlation analysis of mineral elements in soil showed that the ExK
244 concentration in the soil was significantly negatively correlated with ExCs concentrations in
245 the soil in both years but was not likely to be correlated with ExSr and ExMg concentrations
246 in the soil (Figure S4). The ExSr concentration in the soil was significantly positively correlated
247 with the ExCa and ExMg concentrations in the soil in both years (Figure S5). The ExSr
248 concentration in the soil was unlikely to be correlated with ammonium and nitrate
249 concentrations in the soil in 2019 but significantly in 2020 (Figure S5).

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4. Discussion

252 Since the nuclear incident in the FDNPP, the practice of applying fertilizer in cultivation
253 activities has been recommended as a preventive measure to reduce RCs transmission to the
254 edible parts of plants. The application of K in cultivation has successfully reduced the rate of
255 RCs translocation (e.g., Kato et al. 2015). However, there is no explanation for how this
256 countermeasure relates to Sr. It is necessary to consider the simultaneous release of RCs and
257 RSr into the environment should another nuclear accident occur. This implementation may also
258 affect the nutritional balance and the state of other elements such as K, Cs, Sr, Ca, Mg and N,
259 and the interrelationships of these elements are poorly understood.

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4.1. Effect of K application on K, Cs, Sr, Ca, Mg, and N concentration in plant

262 Except for the pods and seeds at the mature stage and stems, leaves, and seeds at the harvest
263 stage in 2019, the K concentration in all plant parts differed significantly among K application
264 in both years (Figures 1 and 2). The largest difference in K concentration in soybean plants was
265 in the pods at the harvest stage in 2020, when high K application was ten times higher than no
266 K application. A higher K concentration in plant organs can be attributed to a higher K
267 concentration in the soil, although the dry weight does not generally vary among the K
268 treatments (Figure S1), as confirmed by previous studies on buckwheat (Kubo et al. 2017) and
269 soybean (Matsunami et al. 2021). However, increased K application has generally led to a
270 decrease in stable Cs concentrations (Figures 1 and 2) in all plant organs. The largest decrease
271 in stable Cs concentration was observed in the seeds at the harvest stage in 2020 with high K
272 application. A similar tendency was also observed in the analysis of RCs uptake behavior using
273 the same field (Suzuki et al., 2023), which indicate that a similar behavior of RCs and Cs was

274 observed nine years after the accident. These results are consistent with other findings that K
275 application effectively reduces RCs (Kato et al. 2015) and stabilizes Cs (Tsukada et al. 2002)
276 in rice. K application might be inhibiting the translocation of Cs from soil to plant regardless
277 of radioactive or stable status due to competition between K and Cs at the root absorption site.
278 Plant root cell membranes appear to be mainly involved in Cs uptake via two transport
279 pathways, namely the K transporter and the K channel pathway (Zhu and Smolders 2000). Cs
280 and K have similar chemical properties and compete for the binding sites in proteins (Avery
281 1995). According to (Fujimura et al. 2014), adequate external K levels inhibit the expression
282 of K transporters with a high affinity for Cs.

283 The increased K application led to decreased Sr concentration in leaves, Ca
284 concentration in the leaves and stems (Figure 1 and 2) as confirmed by previous studies
285 (Nielsen and Edwards 1982; Melnitchouchk and Hodson 2004; Tuma et al. 2004). Additionally,
286 Mg concentrations in plant parts were reduced relatively by increased K application (Figure 1
287 and 2) as confirmed by previous studies (Lanyon and Heald 1983; Kang et al. 2019). Our results
288 showed that with a high K application, the leaves at maturation stages in 2020 displayed the
289 largest drop in Sr and Mg concentrations. However, the largest decrease in Ca concentration
290 appeared with high K application in the pods at the harvest stage in 2020. Sr and Ca or Mg are
291 chemically similar and compete for the same receptor sites on biological membranes, but Sr
292 cannot replace Ca or Mg in plants. More than 50% of Sr is absorbed by plants and accumulates
293 in cell walls, similar to Ca (Anupama et al. 2016; Gupta et al. 2018; Qiu et al. 2021). Ca is
294 relatively immobile in plant cells and is not readily circulated to tissue parts despite the high
295 Ca applied (Knez and Stangoulis 2021). Ca is involved in the response to external stimuli in
296 major cellular processes, but the response depends on the movement of K across membranes
297 (Sardans and Penuelas 2021) while Sr is transported from the roots via a K plasma membrane
298 transporter (Burger and Lichtscheidl 2019). Moreover, the presence of high Ca concentrations
299 can also lead to Mg deficiency (Hansen and Munns, 1988; Plaut and Grieve, 1988). In case of
300 Mg, the physiological role of this divalent cation is different from Ca. There are many
301 fundamental functions of Ca in cellular metabolism, while Mg plays a significant role in
302 chlorophyll synthesis, ion transport, and cation balance regulation, in addition to activating
303 more than 300 enzymes (He et al., 2012). As in this study, the decreased Ca concentrations
304 were similar to the decreases in Sr concentrations due to the K application. The Sr and Ca
305 concentrations and also Sr and Mg concentrations had a similar pattern in leaves, i.e.,
306 decreasing with increasing K application at the pod formation and maturity in 2019, and at the
307 flowering and maturity stage in 2020 (Figures 1 and 2). Sr may use the same cell entry

308 mechanisms as Ca and Mg, such as plasma membrane transporters, due to its physicochemical
309 similarities (Burger and Lichtscheidl, 2019). Ca can be replaced by Sr, thereby lowering Mg
310 and Ca content in plants (Burger and Lichtscheidl, 2019; Moyen and Roblin, 2010). Increasing
311 K in soil solution might influence the presence of other ions (including K, Ca, Mg and Sr)
312 which is played a role in the adsorption and release of Sr and RSr due to competition for
313 exchange sites, thus influencing Sr uptake (Burger and Lichtscheidl 2019). Also, the
314 involvement of other elements, such as Sr, interferes with Ca uptake (Rato et al. 2010) and Mg
315 uptake (Moyen and Roblin, 2010). The decreased Sr and Ca levels in the leaves in this study
316 as confirmed by previous reports (Moyen and Roblin 2010; Chen et al. 2012; Zhang et al. 2020)
317 might be due to the indirect involvement of Mg after K was applied (Trankner et al. 2018; Ding
318 et al. 2016). While these findings suggest that K application in the soils suppresses Sr transport
319 to the leaves but does not affect the soybean's dry weight it might be due to ExMg
320 concentration in the soils (Figure 3) affected to Mg uptake then dry weights as confirmed by a
321 previous study (Hailes et al. 1997). The Mg element is instrumental in forming dry matter and
322 partitioning carbon to sink organs since carbohydrate accumulation in source leaves is reduced
323 by Mg deficiency (Gransee and Fuhrs 2013) as confirmed by our results (Figure 1-2). There is
324 a similar pattern between Sr and Mg concentrations in leaves that decreased with increasing K.
325 Despite its small amount in this study, Sr is not detrimental to plant growth, and its uptake is a
326 side effect of divalent cation absorption. Nevertheless, the K level in this study was adequate
327 for seed production.

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4.2. Effect of K application on ExK, ExCs, ExSr, ExCa, ExMg, ammonium, and nitrate concentration in soil

331 The ExK concentrations in the soil were relatively higher in application with higher K levels
332 in both years, except for the harvest stage in 2020 (Figure 3). This is expected owing to the
333 application of K in this study. However, there is no difference between normal and high K
334 application to ExK concentrations in the soil at beginning (vegetative) and at the end of growth
335 stages (harvest) in both years. It might be due to the characteristics of K uptake which is slowed
336 in the vegetative stage but increases rapidly during flowering maturity stages (Halevy, 1976;
337 Mullins and Burmester, 1990). In addition, it could be caused by soil properties, even though
338 they were excluded from this study. Uzoho and Ekeh (2014) reported that soil K status affects
339 by sand, silt, clay, silt/clay ratio, organic matter, pH, total N, P, Ca, Mg, cation exchange
340 capacity, base saturation, sodium (Na), and hydrogen (H).

341 K application generally led to decreased ExCs concentrations in the soil in both years
342 (Figure 3). Increasing ExK in the soil tends to decrease ExCs, which has also been observed in
343 various crops (Kato et al. 2015; Kubo et al. 2015, 2017, 2018; Matsunami et al. 2021). ExK
344 concentrations in the soil increased following K fertilizer application and suppressed RCs
345 uptake during the growing season (Komatsu et al. 2017), which is also expected for stable Cs.
346 Generally, Cs ions exchange with K ions at frayed edge sites (Okumura et al. 2013). The
347 reduction in ExCs might be due to formation of the frayed edge sites on the clay minerals after
348 K applied (Kubo et al. 2017). In contrast, the ExSr and ExCa, and ExMg concentrations in the
349 soil (Figure 3) did not differ among K applications in either year, except at vegetative and
350 harvest in 2020 of ExMg concentrations. K, Ca and Mg (which have similar characteristics to
351 Sr) share the same soil particle binding site (Bonomelli et al. 2019). Consequently, excess or
352 deficiency of K can affect the availability of the other cations in the soil, including Sr and Ca
353 or Sr and Mg. For example, K application to the soil might decrease the ease of replacing the
354 clay fraction Mg, and consequently, less Mg is available for uptake (Hovland and Caldwell
355 1960). Tuma et al. (2004) revealed that K and Ca could not be handled separately from other
356 nutrients because antagonistic relationships arise. Though we have found that Sr uptake was
357 decreased in the shoot of soybean by the application of K, we did not analyze the root, so the
358 possibility of root-to-shoot transfer was decreased by K application is remained. In order to
359 determine whether K application has caused Sr uptake and/or distribution among plants, a
360 confirmation test should be conducted.

361 The ammonium and nitrate concentrations in the soil (Figure 3) generally decreased
362 with increasing K application, as confirmed by previous reports (Beauchamp 1982; Nguyen et
363 al. 2001; Ajazi et al. 2013). Increased K application might result in saturation in the interlayer
364 space in the soil, which decreases ammonium fixation or impairs ammonium release (Scherer
365 1982; Nieder et al. 2011) and decreases nitrate concentrations in the soil. If plants do not absorb
366 nitrate in the soil solution, it can easily leach because nitrate and soil are negatively charged
367 (Ito 2018). Moreover, nitrate levels in the soil increased from flowering to pod formation in
368 2020, might be due to the additional application of N fertilizer in this study that applied after
369 flowering stages then influences nitrate concentration in the soil.

370 **4.3. The relationship of Sr with K with the reduction of Cs concentration**

371 Correlation analysis showed that the K concentration in the plant organs was significantly
372 negatively correlated with stable Cs and Sr concentrations in the plant organs in both years,
373 and but only with Mg concentrations in 2020 (Figure S2). However, the effect of K application
374 on Sr concentration was not observed unlike Cs or Mg (Figures 1 and 2). These results reveal

375 that K application reduces the transfer of Cs and Mg from soil to plant organs. However, the
376 different mechanisms should be considered in the case of K's relationship with Sr. Though it
377 was also indicated that higher K concentrations in the plant organs were accompanied by lower
378 Cs, Sr, and Mg concentrations in the plant organs after K application, as confirmed by previous
379 studies (Kabata-Pendias and Szteke 2015; Myrvang et al. 2016), we have further analyzed the
380 relationship between K and Sr relationship divided by the growth stages and plant organs
381 (Figure 4). The relationship between K and Sr clearly changed with growth stages, and it was
382 demonstrated that during the early growth stages, the Sr concentration was rather stable
383 regardless of the K concentration level in the plant while there was a clear negative relationship
384 was observed during the maturity and harvest stages. This is indicating that the K and Sr
385 movement in the plant is different. Plants can rapidly transfer K throughout their entire organ
386 system, but Ca becomes largely immobile, and Sr behaves similarly to Ca (Creger and Allen
387 1969; Mengel 1985). It is further confirmed by the differences between plant organs (Figure
388 4). Significant negative correlations were observed except for seeds, and the relationship was
389 most obvious in the leaf, and it was also confirmed that the K and Sr decreased with the growth.
390 Since our results only showed a reduction in Sr concentration in the leaves while reductions in
391 Mg concentrations relatively occurred in all plant organs after K application (Figure 1-2), also
392 the Sr concentration was significantly positively correlated with Ca and Mg concentration in
393 both years (Figure S3), it was estimated that the absorption of Sr was not disturbed by the K
394 application while the re-translocation of Sr was disturbed, while it is further requested to
395 investigate how Sr was stored and distributed with the change of K levels in the organs. When
396 Sr was absorbed into plants and their cells using K and Ca channels (Burger and Lichtscheidl
397 2018, 2019), the K effect may have altered the behavior of these channels.

398 Moreover, the ExK concentration was significantly negatively correlated with the ExCs
399 concentration in both years (Figure S4). The ExK concentration in the soil was unlikely to be
400 correlated with the ExSr concentration in the soil and ExMg concentrations in the soil (Figure
401 S4). It can be explained that increasing the ExK concentration in the soil suppressed ExCs and
402 not ExSr, ExCa and ExMg concentrations in the soil. Previously, Roca and Vallejo (1995)
403 reported on the effects of soil K and Ca on RCs and RSr transfer to lettuce plants, but the
404 relationship of K to Sr has not yet been clarified. Our results revealed that K application directly
405 decreased Cs uptake, and indirectly decreased Sr and Mg uptake by the soybean plants. During
406 root absorption, it may be not only the involvement and competition between K and Cs that
407 influence Cs translocation from soil to plants, but there may also be the effect of related
408 elements (such as Mg) on Sr translocation from soil to plants. The large amounts of K

409 competitively inhibited Mg uptake and resulting in reduced protein synthesis (Guo et al., 2016).
410 An indirect relationship between K suppress the uptake rate of Sr needs further investigation.
411 It is particularly important to examine the mineral balance of the related elements that might
412 support the application of K for reducing RCs and RSr translocation from soil to plants in a
413 preparedness scenario for nuclear accidents.

414 There was significantly positively correlated between Sr with Ca and Sr with Mg
415 concentration occurred in this study, either in plant or soil. However, the role of K in the soil-
416 plant interaction between Sr and Ca is not yet clear. The results of this recent study illustrate
417 that (1) K application did not affect Sr transport, but it might affect re-translocation of Sr; (2)
418 the link between K and Sr clearly changed with different growth phases, and it was shown that
419 throughout the early growth stages, the Sr concentration was largely steady regardless of the
420 quantity of K in the plant; (3) it is likely that K interacts with both Sr and Ca or Mg when
421 entering the plant's cells, since K and Ca or Mg share channels during transport to plant organs
422 with Sr (Burger and Lichtscheidl 2019); or (4) during the reduction of Cs uptake using K
423 application to the soil, these cations (Ca, Mg and Sr) compete through competition in the
424 apoplast of the root cortex (Smolders et al. 1997). The Sr concentration was small and there
425 was no actual reduction was observed by K application, which indicate that K application does
426 not support the idea to reduces RSr. However, as the re-translocation of Sr was reduced when
427 K concentration is low, it is important to investigate whether this mechanism could occur in
428 other species and/or in the combination of other minerals in the future.

429 **5. Conclusions**

430 Our results indicate that K application to soybean plants influenced the variables in this study.
431 K application generally increased the K and N concentrations and decreased the Cs, Ca, and
432 Mg concentrations in plant organs but did not affect dry weight. In addition, increased K
433 application typically leads to decreased Sr concentrations in the leaves. K application increased
434 ExK and decreased ExCs, ammonium, and nitrate concentrations in the soil but did not affect
435 ExSr, ExCa, and ExMg. Our findings imply that increasing ExK concentration in the soil
436 suppressed only ExCs and not ExSr concentration, but it might have affected Sr re-
437 translocation into plant tissues. Though we have hypothesized that Sr uptake was also reduced
438 by the application of K fertilizer, however the results did not support the idea, on the other
439 hand, re-translocation of Sr in the plant was negatively affected by K concentration. Research
440 on the impact of the exclusive use of K fertilizer on Sr translocation and the involvement of
441 other related mineral elements is required.

442 **References**

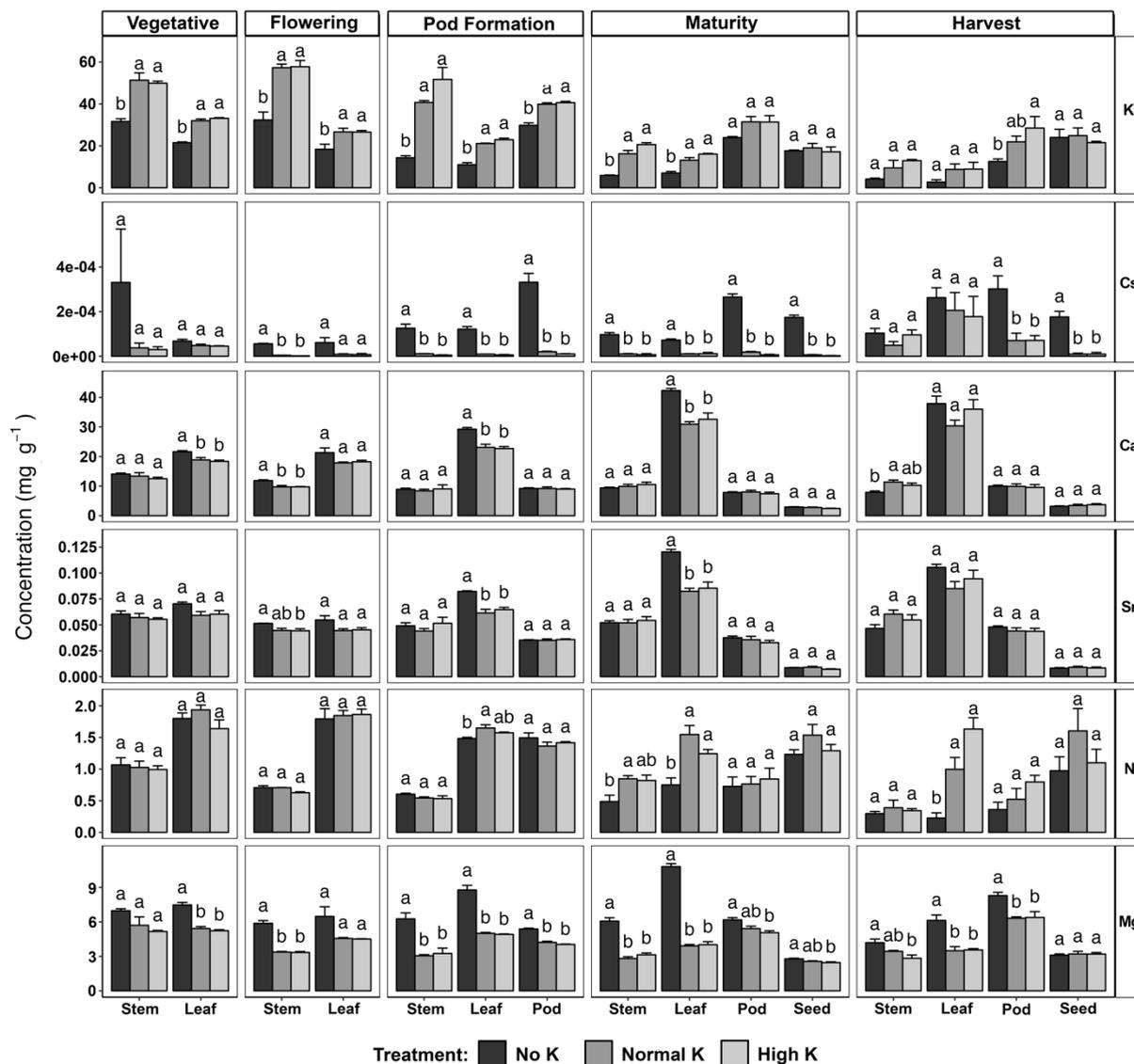
- 443 Ajazi, A., L. Miho, A. Bani, and A. Maci. 2013. "Effect of Potassium on Fixation of
444 Ammonium by Clay Minerals in Different Soil Layers." *Albanian Journal Of*
445 *Agricultural Sciences* 12 (4): 751–757.
- 446 Anupama, M., Ashok. K. K., and Naveena. L. L. J. 2016. "Mechanism of Strontium Uptake
447 and Transport in *Neurospora crassa*." *European Journal of Pharmaceutical and*
448 *Medical Research* 3 (5): 379–386. [https://storage.googleapis.com/journal-](https://storage.googleapis.com/journal-uploads/ejpmr/article_issue/1462018992.pdf)
449 [uploads/ejpmr/article_issue/1462018992.pdf](https://storage.googleapis.com/journal-uploads/ejpmr/article_issue/1462018992.pdf)
- 450 Ando, T., and Ogata, A. 1980. "Trace Rapid Quantification Method of Nitrate." [In Japanese]
451 *Japanese Society of Soil Science and Fertilizer* 51 (1): 48–54.
452 Doi:10.20710/dojo.51.1_48
- 453 Avery, S. V. 1995. "Cesium Accumulation by Microorganisms - Uptake Mechanisms, Cation
454 Competition, Compartmentalization and Toxicity." *Journal of Industrial*
455 *Microbiology* 14 (2): 76–84. doi: 10.1007/bf01569888.
- 456 Beauchamp, E. G. 1982. "Fixed Ammonium and Potassium Release from 2
457 Soils." *Communications in Soil Science and Plant Analysis* 13 (11):927–943. doi:
458 10.1080/00103628209367322.
- 459 Belli, M., U. Sansone, R. Ardiani, E. Feoli, M. Scimone, S. Menegon, and G. Parente. 1995.
460 "The Effect of Fertilizer Applications on Cs-137 Uptake by Different Plant-Species
461 and Vegetation Types." *Journal of Environmental Radioactivity* 27 (1): 75–89. doi:
462 10.1016/0265-931x(94)00038-x.
- 463 Bonomelli, Claudia, Pilar M. Gil, and Bruce Schaffer. 2019. "Effect of Soil Type on Calcium
464 Absorption and Partitioning in Young Avocado (*Persea americana* Mill.)
465 trees." *Agronomy* 9 (12): 837. doi: 10.3390/agronomy9120837.
- 466 Burger, Anna, and Irene Lichtscheidl. 2018. "Stable and Radioactive Cesium: a Review about
467 Distribution in the Environment, Uptake and Translocation in Plants, Plant Reactions
468 and Plants' Potential for Bioremediation." *Science of the Total*
469 *Environment* 618:1459–1485. doi: 10.1016/j.scitotenv.2017.09.298.
- 470 Burger, Anna, and Irene Lichtscheidl. 2019. "Strontium in the Environment: Review About
471 Reactions of Plants Towards Stable and Radioactive Strontium Isotopes." *Science of*
472 *the Total Environment* 653: 1458–1512. doi: 10.1016/j.scitotenv.2018.10.312.
- 473 Chen, M., Y. L. Tang, J. Ao, and D. Wang. 2012. "Effects of Strontium on Photosynthetic
474 Characteristics of Oilseed Rape Seedlings." *Russian Journal of Plant Physiology* 59
475 (6): 772–780. doi: 10.1134/s1021443712060052.
- 476 Chu, Qingnan, Toshihiro Watanabe, Zhimin Sha, Mitsuru Osaki, and Takuro Shinano. 2015.
477 "Interactions Between Cs, Sr, and Other Nutrients and Trace Element Accumulation
478 in Amaranthus Shoot in Response to Variety Effect." *Journal of Agricultural and*
479 *Food Chemistry* 63 (8): 2355–2363. doi: 10.1021/jf5058777.
- 480 Creger, C. R., and Allen, W. S. 1969. "Strontium Mobility in Germinating Seeds and Plants".
481 *Plant Physiology* 44(3):439–441. doi:10.1104/PP.44.3.439
- 482 Ding, K. K., S. J. Liu, Y. X. He, D. Yan, F. S. Zhang, S. F. Wang, J. H. Guo, W. Zhang, X.
483 Wang, and X. Y. Jiang. 2016. "Simulating the Transfer of Strontium-90 from Soil to
484 Leafy Vegetables by Using Strontium-88." *Water Air and Soil Pollution* 227 (11):
485 414. doi: 10.1007/s11270-016-3098-2.

- 486 Evans, E. J., and A. J. Dekker. 1969. "Effect of Nitrogen on Cesium-137 in Soils and Its
487 Uptake by Oat Plants." *Canadian Journal of Soil Science* 49 (3): 349–355. doi:
488 10.4141/cjss69-048.
- 489 Fujimura, Shigeto, Junko Ishikawa, Yuuki Sakuma, Takashi Saito, Mutsuto Sato, and Kunio
490 Yoshioka. 2014. "Theoretical Model of the Effect of Potassium on the Uptake of
491 Radiocesium by Rice." *Journal of Environmental Radioactivity* 138: 122–131. doi:
492 10.1016/j.jenvrad.2014.08.017.
- 493 Gransee, A., and H. Fuhrs. 2013. "Magnesium Mobility in Soils as a Challenge for Soil and
494 Plant Analysis, Magnesium Fertilization and Root Uptake Under Adverse Growth
495 Conditions." *Plant and Soil* 368 (1–2): 5–21. doi: 10.1007/s11104-012-1567-y.
- 496 Guo, W. L., H. Nazim, Z. S. Liang, and D. F. Yang. 2016. "Magnesium Deficiency in Plants:
497 an Urgent Problem." *Crop Journal* 4 (2): 83–91. doi: 10.1016/j.cj.2015.11.003.
- 498 Gupta, D. K., W. Schulz, G. Steinhauser, and C. Walther. 2018. "Radiostrontium Transport in
499 Plants and Phytoremediation." *Environmental Science and Pollution Research* 25
500 (30): 29996–30008. doi: 10.1007/s11356-018-3088-6.
- 501 Hailes, K. J., R. L. Aitken, and N. W. Menzies. 1997. "Magnesium in Tropical and
502 Subtropical Soils from North-Eastern Australia .2. Response by Glasshouse-Grown
503 Maize to Applied Magnesium." *Australian Journal of Soil Research* 35 (3): 629–641.
504 doi: 10.1071/s96082.
- 505 Halevy, J. 1976. "Growth-Rate and Nutrient-Uptake of 2 Cotton Cultivars Grown Under
506 Irrigation." *Agronomy Journal* 68 (5): 701–705. doi:
507 10.2134/agronj1976.00021962006800050002x.
- 508 Hansen, E. H., and D. N. Munns. 1988. "Effect of CaSO₄ and NaCl on Mineral Content of
509 *Leucaena leucocephala*." *Plant and Soil* 107 (1): 101–105. doi: 10.1007/bf02371550.
- 510 He, H. H., T. M. Bleby, E. J. Veneklaas, H. Lambers, and J. Kuo. 2012. "Precipitation of
511 Calcium, Magnesium, Strontium and Barium in Tissues of Four *Acacia* Species
512 (Leguminosae: Mimosoideae)." *Plos One* 7 (7). doi: 10.1371/journal.pone.0041563.
- 513 Hovland, Dwight; Caldwell, A. C. 1960. "Potassium and Magnesium Relationships in Soils
514 and Plants." *Soil Science* 89(2): 92–96.
- 515 Ito, Masanori. 2018. "Improvement of Nitrate-leaching Control Technology Using an Anion
516 Exchange Compound on Agriculture 1: Synthesis of a Mg-Fe System Layered Double
517 Hydroxide and Its Anion Exchange Characteristics." *Soil Science and Plant
518 Nutrition* 64 (1): 123–129. doi: 10.1080/00380768.2017.1413685.
- 519 Kabata-Pendias, A, and B Szteke. 2015. *Trace Elements in Abiotic and Biotic Environments*.
520 Edited by 1st Edition. Boca Raton: CRC Press. doi: 10.1201/b18198
- 521 Kang, D. J., Y. J. Seo, and Y. Ishii. 2019. "Distribution of Cesium and Cationic Mineral
522 Elements in Napiergrass." *Sn Applied Sciences* 1 (12). doi: 10.1007/s42452-019-
523 1750-3.
- 524 Kato, N., N. Kihou, S. Fujimura, M. Ikeba, N. Miyazaki, Y. Saito, T. Eguchi, and S. Itoh.
525 2015. "Potassium Fertilizer and Other Materials as Countermeasures to Reduce
526 Radiocesium Levels in Rice: Results of Urgent Experiments in 2011 Responding to
527 the Fukushima Daiichi Nuclear Power Plant Accident." *Soil Science and Plant
528 Nutrition* 61 (2): 179–190. doi: 10.1080/00380768.2014.995584.

- 529 Knez, M., and J. C. R. Stangoulis. 2021. "Calcium Biofortification of Crops-Challenges and
530 Projected Benefits." *Frontiers in Plant Science* 12: 669053. doi:
531 10.3389/fpls.2021.669053.
- 532 Komatsu, M., K. Hirai, J. Nagakura, and K. Noguchi. 2017. "Potassium Fertilisation Reduces
533 Radiocesium Uptake by Japanese Cypress Seedlings Grown in a Stand Contaminated
534 by the Fukushima Daiichi Nuclear Accident." *Scientific Reports* 7: 15612. doi:
535 10.1038/s41598-017-15401-w.
- 536 Konno, M., and Y. Takagai. 2018. "Simple Radiometric Determination of Strontium-90 in
537 Seawater Using Measurement of Yttrium-90 Decay Time Following Iron Barium Co-
538 precipitation." *Analytical Sciences* 34 (11): 1277–1283. doi: 10.2116/analsci.18P145.
- 539 Kubo, K., S. Fujimura, H. Kobayashi, T. Ota, and T. Shinano. 2017. "Effect of Soil
540 Exchangeable Potassium Content on Cesium Absorption and Partitioning in
541 Buckwheat Grown in a Radioactive Cesium-contaminated Field." *Plant Production
542 Science* 20 (4): 396–405. doi: 10.1080/1343943x.2017.1355737.
- 543 Kubo, K., T. Hirayama, S. Fujimura, T. Eguchi, N. Nihei, S. Hamamoto, M. Takeuchi, T.
544 Saito, T. Ota, and T. Shinano. 2018. "Potassium Behavior and Clay Mineral
545 Composition in the Soil with Low Effectiveness of Potassium Application." *Soil
546 Science and Plant Nutrition* 64 (2): 265–271. doi: 10.1080/00380768.2017.1419830.
- 547 Kubo, K., K. Nemoto, H. Kobayashi, Y. Kuriyama, H. Harada, H. Matsunami, T. Eguchi, N.
548 Kihou, T. Ota, S. Keitoku, T. Kimura, and T. Shinano. 2015. "Analyses and
549 Countermeasures for Decreasing Radioactive Cesium in Buckwheat in Areas Affected
550 by the Nuclear Accident in 2011." *Field Crops Research* 170: 40–46. doi:
551 10.1016/j.fcr.2014.10.001.
- 552 Lanyon, L.E. and Heald, W.R. 1983. "Magnesium, Calcium, Strontium, and Barium." In
553 *Methods of Soil Analysis*, A. Page (Ed.), 247–262. doi:
554 10.2134/agronmonogr9.2.2ed.c14
- 555 Matsunami, H., T. Uchida, H. Kobayashi, T. Ota, and T. Shinano. 2021. "Comparative
556 Dynamics of Potassium and Radiocesium in Soybean with Different Potassium
557 Application Levels." *Journal of Environmental Radioactivity* 233: 106609. doi:
558 10.1016/j.jenvrad.2021.106609.
- 559 Mengel, K. 1985. "Potassium Movement within Plants and Its Importance in Assimilate"
560 Transport. In *Potassium in Agriculture*, edited by R.D. Munson, 397–411. AAS,
561 CSSA, and SSSA, Madison, WI. doi: 10.2134/1985.POTASSIUM.C16
- 562 Melnitchouck, A., and M. Hodson. 2004. "Genotype X Environment Interaction in the
563 Uptake of Cs and Sr from Soils by Plants." *Journal of Plant Nutrition and Soil
564 Science* 167 (1): 72–78. doi: 10.1002/jpln.200321273.
- 565 Morino, Y., T. Ohara, and M. Nishizawa. 2011. "Atmospheric Behavior, Deposition, and
566 Budget of Radioactive Materials from the Fukushima Daiichi Nuclear Power Plant in
567 March 2011." *Geophysical Research Letters* 38. doi: 10.1029/2011gl048689.
- 568 Moyen, C., and G. Roblin. 2010. "Uptake and Translocation of Strontium in Hydroponically
569 Grown Maize Plants, and Subsequent Effects on Tissue Ion Content, Growth and
570 Chlorophyll a/b Ratio: Comparison with Ca Effects." *Environmental and
571 Experimental Botany* 68 (3): 247–257. doi: 10.1016/j.envexpbot.2009.12.004.

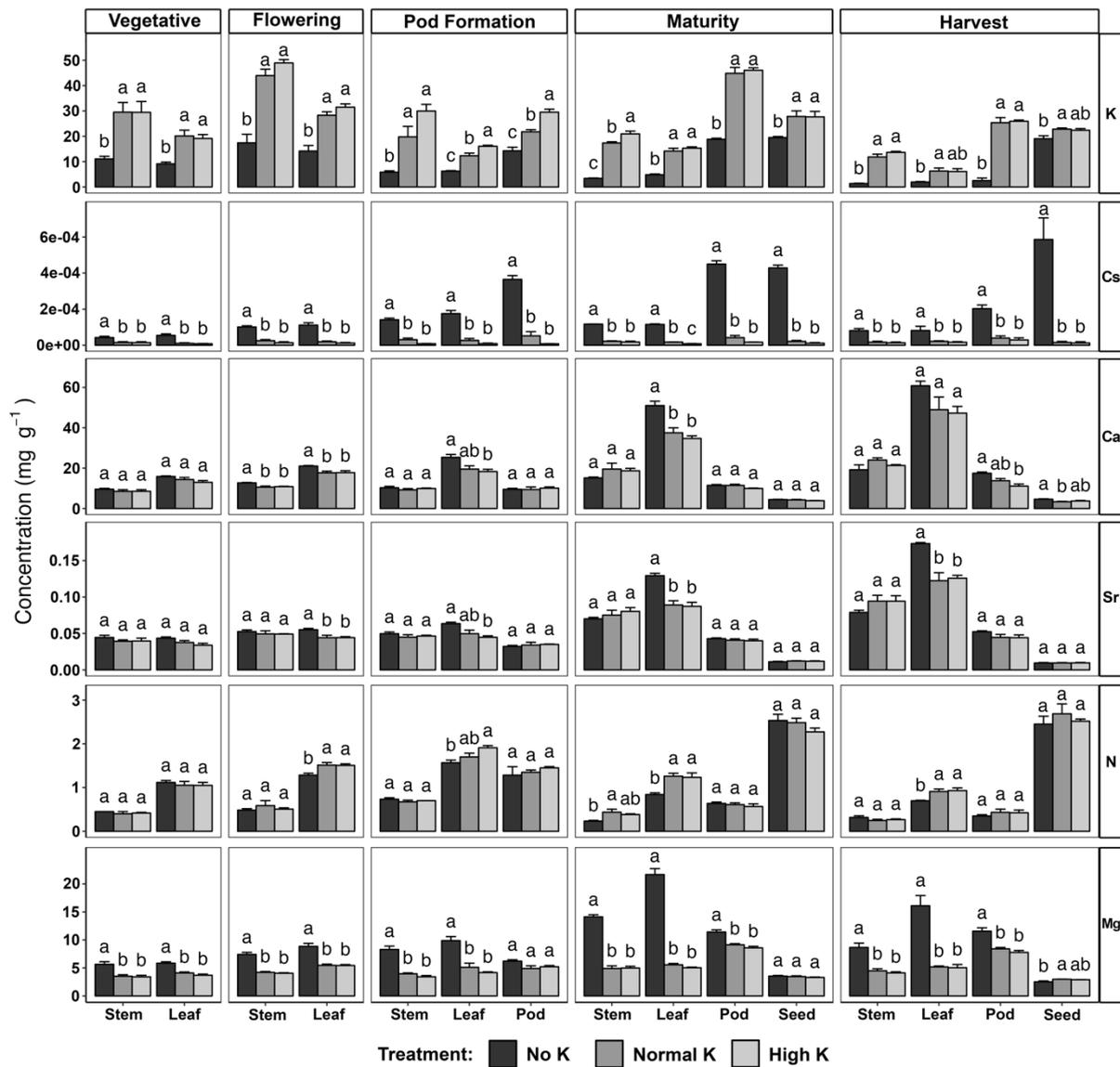
- 572 Mullins, G. L., and C. H. Burmester. 1990. "Dry-matter, Nitrogen, Phosphorus, and
573 Potassium Accumulation by 4 Cotton Varieties." *Agronomy Journal* 82 (4): 729–736.
574 doi: 10.2134/agronj1990.00021962008200040017x.
- 575 Myrvang, M. B., M. H. Hillersoy, M. Heim, M. A. Bleken, and E. Gjengedal. 2016. "Uptake
576 of Macro Nutrients, Barium, and Strontium by Vegetation from Mineral Soils on
577 Carbonatite and Pyroxenite Bedrock at the Lillebukt Alkaline Complex on Stjernoy,
578 Northern Norway." *Journal of Plant Nutrition and Soil Science* 179 (6): 705–716. doi:
579 10.1002/jpln.201600328.
- 580 Neilsen, G. H., and T. Edwards. 1982. "Relationships between Ca, Mg, and K in Soil, Leaf,
581 and Fruits of Okanagan Apple Orchards." *Canadian Journal of Soil Science* 62 (2):
582 365–374. doi: 10.4141/cjss82-040.
- 583 Nguyen, H., J. J. Schoenau, K. Van Rees, D. Nguyen, and R. Qian. 2001. "Long-term
584 Nitrogen, Phosphorus and Potassium Fertilization of Cassava Influences Soil
585 Chemical Properties in North Vietnam." *Canadian Journal of Soil Science* 81 (3):
586 481–488. doi: 10.4141/s00-048.
- 587 Nieder, R., D. K. Benbi, and H. W. Scherer. 2011. "Fixation and Defixation of Ammonium in
588 Soils: a Review." *Biology and Fertility of Soils* 47 (1): 1–14. doi: 10.1007/s00374-
589 010-0506-4.
- 590 Okumura, M., H. Nakamura, and M. Machida. 2013. "Mechanism of Strong Affinity of Clay
591 Minerals to Radioactive Cesium: First-Principles Calculation Study for Adsorption of
592 Cesium at Frayed Edge Sites in Muscovite." *Journal of the Physical Society of
593 Japan* 82 (3). doi: 10.7566/jpsj.82.033802.
- 594 Osaki, M., T. Shinano, and T. Tadano. 1992. "Carbon-nitrogen Interaction in Field Crop
595 Production." *Soil Science and Plant Nutrition* 38 (3): 553–564. doi:
596 10.1080/00380768.1992.10415087.
- 597 Qiu, N. W., L. Tian, X. F. Yan, H. Y. Dong, M. Y. Zhang, G. L. Han, and F. Zhou. 2021.
598 "The Interplay Between Calcium and Strontium in Chinese Cabbage Under Normal
599 and Low Calcium Conditions." *Hortscience* 56 (8): 875–880. doi:
600 10.21273/hortsci15867-21.
- 601 Plaut, Z., and C. M. Grieve. 1988. "Photosynthesis of Salt-stressed Maize as Influenced by
602 Ca:Na Ratios in the Nutrient Solution." *Plant and Soil* 105 (2): 283–286. doi:
603 10.1007/bf02376793.
- 604 Rato, A. E., A. C. Agulheiro, J. M. Barroso, and F. Riquelme. 2010. "Effect of Different
605 Calcium Fruit Content in Physical and Chemical Properties of European
606 Plum." *Journal of Plant Nutrition* 33 (3): 391–404. doi:
607 10.1080/01904160903470448.
- 608 Roca, M. C., and V. R. Vallejo. 1995. "Effect of Soil potassium and Calcium on Cesium and
609 Strontium Uptake by Plant-Roots." *Journal of Environmental Radioactivity* 28 (2):
610 141–159. doi: 10.1016/0265-931x(94)00052-x
- 611 Sardans, J., and J. Penuelas. 2021. "Potassium Control of Plant Functions: Ecological and
612 Agricultural Implications." *Plants* 10 (2): 419. doi: 10.3390/plants10020419.
- 613 Scheiner, D. 1976. "Determination of Ammonia and Kjeldahl Nitrogen by Indophenol
614 Method." *Water Research* 10 (1): 31–36. doi: 10.1016/0043-1354(76)90154-8.

- 615 Scherer, H. W. 1982. "Fixed NH_4N in Relation to Euf-extractable- K." *Plant and Soil* 64 (1):
616 67–71. doi: 10.1007/bf02375160.
- 617 Smolders, E., L. Sweeck, R. Merckx, and A. Cremers. 1997. "Cationic Interactions in
618 Radiocaesium Uptake from Solution by Spinach." *Journal of Environmental*
619 *Radioactivity* 34 (2): 161–170. doi: 10.1016/0265-931x(96)00023-9.
- 620 Suzuki, M., Eguchi, T., Azuma, K., Nakao, A., Kubo, K., Fujimura, S., Syaifudin, M.,
621 Maruyama, H., Watanabe, T., and Shinano, T. 2023. "The Ratio of Plant ^{137}Cs to
622 Exchangeable ^{137}Cs in Soil is a Crucial Factor in Explaining the Variation in ^{137}Cs
623 Transferability from Soil to Plant". *Science of the Total Environment* 857: 159208.
624 doi: 10.1016/J.SCITOTENV.2022.159208
- 625 Trankner, M., E. Tavakol, and B. Jakli. 2018. "Functioning of Potassium and Magnesium in
626 Photosynthesis, Photosynthate Translocation and Photoprotection." *Physiologia*
627 *Plantarum* 163 (3): 414–431. doi: 10.1111/ppl.12747.
- 628 Tsukada, H., H. Hasegawa, S. Hisamatsu, and S. Yamasaki. 2002. "Transfer of Cs-137 and
629 Stable Cs from Paddy Soil to Polished Rice in Aomori, Japan." *Journal of*
630 *Environmental Radioactivity* 59 (3): 351–363. doi: 10.1016/s0265-931x(01)00083-2.
- 631 Tsukada, H., A. Takeda, T. Takahashi, H. Hasegawa, S. Hisamatsu, and J. Inaba. 2005.
632 "Uptake and Distribution of Sr-90 and Stable Sr in Rice Plants." *Journal of*
633 *Environmental Radioactivity* 81 (2-3): 221–231. doi: 10.1016/j.jenvrad.2004.01.037.
- 634 Tuma, J., M. Skalicky, L. Tumova, P. Blahova, and M. Rosulkova. 2004. "Potassium,
635 Magnesium and Calcium Content in Individual Parts of *Phaseolus vulgaris* L. Plant as
636 Related to Potassium and Magnesium Nutrition." *Plant Soil and Environment* 50 (1):
637 18–26. doi: 10.17221/3637-pse.
- 638 Uzoho, B. U., & Ekeh, C. 2014. "Potassium Status of Soils in Relation to Land use Types in
639 Ngor-Okpala, Southeastern Nigeria." *Journal of Natural Sciences Research* 4(6).
- 640 Watanabe, T., R. Tomizaki, R. Watanabe, H. Maruyama, T. Shinano, M. Urayama, and Y.
641 Kanayama. 2021. "Ionic Differences between Tomato Introgression Line IL8-3
642 and Its Parent Cultivar M82 with Different Trends to the Incidence of Blossom-end
643 rot." *Scientia Horticulturae* 287: 110266. doi: 10.1016/j.scienta.2021.110266.
- 644 Watanabe, T., M. Urayama, T. Shinano, R. Okada, and M. Osaki. 2015. "Application of
645 Ionics to Plant and Soil in Fields Under Long-term Fertilizer
646 Trials." *Springerplus* 4: 781. doi: 10.1186/s40064-015-1562-x.
- 647 Zhang, W. R., Z. Kang, Q. Wang, N. W. Qiu, M. Chen, and F. Zhou. 2020. "The Biological
648 Effects of Strontium (Sr-88) on Chinese cabbage." *Plant Soil and Environment* 66 (4):
649 149–154. doi: 10.17221/108/2020-pse.
- 650 Zhu, Y. G., and E. Smolders. 2000. "Plant uptake of Radiocaesium: a Review of
651 Mechanisms, Regulation and Application." *Journal of Experimental Botany* 51 (351):
652 1635–1645. doi: 10.1093/jexbot/51.351.1635.



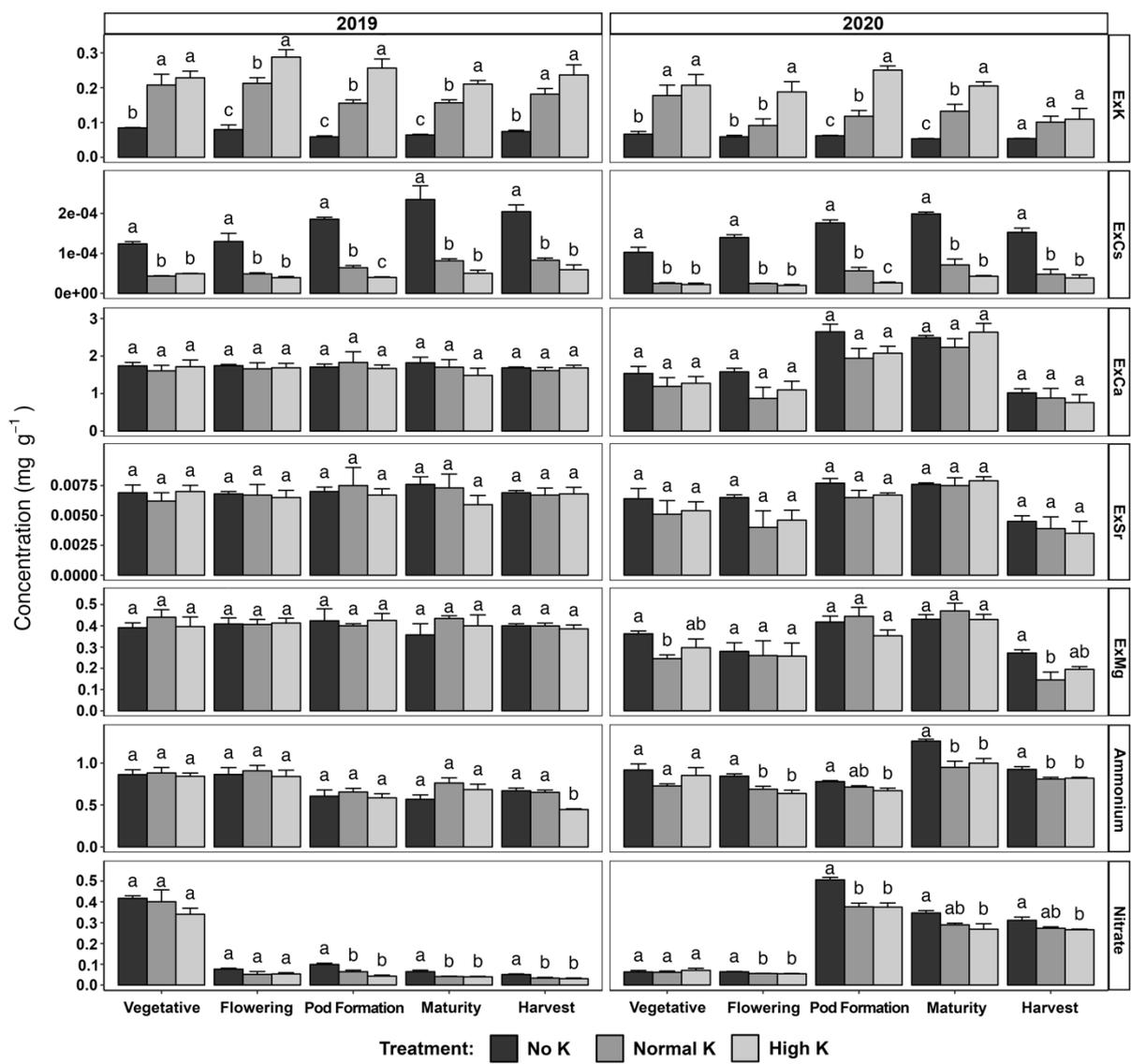
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655 **Figure 1.** The effect of K applications on K, Cs, Sr, Ca, N and Mg concentrations in soybean
 656 plants at Date City in 2019. The vertical bars indicate the standard error of three replicates. The
 657 different letters (a, b, and ab) represent significant differences ($p < 0.05$) according to Tukey's
 658 test following a one-way ANOVA ($n = 3$).



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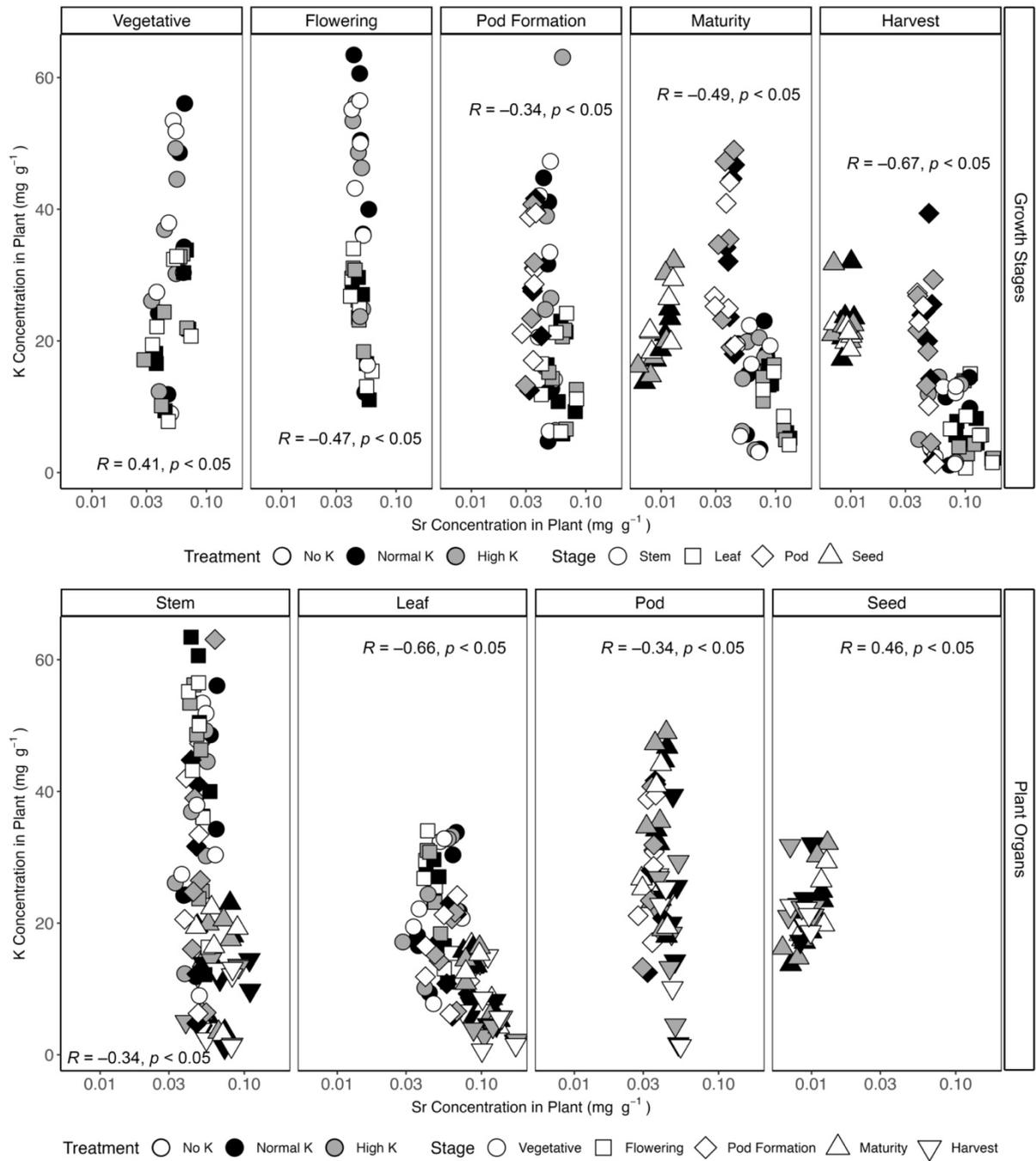
660 **Figure 2.** The effect of K applications on K, Cs, Sr, Ca, N and Mg concentrations in soybean
 661 plants at Date City in 2020. The vertical bars indicate the standard error of three replicates. The
 662 different letters (a, b, ab, and c) represent significant differences ($p < 0.05$) according to
 663 Tukey's test following a one-way ANOVA ($n = 3$).



665

666 **Figure 3.** The effect of K applications on ExK, ExCs, ExSr, ExCa, ExMg, ammonium and
 667 nitrate concentrations in the soil at Date City in 2019 and 2020. The vertical bars indicate the
 668 standard error of three replicates. Different letters (a, b, c, and ab) represent significant
 669 differences ($p < 0.05$) according to Tukey's test following a one-way ANOVA ($n = 3$).

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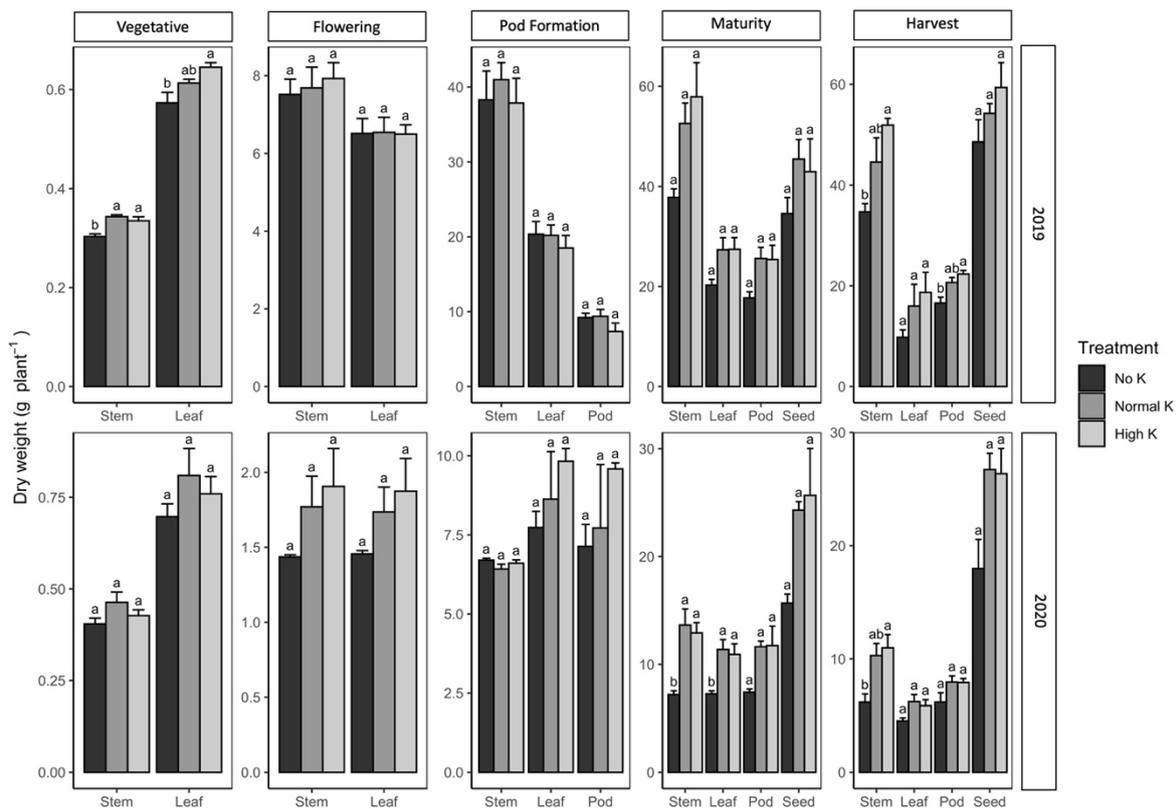
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Figure 4. Pearson's correlation between K and Sr concentration in soybean plants after K applications at Date City in the different growth stages and plant organs.

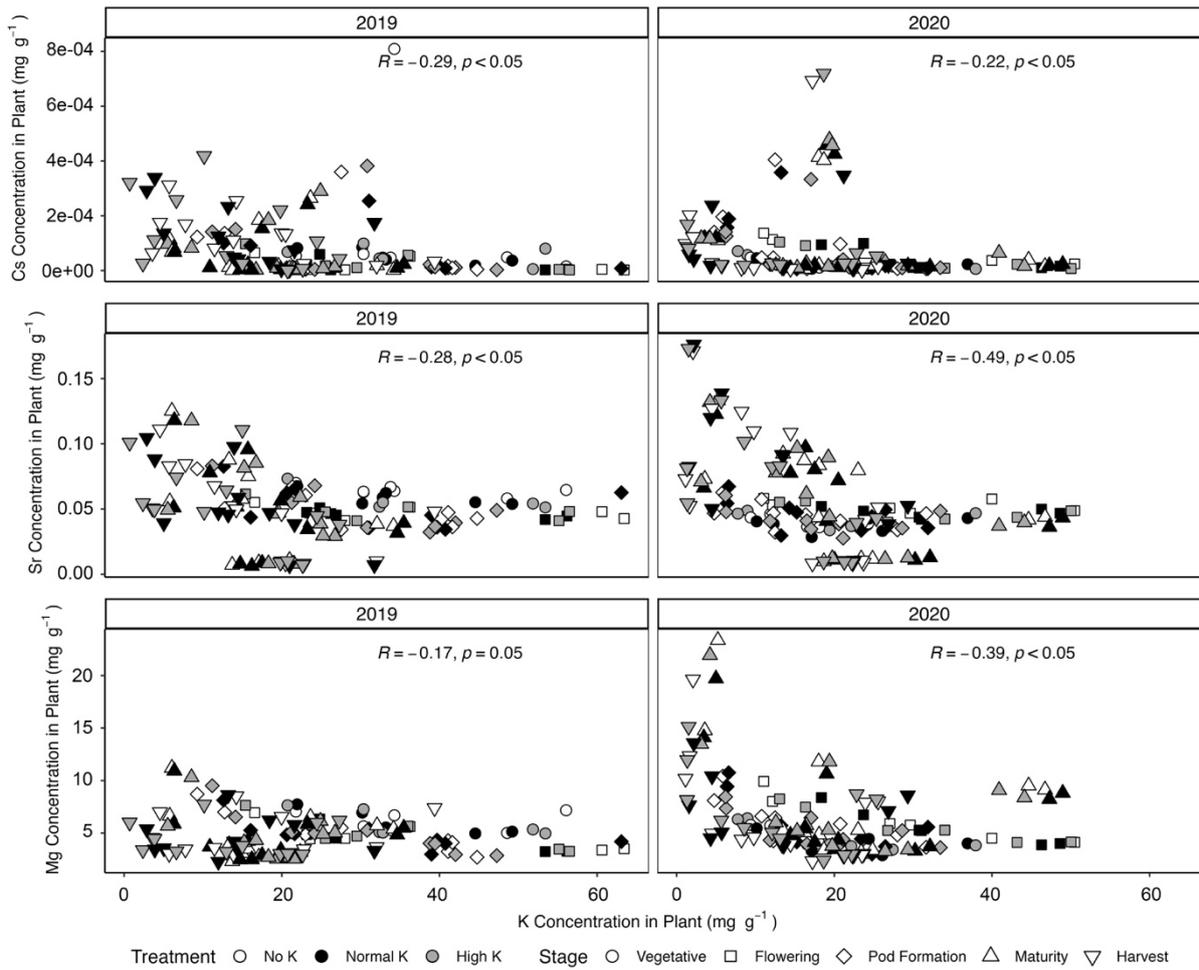
674 **Table 1.** Tabulated summary of Pearson correlation analysis among elements in plant and soil.

Parameters	2019		2020	
	Pearson's <i>r</i>	<i>p</i> -value	Pearson's <i>r</i>	<i>p</i> -value
K vs Cs (plant)	-0.29	0.05*	-0.22	0.05*
K vs Sr (Plant)	-0.28	0.05*	-0.49	0.05*
K vs Mg (plant)	-0.17	0.05	-0.39	0.05*
Sr vs Ca (plant)	0.92	0.05*	0.93	0.05*
Sr vs N (plant)	0	0.95	-0.47	0.05*
Sr vs Mg (plant)	0.5	0.05*	0.52	0.05*
ExK vs ExCs (soil)	-0.83	0.05*	-0.7	0.05*
ExK vs ExSr (soil)	-0.13	0.4	0.16	0.3
ExK vs ExMg (soil)	-0.07	0.7	0.17	0.3
ExSr vs ExCa (soil)	0.92	0.05*	0.93	0.05*
ExSr vs ExMg (soil)	0.88	0.05*	0.96	0.05*
ExSr vs ammonium (soil)	-0.11	0.5	0.4	0.05*
ExSr vs nitrate (soil)	-0.04	0.8	0.34	0.05*

675 Significant modules are denoted with * ($p < 0.05$).

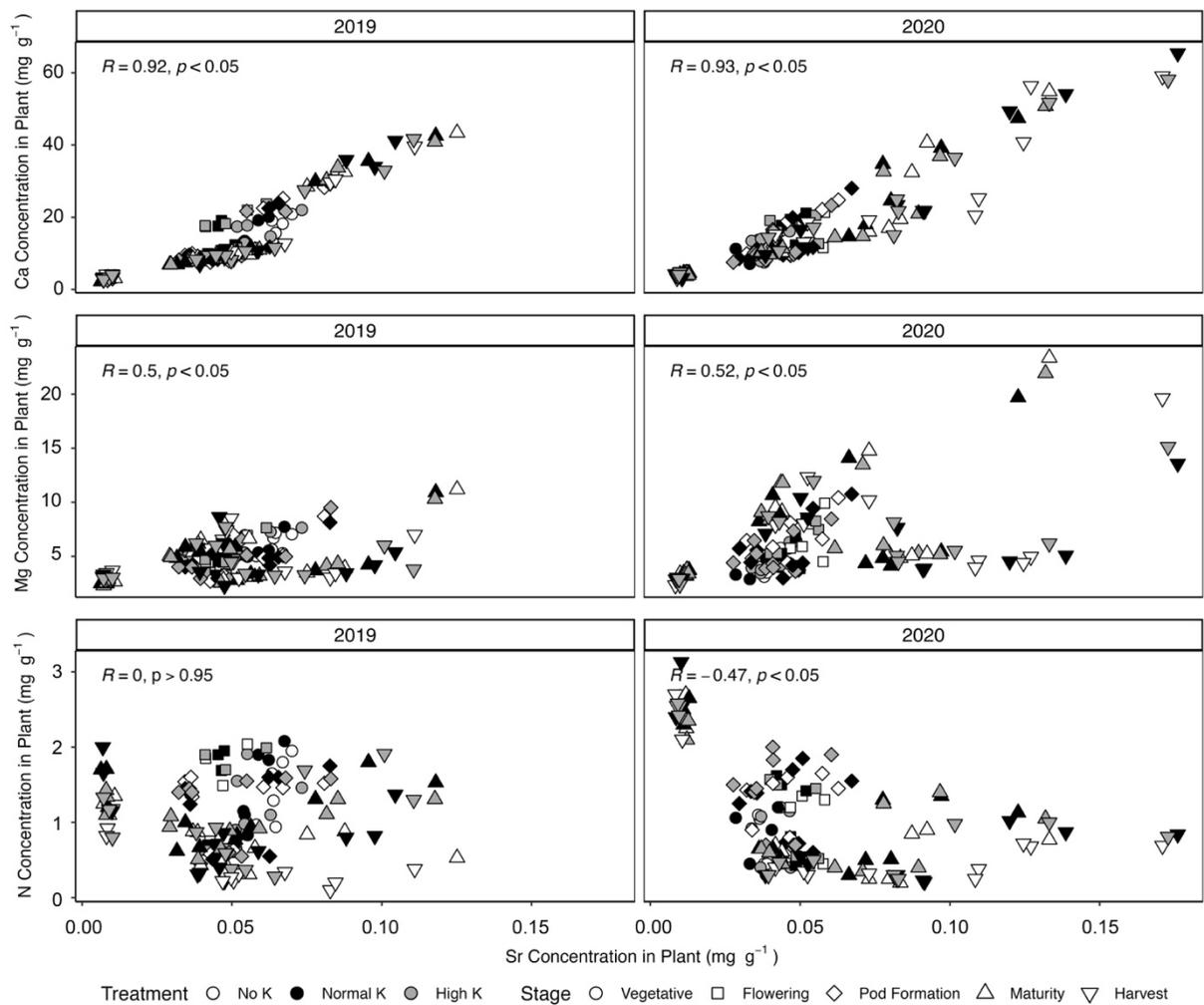


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 678 **Figure S1.** The effect of K applications on the dry weight of soybean plants at Date City in
 679 2019 and 2020. The vertical bars indicate standard error of three replicates. Different letters (a,
 680 b, and ab) represent significant differences ($p < 0.05$) according to Tukey's test following a
 681 one-way ANOVA ($n = 3$).



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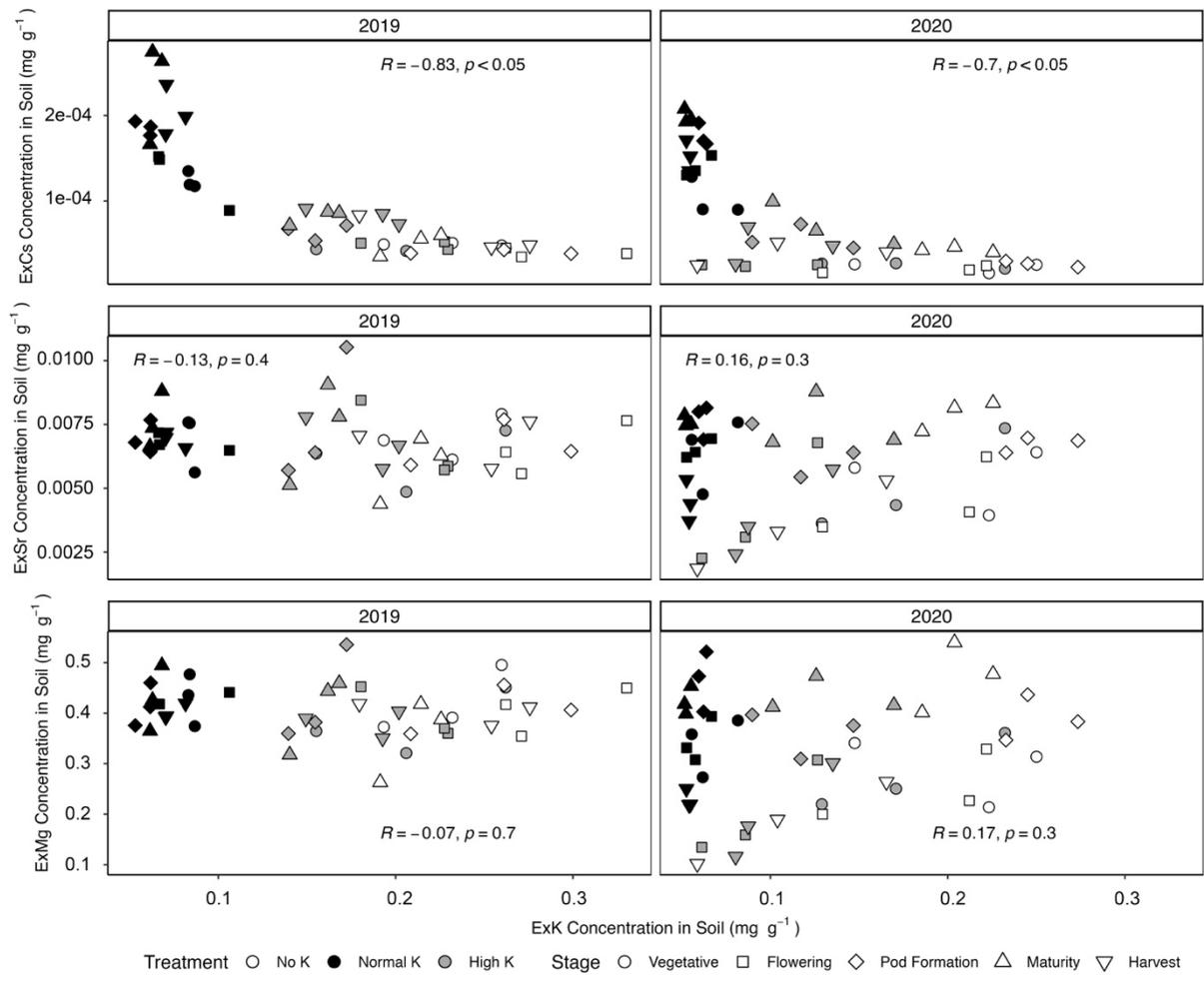
683 **Figure S2.** Pearson's correlation of K with Cs, Sr, and Mg concentration in soybean plants
 684 after K applications at Date City in 2019 and 2020.



685

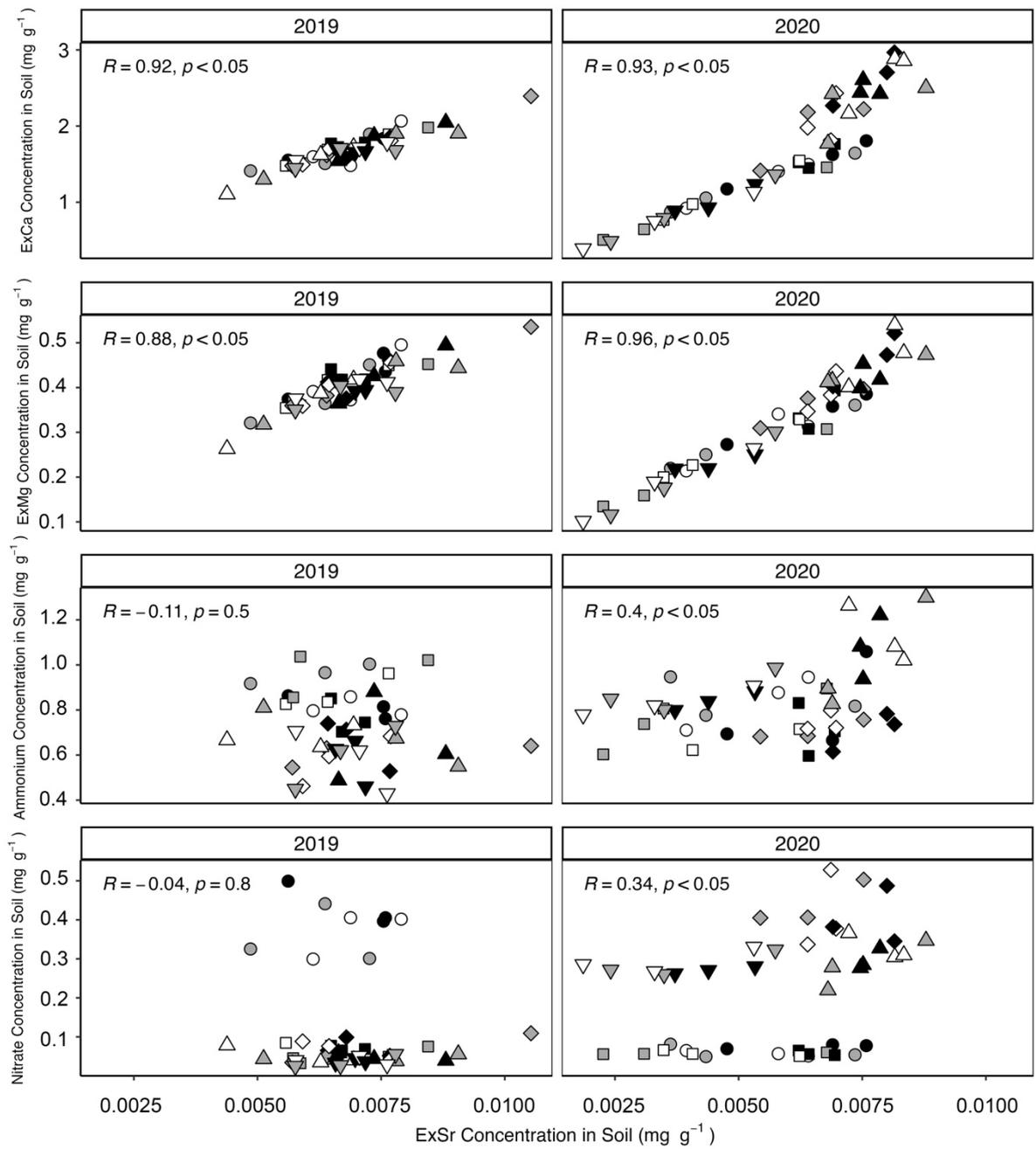
686 **Figure S3.** Pearson's correlation of Sr with Ca, Mg, and N concentration in soybean plants
 687 after K applications at Date City in 2019 and 2020.

688



689

690 **Figure S4.** Pearson's correlation of ExK with ExCs, ExSr, and ExMg concentration in the soil
 691 after K applications at Date City in 2019 and 2020.



692

Treatment ○ No K ● Normal K ● High K Stage ○ Vegetative □ Flowering ◇ Pod Formation △ Maturity ▽ Harvest

693

Figure S5. Pearson's correlation of ExSr with ExCa, ExMg, Ammonium, and Nitrate concentration in the soil after K applications at Date City in 2019 and 2020.

694

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