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1 **Dependency of radioiodine root uptake by crops on soil characteristics**

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26

27 **Abstract**

28 The aim of this study was to quantify the parameters of root uptake of radioiodine
29 by agricultural crops under steady state conditions depending on the main soil
30 characteristics. For this purpose, a long-term (483-days) pot experiment was conducted
31 under natural conditions in the Chernobyl Exclusion Zone to grow radish in soils of four
32 different types with added isotope ^{125}I . The experiment demonstrated an increase in root
33 uptake of radioiodine by radish roots in the following sequence of soil types: clay soil <
34 loam soil << sandy soil (Chernozem \approx Phaeozem<Greyzem<<Podzoluvisol). The
35 obtained results have been analyzed in conjunction with the results of our previous
36 studies to identify the factors determining the parameters of root uptake of radioiodine
37 by the studied crop species. The ^{125}I concentration ratios (*CRs*) in edible parts of crop
38 species (radish roots: from 0.003 for Chernozem to 0.02 for Podzoluvisol; lettuce
39 leaves: 0.004-0.04; bean pods: 0.0003-0.004; wheat straw: 0.01-0.1; and wheat seeds:
40 0.0001-0.001) anticorrelated with the characteristics of the soils studied: the distribution
41 coefficients *Kd* of ^{125}I (from 112 L kg $^{-1}$ for clay soils to 19 L kg $^{-1}$ for sandy soil, $R^2=0.56-$
42 0.97) and *Kd'* of stable iodine (93-19 L kg $^{-1}$, $R^2=0.43-0.74$), stable iodine concentration
43 in soil (6.2-0.5 mg kg $^{-1}$, $R^2=0.71-0.88$), and humus content (4.0-0.8%, $R^2=0.44-0.78$).
44 The obtained steady-state *CR* values and their dependence on the soil characteristics
45 can be used to model the root uptake of ^{129}I , a long-lived radiological contaminant, and
46 to predict its accumulation in human food and animal feed.

47

48 **Keywords:** radioiodine; concentration ratio; transfer factor; root uptake; activity
49 concentration; pot experiment.

50

51 **Highlights**

52

53 Radioiodine root uptake into plants has been studied in a long-term pot experiment

54 Radioiodine concentration ratios CRs were determined for four different soil types

55 Radioiodine CRs inversely correlate with iodine distribution coefficients in soil

56 Radioiodine CRs inversely correlate with stable iodine and humus contents in soil

57

59 1. Introduction

60 Long-term radioactive waste storage facilities in various geological formations
61 can be a source of radioactive contamination of the environment with long-lived
62 radionuclides, such as ^{129}I ($T_{1/2}=15.7\cdot 10^6$ y). To date, the major sources of ^{129}I releases
63 into the environment are nuclear weapon tests with an estimated input of 10^{11} - 10^{12} Bq
64 (Tikhomirov, 1983; Deitermann et al., 1989), and nuclear fuel cycle plants, especially
65 those that reprocess irradiated fuel (Daly et al., 1974; Robens et al., 1988; Wershofen et
66 al., 1991; Satoh et al., 2019). The Chernobyl (1986) and Fukushima (2011) accidents
67 resulted in releases of $(4-5)\cdot 10^{10}$ Bq and $(0.7-6)\cdot 10^{10}$ Bq of ^{129}I , respectively
68 (Steinhauser et al., 2014) and caused a sharp increase in the $^{129}\text{I}/^{127}\text{I}$ ratio in the
69 contaminated areas (Szidat et al., 2000; Hoshi et al., 1994; Sahoo et al., 2009; Miyake
70 et al., 2012).

71 Iodine is an important element involved in the metabolism in animal and human
72 organisms. The United Nations Scientific Committee on the Effects of Atomic Radiation
73 (UNSCEAR) considers several pathways of iodine intake to humans (UNSCEAR, 2016):
74 inhalation (average daily intake of $0.29 \mu\text{g d}^{-1}$); ingestion of surface water ($5.3 \mu\text{g d}^{-1}$);
75 ingestion of marine fish and shellfish ($11 \mu\text{g d}^{-1}$); deposition onto crops that are directly
76 consumed by humans or ingested by dairy and beef cattle and then subsequently
77 ingested by humans ($6.6 \mu\text{g d}^{-1}$); and root uptake from soil and surface waters followed
78 by ingestion of crops and animal products ($200 \mu\text{g d}^{-1}$, i.e., major contribution). Due to
79 its long half-life period, ^{129}I can significantly influence the radioecological situation on the
80 Earth and contribute to the collective human exposure doses to in the long term.

81 UNSCEAR estimates the average daily intake of ^{129}I into human based on the
82 concentration ratio or the transfer factor of radionuclides from soil and water to food
83 without considering the intake rate of stable iodine (^{127}I). According to these estimates,
84 for equal rates of atmospheric releases of the long-lived volatile radionuclides (^3H , ^{14}C ,

85 ^{85}Kr and ^{129}I), ^{129}I provides the largest contribution to annual collective doses to
86 population (UNSCEAR, 2016). The soil-to-plant transfer of radioactive isotopes of iodine
87 and, consequently, their intake into the human body may depend on the stable iodine
88 content in soil (Korobova et al., 2010a). Therefore, assessment of the concentration
89 ratio (CR , the ratio of the activity concentration of radionuclide in a plant, Bq kg^{-1} , to its
90 concentration in the soil, Bq kg^{-1} ; referred also as the transfer factor, TF (IAEA, 2010))
91 of radioiodine for agricultural plants in various soil conditions is an important scientific
92 and practical task.

93 After the contamination of pasture vegetation and cattle fodder with radioactive
94 iodine isotopes released by the Chernobyl accident, the short-lived ^{131}I isotope
95 contributed more than 90% of the dose absorbed by the human thyroid gland due to
96 intake of radionuclides with milk (Bazyka et al., 2016). Since the physical-chemical
97 properties of ^{131}I and ^{129}I are identical, analysis of the long-lived ^{129}I contents in soil and
98 components of animal and human diets is the most efficient method for retrospective
99 assessment of the doses from ^{131}I in the early stages after the Chernobyl and
100 Fukushima accidents (Michel et al., 2015; Muramatsu et al., 2015; Balonov et al., 2018).

101 Iodine metabolism in humans and animals is well studied (Howard et al., 1996;
102 Voigt and Kiefer, 2007; Vandecasteele et al., 2000). Also, the experimental data on
103 foliar contamination of vegetation and resulting translocation of the short-live iodine
104 radioisotope (^{125}I) to edible parts of various crops are available (Henner et al., 2013;
105 Hurtevent et al., 2013). These data were acquired to assess the consequences of an
106 irrigation with contaminated water. Long-term prediction of human intake of ^{129}I that
107 radioactive waste repositories could release requires knowledge of relevant factors
108 driving root uptake of radioiodine by edible parts of crops under different soil-climate
109 conditions. However, until recently, relatively little attention has been paid to the
110 radioiodine root uptake studies (Prister et al., 1979; Tikhomirov et al., 1980; Tikhomirov,
111 1983; Kashin, 1987; Haushild and Aumann, 1989), as well as to the behavior of iodine

112 in soil (Prister et al., 1977; Prokhorov et al., 1978; Katagiri et al., 1997; Sheppard et al.,
113 1992, 1995; Muramatsu and Yoshida, 1996, Yoshida et al., 1998, Sheppard, 2003).
114 Literature data are rather limited and contradictory, and reported root uptake
115 parameters of radioiodine in agricultural ecosystems vary within two orders of
116 magnitude (IAEA, 2010).

117 Quasi-equilibrium distribution in soil of ionic forms of radioiodine (iodide and
118 iodate) is achieved by relatively rapid processes (Whitehead, 1973; Bors et al., 1991;
119 Yoshida et al, 1992; Sheppard et al, 1995). The results of numerous studies of sorption
120 dynamics in soil are in agreement to indicate that iodine is absorbed mainly by organic
121 matter of soil and, to a lesser extent, by sesquioxides of iron and aluminum (Whitehead,
122 1974a, 1974b, 1978; Bors et al., 1988; Christiansen and Carlsen, 1989; Muramatsu et
123 al., 1990, 2002; Muramatsu and Yoshida, 1996; Sheppard and Thibault, 1992;
124 Sheppard et al., 1995; Yoshida et al., 1998; Bostok et al., 2002, 2003).

125 Studies of iodine radioisotopes transfer in different soils have not allowed to
126 establish a reliable correlation between radioiodine bioavailability and main soil
127 properties (Tikhomirov et al., 1980; Muramatsu et al., 1990; Evans and Hammad, 1995;
128 Marumatsu, 1996). Radioiodine concentration ratios obtained in field experiments
129 (Prister et al., 1977; Deitermann et al., 1989; Hauschild, 1989; Muramatsu et al., 1993,
130 2002) for major crop species ranged from 0.1 to 5 in vegetative plant organs and from
131 0.0005 to 0.07 in reproductive organs i.e. fruits. ^{129}I environmental concentrations are
132 very low and their measurement is a challenge. In this regard, another iodine
133 radioisotope, ^{125}I ($T_{1/2}=59.16$ days), is more convenient for studying radioiodine
134 behavior in the soil-plant system experiments. Most of the available studies of the
135 radioiodine isotopes transfer into plants (Deitermann et al., 1989; Hauschild, 1989;
136 Muramatsu et al., 1993, 2002; Kashparov et al., 2005a) were conducted during the
137 initial dynamic phase of remobilization between the soil components, i.e. without
138 reaching an apparent steady state. The long-term dynamics of radioiodine soil-to-plant

139 transfer and concentration ratios depending on soil characteristics remain poorly
140 studied.

141 In a previous micro-field experiment carried out under natural conditions in the
142 Chernobyl Exclusion Zone, we studied the dynamics of root uptake of ^{125}I by plants from
143 four types of soils, namely Podzoluvisol, Greyzem, Phaeozem and Chernozem
144 (Kashparov et al., 2005a). In that study, injection of 500 Bq of ^{125}I per kilogram of soil
145 enabled reliable measurements of its concentrations in the soil, soil solution, and plants
146 samples only within half a year after the experiment began because of its rapid decay
147 and fixation by soil solid phases.

148 This paper reports the results of a long term (483 days, 18.04.2002-14.08.2003)
149 pot experiment on ^{125}I uptake by radish root in natural conditions achieved through a
150 thousand times higher soil contamination with ^{125}I than in the earlier study by Kashparov
151 et al. (2005a). The main objectives of this study were to obtain parameters of
152 radioiodine transfer from soil to radish roots and to identify the most reliable soil
153 parameters governing the long-term bioavailability of radioiodine in soil. We also
154 compared data obtained from this pot experiment (radish) and original non-published
155 data from the above-mentioned micro-field experiment (lettuce leaves, bean pods,
156 wheat grain and straw) to analyze variability of radioiodine uptake parameters.

157

158 **2. Material and methods**

159 **2.1 Soil characteristics and experimental design**

160 In this experiment we used the same soils (Podzoluvisol, Greyzem, Phaeozem
161 and Chernozem according to FAO-WRB classification (IUSS, 2006)) as in our previous
162 micro-field studies in the Chernobyl Exclusion Zone (Kashparov et al., 2005a, 2005b,
163 2007a, 2007b). These soils with contrasting agrochemical characteristics (texture, pH,
164 organic matter content (OMC), cation exchange capacity (CEC), stable iodine content)
165 are most typical for continental Ukraine and were taken from a 20-cm arable layer of

166 agricultural lands in different regions of Ukraine (Table 1). Soil characteristics in Table 1
167 are from Kashparov et al. (2005a); they were determined according to methods
168 published by Arynushkina (1970) and Lisoval et al. (1984). Stable iodine content in each
169 soil was determined using the method of Proskuryakova (1966) for soils, and the size
170 distributions of the soil particles were obtained using a laser granulometer (HR 850-B).
171 The values presented are average values obtained from 5-12 sample measurements
172 per soil type. According to the IAEA (2010) soil classification, the studied soils can be
173 classified as Sand soil (Podzoluvisol), Loam soil (Greyzem) and Clay soil (Phaeozem
174 and Chernozem) (Table 1).

175 After homogenization, the soils were placed into cylindrical pots 19.5 cm in
176 diameter and 20 cm high. Each pot contained approximately 5 kg of soil at natural field
177 humidity (soil moisture contents were 11-23%, Table 1). On April 18th, 2002, ¹²⁵I in KI
178 form (Amersham Pharmacia Biotech UK Limited, England) at 7.4 MBq per pot (N=2, in
179 duplicate for each soil type) was simultaneously injected into all soil pots, which were
180 then kept in field at the experimental site in the Chernobyl Exclusion Zone (Kashparov
181 et al., 2005a, 2018). After injection, the soil in each pot was thoroughly mixed and
182 sampled for radioactive and stable iodine isotope measurements. The ¹²⁵I activity
183 concentrations and stable iodine concentrations in the soil pots at the initial moment
184 after injection are presented in Table 2.

185

186 **2.2 Plants cultivation**

187 After the injection of ¹²⁵I, we again homogenized the soils in the pots and sowed
188 radish (*Raphanus sativus L.*, French Breakfast variety) according to standard agronomic
189 recommendations. The distance between the seeds was 4-5 cm. The vegetation pots
190 were placed on the ground and kept in natural weather conditions throughout the
191 experiment. When necessary, watering was applied to allow maintaining biomass
192 growth during the vegetation periods.

193 A total of 5 vegetation cycles were carried out for 483 days of the experiment.

194

195 **2.3. Sampling and measurements**

196 Soil from each vegetation pot was sampled after each harvest. For this purpose,
197 we used a cylindrical soil corer (N=5, 1 cm in diameter, 20 cm long) allowing the soil
198 core to be sampled to the full depth of the pot (about 100 g from each vegetation pot).
199 Soil solution was extracted by centrifugation from 20 g aliquots taken from soil core
200 samples, and ^{125}I activities and stable iodine concentrations in the extracts were
201 measured. The aliquot weights were measured before and after centrifugation. The soil
202 solution extracts were then adjusted to a fixed volume with distilled water to measure
203 ^{125}I activity by scintillation γ -spectrometry using a Gamma Track 1185 Series (USA) low-
204 background modular automatic γ -counting system with passive shielding and
205 scintillation NaI detector in the well. Stable iodine content in soil was measured 2 times,
206 before the ^{125}I injection and after the end of the experiment (483 days) by means of
207 kinetic rhodanide-nitrite method for soils (Proskuryakova, 1966). After sampling the
208 aliquots for extraction of soil solution, the remaining portions of the soil cores were
209 thoroughly homogenized and divided into 5 subsamples of 18 g each. In each
210 subsample, ^{125}I activity was determined as the average of 10 measurements by means
211 of scintillation γ -spectrometry. Once measured, the soil samples were returned to the
212 same place from where they were taken from the pots, then the soils in the pots were
213 carefully mixed, and radish was sown again.

214 In the earlier micro-field experiment (Kashparov et al., 2005a), we observed a
215 sharp decrease in the bioavailability of ^{125}I within 80 days after its injection due to its
216 rapid fixation to organic compounds of soils. Accordingly, the radionuclide uptake into
217 radish root decreased during the first and second vegetation periods. For this reason, in
218 the present study, the first harvesting was carried out 83 days after injection of ^{125}I , i.e.,
219 when the equilibrium in the soil–soil solution system was expected to be reached (Table

220 3). Once harvested, the radish roots were washed with distilled water to remove soil
221 particles, homogenized and placed into 20 mL test-tubes. For each vegetation pot, ^{125}I
222 activities were measured in 3-5 samples by means of scintillation γ -spectrometry. To
223 determine the content of stable iodine in the radish root samples, the method reported
224 by Titova (1981) for plants was used. All measurements were performed in fresh
225 samples to avoid iodine volatilization. Iodine concentrations in the soil were converted to
226 dry weight taking into account the soil moisture contents in the samples.

227

228 **2.4 Data processing**

229 All measured activities of ^{125}I were decay corrected on the date of injection.

230 Distribution coefficients (Kds , L kg^{-1}) of ^{125}I and stable iodine were determined as
231 ratios of ^{125}I activity concentrations or stable iodine concentrations in dry soil (Bq kg^{-1} or
232 mg kg^{-1} , respectively, dry weight (DW)) to their concentrations in soil solutions (Bq L^{-1} or
233 mg L^{-1}). Concentration ratios (CRs , dimensionless) of ^{125}I and stable iodine were
234 calculated as the ratios of ^{125}I activity concentrations or stable iodine concentrations in
235 radish roots (Bq kg^{-1} or mg kg^{-1} , respectively, fresh weight (FW)) to their concentrations
236 in soil (Bq kg^{-1} or mg kg^{-1} DW). CR corresponds to the transfer factor (F_V) under
237 equilibrium conditions (IAEA, 2010).

238 We calculated CR values based on the measured soil parameters. Under the
239 equilibrium hypothesis, the radioiodine concentration in the plant is assumed to be
240 linearly correlated with its concentration in the soil solution (IAEA, 2010), i.e.

$$241 \quad A_{radish} = k \cdot A_{sol} \quad (1)$$

242 where A_{radish} is the average ^{125}I activity concentration in radish (kBq kg^{-1}), A_{sol} is
243 the average ^{125}I activity concentration in soil solution (kBq L^{-1}), and k is the
244 bioaccumulation factor (i.e., the plant to soil solution concentrations ratio, L kg^{-1}).

245 CR of ^{125}I can be defined as follows:

$$246 \quad CR = A_{radish}/A_{soil} = k \cdot A_{sol}/A_{soil} = k/Kd \quad (2)$$

247 where A_{soil} is the ^{125}I activity concentration in soil (kBq kg^{-1}).

248 The stable iodine concentration ratio (CR') is defined as follows:

$$249 \quad CR' = k'/Kd' \quad (3)$$

250 where k' is the bioaccumulation factor (L kg^{-1}) and Kd' is the distribution
251 coefficient (L kg^{-1}) for stable iodine.

252 The conventional statistical methods (t -test, non-parametric test, regression
253 analysis) were used to establish the relationships between the studied parameters.

254

255 **3. Results and discussion**

256 **3.1 Iodine isotope concentrations in the soil and plant samples**

257 By the end of the experiment, approximately 20% of the injected ^{125}I activities
258 was lost (Table 2). Taking into account the estimate uncertainties, there was no
259 difference in losses between the 4 soil types. We found no reliable change of the stable
260 iodine contents of the soils over the entire 483-day period of the experiment (Table 2).
261 Prister et al. (1977) reported high rates of radioiodine volatilization (up to 80%) after its
262 application onto the ground surface without further soil mixing. In contrast, in our
263 previous micro-field experiments under natural conditions in the Chernobyl Exclusion
264 Zone (Kashparov et al., 2005a), release of radioiodine from the arable layer of all soils
265 was not reliably detected, because the experimental design suppressed evaporation of
266 the injected radionuclide (soils were moistened and thoroughly mixed to a depth of 10
267 cm following radioiodine injection and to a depth of 20 cm after 1 hour).

268 For all soil types, average stable iodine concentrations in soil solutions were quite
269 close ($0.03\text{-}0.09 \text{ mg L}^{-1}$), and average ^{125}I activity concentrations in soil solutions and
270 radish roots in Podzoluvisol were 5-8 and 3-5 times higher, respectively, compared with
271 other soil types (Tables 2 and 3). Average FW concentrations of stable iodine in radish
272 roots were similar in all soils ($0.02\text{-}0.03 \text{ mg kg}^{-1}$) and did not depend on its
273 concentrations in soil.

274 In winter, when air temperature dropped below 0°C, the ¹²⁵I activity
275 concentrations in soil solutions decreased in all soil types (Table 2). As a result, the
276 values of the distribution coefficient *K_d* of ¹²⁵I in soils in winter were higher than the
277 average for each soil (Table 4), and seasonal changes in *K_d*s were inversely
278 proportional to changes in the ¹²⁵I concentrations in soil solutions. The concentration
279 decreased by an order of magnitude in Podzoluvisol, , whereas this effect was much
280 less pronounced in other soil types. The “freezing” effect was also noted in a study
281 conducted by Bostock et al. (2003). These authors concluded that the decrease in ¹²⁵I
282 extractability due to freezing was indicative of a microbially mediated sorption process.
283 Such an assumption, however, does not explain the absence of a similar decrease in
284 the concentrations of stable iodine in the soil solution sampled in winter (Table 2). On
285 the other hand, the values of ¹²⁵I activity concentration in the soil solution varied
286 significantly during the observation period, even if winter samples were excluded (by an
287 order of magnitude in Podzoluvisol, and by a factor of 3 in other soils; Table 2). Several
288 studies have shown such variations even within a single vegetation period because ¹²⁵I
289 activity concentrations in soil solution are sensitive to variations in environmental factors
290 such as temperature, soil moisture content, and microbial activity factors (Muramatsu et
291 al., 1991, 1993, Yoshida et al., 1998, Bostock et al., 2003). The concentrations of stable
292 iodine in the soil solution in the studied soils varied 3-5-fold during the observation
293 period (Table 2).

294 In the plant samples, the concentrations of both isotopes in each soil differed
295 greatly between harvests (Table 3). Average concentrations of stable iodine in the
296 radish root samples did not differ between the soils, while for ¹²⁵I the concentrations in
297 roots of radish planted in Podzoluvisol were significantly higher (t-test *p*<0.05) than in
298 other three soils. The factors influencing iodine uptake by plants are analyzed below.

299

300 **3.2 Bioaccumulation factors and concentration ratios of iodine in radish roots** 301 **and K_d in soils**

302 Non-parametric analysis revealed a rather weak correlation ($r_s=0.48$, $p=0.03$)
303 between the ^{125}I activity concentrations in radish roots (Table 3) and in soil solutions
304 (Table 2) at harvesting times. The weak correlation can be explained by the fact that the
305 measurement results indicate the concentrations in the soil solution A_{sol} at the moments
306 of sampling, while the concentrations in radish roots A_{radish} were formed by intake of the
307 radionuclide during the whole vegetation period, when the values of A_{sol} could differ
308 from those measured at harvesting. However, a strong linear correlation ($R^2=0.98$)
309 occurs between the averaged values of these two variables for all soil types (with the
310 winter values excluded), i.e., when the influence of temporal variation in the
311 concentrations is eliminated. The average ratio of the concentrations, i.e., the ^{125}I
312 bioaccumulation factor for all soils (eq. 1), can be estimated as $k=0.35\pm 0.07 \text{ L kg}^{-1}$
313 ($R=0.99$). A close average value of the bioaccumulation factor, with greater variation
314 between the soil types, $k=0.40\pm 0.24 \text{ L kg}^{-1}$, was found for stable iodine.

315 The ^{125}I concentration ratios (CR s) for radish roots in all soils (Table 4) agree well
316 with the data obtained in the micro-field experiments (Kashparov et al., 2005a). In
317 Podzoluvisol and Greyzem, the mean values of ^{125}I CR were about half as high as I_{st}
318 CR , whereas in Phaeozem these values did not differ significantly, and in Chernozem
319 they were similar. CR variations over the observation period were greater for ^{125}I (up to
320 a factor of 4) than for I_{st} . For both isotopes, the concentration ratios decreased in the
321 order Podzoluvisol>Greyzem>Phaeozem>Chernozem. Except for Podzoluvisol, the
322 average K_d s of ^{125}I were higher than the K_d 's of the stable isotope. Since concentration
323 ratios are inversely correlated with distribution coefficients (eq. 2 and 3), the average
324 K_d s and K_d 's increased in the same order by soil type. Overall, the values of both
325 analyzed parameters, CR and K_d , in each soil were close for the two isotopes,
326 suggesting that the quasi-equilibrium state of ^{125}I in the soils was approaching. The

327 average concentration ratios of both isotopes can be approximated by the same inverse
 328 dependence on the distribution coefficients with a coefficient equal to the average of the
 329 k and k' values in all soils, $0.39 \pm 0.18 \text{ L kg}^{-1}$ (Fig. 1a). The only outlier is the point for I_{st}
 330 in Podzoluvisol; without this data, R^2 of the correlation increases to 0.97. For steady
 331 state conditions, CR of ^{125}I can be predicted based on the apparent Kd' of stable iodine.
 332 In our observations, CR was negatively correlated ($R^2=0.74$, Fig. 1b) to Kd' with the
 333 coefficient of $0.31 \pm 0.08 \text{ L kg}^{-1}$, which is a mean of the k' values in three soils (without
 334 Podzoluvisol).

335 The average background (natural) concentrations of stable iodine in soil solutions
 336 of the studied soils (A'_{soil}) remained in the range $0.03\text{-}0.09 \text{ mg L}^{-1}$ (Table 2), i.e., were
 337 weakly dispersed and almost constant, leading to consider the proportionality of ^{125}I CR
 338 to the stable iodine concentration (A'_{soil} , Table 2):

$$339 \quad CR = k'/Kd' = k' \cdot A'_{soil} / A'_{soil} = C_I / A'_{soil} \quad (4)$$

340 Therefore, ^{125}I CR in radish roots is negatively correlated to the stable iodine
 341 concentration in the soil ($R^2 = 0.71$, Table 5) as shown in Fig. 1c, and
 342 with $C_I = 0.014 \pm 0.004 \text{ mg kg}^{-1}$.

343 Tikhomirov (1983) suggested a linear dependence of the stable iodine
 344 background level in soil A'_{soil} on humus content H , %:

$$345 \quad A'_{soil} = a \cdot H + b \quad (5)$$

346 with $a = 0.43$ and $b = 0.25$

347 In this pot experiment, the coefficients of this linear equation were different when
 348 plotting data from Tables 1 and 2: $a = 1.6$ and $b = -0.76$, with a pairwise correlation
 349 coefficient $r = 0.97$ between A'_{soil} and H . ^{125}I CR in radish roots and H in soil were
 350 negatively correlated ($R^2 = 0.78$, Table 5, Fig. 1d).

351 In our experiment, the accuracy of the CR assessment did not differ significantly
 352 ($RMSE = 0.003\text{-}0.004$) between the $CR(Kd')$, $CR(A'_{soil})$, and $CR(H)$ variants (Fig. 1b-d).

353

354 3.3 Comparison of CR values for different species

355 ^{125}I CRs were measured for lettuce (*L. sativa*), beans (*P. vulgaris*) and wheat (*T.*
356 *aestivum*) grown on the same four soil types (Podzoluvisol, Greyzem, Phaeozem and
357 Chernozem) from 2000 to 2002 in the micro-field experiment conducted under natural
358 conditions in the Chernobyl Exclusion Zone (Kashparov et al., 2005a). The averaged
359 ^{125}I CR values for the lettuce leaves, bean pods and wheat grain and straw obtained 40
360 days after iodine injection, i.e. on the completion of its rapid absorption stage by soil
361 components, were analyzed for correlation with the averaged values of the soil
362 characteristics studied in this pot experiment (i.e., Kd of ^{125}I and Kd' of stable iodine,
363 stable iodine concentrations in soil A'_{soil} , and humus contents H). The corresponding
364 correlation coefficients and parameters values for each crop are presented in Table 5.
365 For all crops, ^{125}I CRs are negatively correlated with the studied soil characteristics.
366 Figs. 2 and 3 show the dependencies of ^{125}I CR on ^{125}I Kd and stable iodine content in
367 soil A'_{soil} , respectively.

368 In lettuce leaves, bean pods, and wheat straw, the highest correlations were
369 observed ($R^2 > 0.86$) between ^{125}I CRs and A'_{soil} , whereas for radish roots and wheat
370 grain, predictions based on Kds were more accurate ($R^2 > 0.94$) (Figs. 2 and 3, Table 5).
371 To a lesser extent than for radish, ^{125}I CRs in all crops also correlated with the other
372 variables studied, Kd' and H ($R^2 = 0.43-0.72$; Table 5).

373 Under the same soil conditions, the highest accumulation of ^{125}I occurred in wheat
374 straw (Table 5). The CRs of ^{125}I in lettuce leaves and radish roots (FW) are
375 approximately twice as low, and in bean pods and wheat grain are 30 and 60 times
376 lower than in wheat straw, respectively. The ^{125}I CRs for radish (roots), lettuce (leaves),
377 bean (pods) and wheat (grain) in air-dry state can be recalculated from the values
378 presented in Table 5 using the FW/DW ratios of 20 ± 3 , 19 ± 2 , 5 ± 1 , 1.1 ± 0.1 , respectively,
379 which were obtained in our earlier studies (Kashparov et al., 2005a, 2007a).

380

381 **3.4 Use of the obtained parameters for radiological assessments**

382 The ratios between the ^{125}I activity concentrations in wheat grain and straw are in
383 good agreement with the results reported by Prister et al. (1979). The parameters and
384 equations for obtaining the ^{125}I CR values in wheat straw can be used for estimating the
385 transfer of the long-lived radiological contaminant ^{129}I into perennial cereal forage grass,
386 cattle forage, and products for human consumption (milk and meat).

387 Thus, based on the data obtained in this long-term experimental study (root
388 uptake of ^{125}I under natural conditions in steady state), the correlations between ^{125}I
389 CRs in various edible crop species and the characteristics of the main soil types of
390 continental Ukraine and the corresponding model parameters were assessed. This
391 makes it possible to estimate the root uptake of radioactive iodine in the studied wide
392 range of soil conditions and to predict its accumulation in the edible parts of the studied
393 crops at harvesting. Root uptake of radioiodine by plants was anticorrelated with the
394 stable iodine contents in soil (Fig.1 and 3, Table 4 and 5). It means that at the same
395 levels of ^{129}I deposition, its highest concentrations will be found in plants grown on
396 sandy soils, which are characterized by the lowest contents of stable iodine and humus.

397 As it was shown earlier, under steady state conditions $CR=CR'=A'_{radish}/A'_{soil}$.
398 Therefore, a meaning of C_I in Table 5 is a constant concentration of stable iodine in a
399 certain plant, which does not depend on iodine abundance in soil and is determined by
400 the plant physiology. In our pot experiment, the measured ^{127}I concentrations in radish
401 roots in all soils during the observation period were $0.02\pm 0.01 \mu\text{g g}^{-1}$ and were
402 independent of soil type and its concentration in the soil (Table 3). This value is close to
403 C_I of radish, 0.014 ± 0.004 (Table 5), which indicates approaching the equilibrium
404 between the two iodine isotopes studied. Available literature data (Tikhomirov, 1983;
405 Kashin, 1987) show that stable iodine concentrations in various plant species on the
406 continental territory (i.e., located more than 200 km from the sea) of the former USSR
407 vary less than twofold and correspond to the concentrations obtained in our study. They

408 do not depend on soil type and the contents of stable iodine or humus in soil, which
409 show variations within an order of magnitude. Higher concentrations of stable iodine in
410 plants were observed in coastal regions as a result of interception and foliar uptake of
411 iodine aerosols (Tikhomirov and Rusina, 1983). Therefore, in the case of irrigated
412 agriculture, foliar pathway may provide additional uptake of stable iodine into plants,
413 which depends on its concentration in irrigation water.

414

415 **4. Conclusions**

416 In this long-term study conducted under natural conditions, correlations between
417 ^{125}I CRs in various crop species and characteristics of the main soil types of continental
418 Ukraine (distribution coefficients of ^{125}I and stable natural iodine, stable iodine
419 concentrations in soil and humus contents) under stationary conditions were assessed.
420 The strongest correlations were found between ^{125}I CR and ^{125}I Kd and stable iodine
421 concentrations in the soil. This allows estimating the root uptake of $^{125,129}\text{I}$ by the studied
422 crop species and predicting the radioiodine isotopes accumulation in the edible parts in
423 the range of soil conditions under study. The transfer parameters of radioiodine root
424 uptake by radish roots from four different soils increased in the following order: clay soil
425 < loam soil << sandy soil (Chernozem~Phaeozem<Greyzem<<Podzoluvisol).

426 Among the plant species studied in the same soil conditions after the completion
427 of the rapid sorption phase, the highest uptake of ^{125}I occurs in wheat straw, while its
428 uptake in lettuce leaves and radish roots (FW) is two times lower, and in bean pods and
429 wheat grain is 30 and 60 times lower than in wheat straw, respectively. The parameters
430 and equations for obtaining ^{125}I CR values in wheat straw and grain can be used to
431 assess the transfer of radioiodine (including ^{129}I) to cereals and forage fed to cattle, and
432 thus to estimate $^{125,129}\text{I}$ activity concentrations in human diet components (milk and
433 meat) in case of a release of radioiodine into the environment.

434

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441

442 **References**

- 443 Arynushkina E.V., 1970. Soil chemical analysis guidelines. Moscow University
444 Publishers, Moscow (In Russian).
- 445 Balonov, M., Kashparov, V., Nikolaenko, A., Berkovskyy, V., Fesenko, S., 2018.
446 Harmonization of standards for permissible radionuclide activity concentrations in
447 foodstuffs in the long term after the Chernobyl accident. J. Radiol. Prot. 38: 854–
448 867. <https://doi.org/10.1088/1361-6498/aabe34>.
- 449 Bazyka, D.A., Tronko, M.D., Antypkin, Y.G., Serdiuk, A., Sushko, V.O. (Eds.), 2016.
450 Thirty years of Chornobyl catastrophe: radiological and health effects: National
451 Report of Ukraine. National Academy of Medical Sciences of Ukraine, National
452 Research Centre for Radiation Medicine, Kyiv.
453 <https://drive.google.com/file/d/0B1bUW1YACgZelRkWmhEMVVldGc/view>.
- 454 Bors, J., Erten, H., Martens, R., 1991. Sorption studies of radioiodine on soils with
455 special references to soils microbial biomass. Radiochim. Acta. 52/53, 317-325.
456 <https://doi.org/10.1524/ract.1991.5253.2.317>.
- 457 Bors, J., Martens, R., Kühn, W., 1988. Studies on the role of natural and anthropogenic
458 organic substances in the mobility of radioiodine in soils. Radiochim. Acta. 44/45,
459 201-206. <https://doi.org/10.1524/ract.1988.4445.1.201>.
- 460 Bostok, A., Ashworth, D., Shaw, G., 2002. Physical, chemical and biological behaviour
461 of radioactive chlorine and iodine in soils. Radioprot. 37 C1, 341-346.
462 <https://doi.org/10.1051/radiopro/2002064>.
- 463 Bostok, A.C., Shaw G., Bell J.N., 2003. The volatilisation and sorption of ¹²⁹I in
464 coniferous forest, grassland and frozen soil. J. Environ. Radioact. 70, 29-42.
465 [https://doi.org/10.1016/S0265-931X\(03\)00120-6](https://doi.org/10.1016/S0265-931X(03)00120-6).
- 466 Christiansen, J.V., Carlsen, L., 1989. Iodine in the environment revisited. An evaluation
467 of the chemical and physico-chemical processes possibly controlling the migration

468 behaviour of iodine in the terrestrial environment. Risø National Laboratory,
469 Roskilde. ISBN 87-550-1534-4.

470 Daly, J.C., Goodyear, S., Paperiello, C.J., Matuszek, J.M., 1974. Iodine-129 Levels in
471 Milk and Water Near a Nuclear Fuel Reprocessing Plant. *Health Phys.* 26(4), 333-
472 342.

473 Deitermann, W.I., Hauschild, J., Robens-Palavinskas, E., Aumann, D.C., 1989. Soil to
474 vegetation transfer of natural ^{127}I , and of ^{129}I from global fallout, as revealed by
475 field measurements on permanent pastures. *J. Environ. Radioact.* 10(1), 79-88.
476 [https://doi.org/10.1016/0265-931X\(89\)90006-4](https://doi.org/10.1016/0265-931X(89)90006-4).

477 Evans, G.J., Hammad, K.A., 1995. Radioanalytical studies of iodine behaviour in the
478 environment. *J. Radioanal. Nucl. Chem.* 192(2), 239-247.
479 <https://doi.org/10.1007/bf02041727>.

480 Henner, P., Hurtevent, P., Thiry, Y., Levchuk, S., Yoschenko, V., Kashparov, V., 2013.
481 Translocation of ^{125}I , ^{75}Se and ^{36}Cl to edible parts of radish, potato and green bean
482 following wet foliar contamination under field conditions. *J. Environ. Radioact.* 124,
483 171–184. <https://doi.org/10.1016/j.jenvrad.2013.05.012>.

484 Hurtevent, P., Thiry, Y., Levchuk, S., Yoschenko, V., Henner P., Madoz-Escande C.,
485 Leclerc, E., Colle, C., Kashparov, V., 2013. Translocation of ^{125}I , ^{75}Se and ^{36}Cl to
486 Wheat edible parts following wet foliar contamination under field conditions. *J.*
487 *Environ. Radioact.* 121, 43–54. <https://doi.org/10.1016/j.jenvrad.2012.04.013>.

488 Hauschild, J., Aumann, D.C., 1989. Iodine-129 in the environment of a nuclear fuel
489 reprocessing plant: V. The transfer of ^{129}I and ^{127}I in the soil-pasture-cow-
490 milk/meat pathway, as obtained by field measurements. *J. Environ. Radioact.* 9,
491 145-162. [https://doi.org/10.1016/0265-931X\(89\)90021-0](https://doi.org/10.1016/0265-931X(89)90021-0).

492 Hoshi, M., Yamamoto, M., Kawamura, H., Shinohara, K., Shibata, Y., Kozlenko, M.T.,
493 Takatsuji, T., Yamashita, S., Namba, H., Yokoyama, N., 1994. Fallout radioactivity
494 in soil and food samples in the Ukraine: measurements of iodine, plutonium,

495 cesium, and strontium isotopes. Health Phys. 67(2), 187-191.
496 <https://doi.org/10.1097/00004032-199408000-00012>.

497 Howard, B.J., Voigt, G., Segal, M.G., Ward, G.M., 1996. A review of iodine metabolism
498 and available countermeasures to reduce radioiodine transfer to milk. Health Phys.
499 71, 661-673.

500 IAEA, 2010. Handbook of parameter values for the prediction of radionuclide transfer in
501 terrestrial and fresh-water environments. IAEA-TRS-472, Vienna.

502 IUSS Working Group WRB, 2006. World Reference Base for Soil Resources, 2nd ed.
503 World Soil Resources Reports no 103. UN Food and Agriculture Organization,
504 Rome.

505 Kashin, V.K., 1987. Biogeochemistry, phytophysiology and agrochemistry of iodine.
506 Book Company Nauka, Leningrad (In Russian).

507 Kashparov, V., Colle, C., Zvarich, S., Yoschenko, V., Levchuk, S., Lundin, S., 2005a.
508 Soil-to-plant halogens transfer studies 1. Root uptake of radioiodine by plants. J.
509 Environ. Radioact. 79(2), 187-204. <https://doi.org/10.1016/j.jenvrad.2004.06.005>.

510 Kashparov, V., Colle, C., Zvarich, S., Yoschenko, V., Levchuk, S., Lundin, S., 2005b.
511 Soil-to-plant halogens transfer studies 2. Root uptake of radiochlorine by plants. J.
512 Environ. Radioact. 79(3), 233-253. <https://doi.org/10.1016/j.jenvrad.2004.07.001>.

513 Kashparov, V., Colle, C., Levchuk, S., Yoschenko, V., Zvarich, S., 2007a. Radiochlorine
514 concentration ratios for agricultural plants in various soil conditions. J. Environ.
515 Radioact. 95(1), 10-22. <https://doi.org/10.1016/j.jenvrad.2007.01.008>.

516 Kashparov, V., Colle, C., Levchuk, S., Yoschenko, V., Svydynuk, N., 2007b. Transfer of
517 chlorine from the environment to agricultural foodstuffs. J. Environ. Radioact. 94,
518 1-15. <https://doi.org/10.1016/j.jenvrad.2006.12.006>.

519 Kashparov, V., Levchuk, S., Zhurba, M., Protsak, V., Khomutinin, Yu., Beresford, N.A.,
520 Chaplow, J.S., 2018. Spatial datasets of radionuclide contamination in the

521 Ukrainian Chernobyl Exclusion Zone. Earth System Sci. Data (ESSD). 10, 339-
522 353. <https://doi.org/10.5194/essd-10-339-2018>.

523 Katagiri, K., Shimizu T., Akatsu Y., Ishiguro, H., 1997. Study of the behavior of ¹²⁹I in
524 the terrestrial environment. J. Radioanal. Nuclear Chem. 226, 23-27.
525 <https://doi.org/10.1007/BF02063619>.

526 Korobova, E., Anoshko, Y., Kesminiene, A., Kouvyline, A., Romanov, S., Tenet, V.,
527 Suonio, E., Cardis, E., 2010a. Evaluation of stable iodine status of the areas
528 affected by the Chernobyl accident in an epidemiological study in Belarus and the
529 Russian Federation. J. Geochem. Explor. 107(2), 24-135.
530 <https://doi.org/10.1016/j.gexplo.2010.08.005>.

531 Korobova, E., Anoshko, Y., Kesminiene, A., Cardis, E., Kouvyline, A., Chesalova E.,
532 2010b. Spatially differentiated assessment of the contribution of natural
533 geochemical background of iodine into the risk of thyroid cancer after the
534 Chernobyl accident. Report at the VI Congress on radiation researches
535 (radiobiology, radioecology, radiation safety). 25-28 October 2010, Moscow (In
536 Russian).

537 Lisoval, A.P., Davydenko, U.M., Moyseyenko, B.M., 1984. Agrochemistry. Book
538 Company Vyschcha Schkola, Kiev (In Russian).

539 Michel, R., Daraoui, A., Gorny, M., Jakob, D., Sachse, R., Romantschuk, L.D., Alfimov,
540 V., Synal, H.-A., 2015. Retrospective dosimetry of Iodine-131 exposures using
541 Iodine-129 and Caesium-137 inventories in soils - A critical evaluation of the
542 consequences of the Chernobyl accident in parts of Northern Ukraine. J. Environ.
543 Radioact. 150, 20-35. <https://doi.org/10.1016/j.jenvrad.2015.07.023>.

544 Miyake, Y., Matsuzaki, H., Fujiwara, T., Saito, T., Yamagata, Y., Honda, M., Muramatsu,
545 Y., 2012. Isotopic ratio of radioactive iodine (¹²⁹I/¹³¹I) released from Fukushima
546 Daiichi NPP accident. Geochem. J. 46, 327-333.
547 <https://doi.org/10.2343/geochemj.2.0210>.

548 Muramatsu, Y., Uchida, S., Sriyotha, P., Sriyotha, K., 1990. Some considerations on the
549 sorption and desorption phenomena of iodide and iodate on soil. *Water, Air and*
550 *Soil Pollut.* 49, 125-138. <https://doi.org/10.1007/BF00279516>.

551 Muramatsu, Y., Uchida, S., Yoshida, S., 1991. Radiotracer experiments on the
552 desorption of iodine from paddy soil with and without rice plants. *Radioisot.* 40(11),
553 10-13.

554 Muramatsu, Y., Uchida, S., Ohmomo, Y., 1993. Root-uptake of radioiodine by rice
555 plants. *J. Radiat. Research.* 34/3, 214-220. <https://doi.org/10.1269/jrr.34.214>.

556 Muramatsu, Y., Yoshida, S., 1996. Behaviour of iodine-129 in the soil-plant system, in:
557 Gerzabek, M., Desmet, G., Howard, B.J., Heinrich, G., Schimmack, W. (Eds.)
558 *Proceedings of the International Symposium on Radioecology, 22nd-24th April*
559 *1996, Vienna. Ten Years Terrestrial Radioecological Research Following the*
560 *Chernobyl Accident. Austrian Soil Science Society, Vienne, pp. 207-214.*

561 Muramatsu, Y., Yoshida, S., Ban-nai, T., Amachi, S., 2002. Behavior of iodine in the
562 soil-plant system. *Radioprot.* 37 C1, 479-484.
563 <https://doi.org/10.1051/radiopro/2002089>.

564 Muramatsu Y., Matsuzaki, H., Toyama, C., Ohno, T., 2015. Analysis of ^{129}I in the soils of
565 Fukushima Prefecture: preliminary reconstruction of ^{131}I deposition related to the
566 accident at Fukushima Daiichi Nuclear Power Plant (FDNPP). *J. Environ.*
567 *Radioact.* 139, 344-350. <https://doi.org/10.1016/j.jenvrad.2014.05.007>.

568 Prister, B.S., Grigoriyeva, T.A., Perevezentzev, V.M., Tikhomirov, F.A., Sal'nikova, V.G.,
569 Ternovskaya, I.M., Karaban, T.T., 1977. Behavior of iodine in soil.
570 *Pochvovedeniye (Soviet Soil Sci.)*. 6, 32-39 (In Russian).

571 Prister, B.S., Grigoriyeva, T.A., Perevezentzev, V.M., 1979. Behavior of iodine in soil-
572 plants system. *Agrohim. (Agrochem.)*. 3, 93-99 (In Russian).

573 Prokhorov, V.M., Schukin, A.B., Kvetnaya, O.M., Malkovich, R.S., 1978. Studies of
574 migration of radioiodine in soil. *Pochvovedeniye (Soviet Soil Sci.)*. 11, 33-40 (In
575 Russian).

576 Proskuryakova, G.F., 1966. Kinetic rhodanide-nitrite method of determination of
577 microamounts of iodine in soil. *Agrochim. (Agrochem.)*. 11, 125-129 (In Russian).

578 Robens, E., Hauschild, J., Aumann, D.C., 1988. Iodine-129 in the environment of a
579 nuclear fuel reprocessing plant: III. Soil-to-plant concentration factors for iodine-
580 129 and iodine-127 and their transfer factors to milk, eggs and pork. *J. Environ.*
581 *Radioact.* 8, 37-52. [https://doi.org/10.1016/0265-931X\(88\)90013-6](https://doi.org/10.1016/0265-931X(88)90013-6).

582 Sahoo, S. K., Muramatsu Y., Yoshida, S., Matsuzaki H., Rühm W., 2009. Determination
583 of ¹²⁹I and ¹²⁷I concentration in soil samples from the Chernobyl 30-km zone by
584 AMS and ICP-MS. *J. Radiat. Res.* 50, 325–332.

585 Satoh, Y., Kakiuchi, H., Ueda, S., Akata, N., Hisamatsu, S., 2019. Concentrations of
586 iodine-129 in livestock, agricultural, and fishery products around spent nuclear fuel
587 reprocessing plant in Rokkasho, Japan, during and after its test operation.
588 *Environ. Monit. Assess.* 191, 61. <https://doi.org/10.1007/s10661-019-7211-z>.

589 Steinhauser, G, Brandl, A, Johnson, T.E., 2014. Comparison of the Chernobyl and
590 Fukushima nuclear accidents: a review of the environmental impacts. *Sci. Total*
591 *Environ.* 470–471, 800–817. <http://dx.doi.org/10.1016/j.scitotenv.2013.10.029>

592 Sheppard, M.I., Thibault, D.H., 1992. Chemical behaviour of iodine in organic and
593 mineral soils. *Appl. Geochem.* 7, 265-272. [https://doi.org/10.1016/0883-
594 2927\(92\)90042-2](https://doi.org/10.1016/0883-2927(92)90042-2).

595 Sheppard, M.I., Thibault, D.H., McMurry, J., Smith, P.A., 1995. Factors affecting the soil
596 sorption of iodine. *Water, Air and Soil Pollut.* 83, 51-67.
597 <https://doi.org/10.1007/BF00482593>.

598 Sheppard, S.C., 2003. Interpolation of soil/liquid partition coefficients, K_d for iodine in
599 soil. J. Environ. Radioact. 70, 21-27. [https://doi.org/10.1016/S0265-](https://doi.org/10.1016/S0265-931X(03)00129-2)
600 [931X\(03\)00129-2](https://doi.org/10.1016/S0265-931X(03)00129-2).

601 Szidat S., Schmidt A., Handl J., Jakob D., Botsch W., Michel R., Synal H.-A., Schnabel
602 C., Suter M., Lopez-Gutierrez J.M., Stad W., 2000. Iodine-129: Sample
603 preparation, quality control and analyses of pre-nuclear materials and natural
604 waters from Lower Saxony, Germany. Nuclear Instruments and Methods in
605 Physics Research Section B. 172, 699-710. [https://doi.org/10.1016/S0168-](https://doi.org/10.1016/S0168-583X(00)00377-3)
606 [583X\(00\)00377-3](https://doi.org/10.1016/S0168-583X(00)00377-3).

607 Tikhomirov, F.A., 1983. Radioecology of iodine. Book Company Energoatomizdat,
608 Moscow (In Russian).

609 Tikhomirov, F.A., Moiseev, I.T., Rusina, T.V., 1980. Dynamics of bioavailability of
610 radioiodine for plants growing at different soils. Agrohim. (Agrochem.). 11, 115-120
611 (In Russian).

612 Tikhomirov, F.A., Rusina, T.V., 1983. Atmospheric and soil pathways of iodine uptake
613 by aboveground phytomass of grass plants. Agrohim. (Agrochem.). 5, 92-96 (In
614 Russian).

615 Titova A.A., 1981. Determination of iodine in forage and plants. Chem. Agric. 19, 57 –
616 60 (In Russian).

617 UNSCEAR, 2016. Sources, effects and risks of ionizing radiation. United Nations
618 Scientific Committee on the Effects of Atomic Radiation UNSCEAR. Report to the
619 General Assembly, with Scientific Annexes. United Nations, New York.

620 Vandecasteele, C.M., Van Hees, M., Hardeman, F., Voigt, G., Howard, B.J., 2000. The
621 true absorption of ¹³¹I, and its transfer to milk in cows given different stable iodine
622 diets. J. Environ. Radioact. 47, 301-317. [https://doi.org/10.1016/S0265-](https://doi.org/10.1016/S0265-931X(99)00047-8)
623 [931X\(99\)00047-8](https://doi.org/10.1016/S0265-931X(99)00047-8).

- 624 Voigt, G., Kiefer, P., 2007. Stable and radioiodine concentrations in cow milk:
625 dependence on iodine intake. J. Environ. Radioact. 98, 218-227.
626 <https://doi.org/10.1016/j.jenvrad.2006.12.016>.
- 627 Wershofen, H., Aumann, D.C., Hübschmann, W.G., 1991. Iodine-129 in the
628 environment of a nuclear fuel reprocessing plant: VIII. Comparison of measured
629 ¹²⁹I concentrations in the atmosphere with those predicted by a radiological
630 assessment code. J. Environ. Radioact. 13, 93-101. [https://doi.org/10.1016/0265-
631 931X\(91\)90052-H](https://doi.org/10.1016/0265-931X(91)90052-H).
- 632 Whitehead, D.C., 1974a. The sorption of iodide by soil components. J. Sci. Food Agric.
633 25, 73-79. <https://doi.org/10.1002/jsfa.2740250109>.
- 634 Whitehead, D.C., 1974b. The influence of organic matter, chalk, and sesquioxides on
635 the solubility of iodide, elemental iodine and iodate incubated with soil. Eur. J. Soil
636 Sci. 25, 461-470. <https://doi.org/10.1111/j.1365-2389.1974.tb01141.x>.
- 637 Whitehead, D.C., 1978. Iodine in soils profiles in relation to iron and aluminium oxides
638 and organic matter. Eur. J. Soil Sci. 29, 88-94. [https://doi.org/10.1111/j.1365-
639 2389.1978.tb02035.x](https://doi.org/10.1111/j.1365-2389.1978.tb02035.x).
- 640 Yoshida, S., Muramatsu, Y., Uchida, S., 1998. Soil-solution distribution coefficients, K_d s,
641 of I^- and IO_3^- for 68 Japanese soils. Radiochim. Acta. 82, 293-297.
642 <https://doi.org/10.1524/ract.1998.82.special-issue.293>.

643

644 **Table captions**

645

646 Table 1. Average agrochemical characteristics of soils ($\text{mean} \pm 2\sigma$) and size class
647 distribution parameters (from Kashparov et al., 2005a).

648

649 Table 2. ^{125}I activity concentrations and stable iodine (I_{st}) concentrations in the soil
650 samples, and soil moisture contents.

651

652 Table 3. ^{125}I activity concentrations and stable iodine (I_{st}) concentrations in the radish
653 root samples.

654

655 Table 4. Distribution coefficients (Kd) and concentration ratios (CR) for ^{125}I and stable
656 iodine (^{127}I) in radish roots.

657

658 Table 5. Parameters of relationships between ^{125}I CR for crops and main characteristics
659 of the studied soils, and associated coefficients of determination (R^2).

660

661 **Figure captions**

662

663 Fig. 1. Correlations between concentration ratios of iodine isotopes in radish roots and
664 soil properties: (a) CR and CR' vs distribution coefficients Kd (^{125}I) and Kd' (I_{st}), (b) CR
665 vs Kd' , (c) CR vs A'_{soil} , and (d) CR vs humus content H . Open and shaded symbols
666 indicate the mean values for I_{st} and ^{125}I , respectively, and vertical and horizontal bars
667 show standard deviations. R^2 and RMSE denote the coefficient of determination and
668 root mean square error RMSE of approximation, respectively. In (a), the values in

669 parentheses are R^2 and RMSE calculated without considering the data for stable iodine
670 in Podzoluvisol. Solid and dotted lines represent the approximating trends and the
671 associated 95% confidence intervals.

672

673 Fig. 2. ^{125}I CR in lettuce leaves (a), bean pods (b), wheat straw (c) and grain (d) vs ^{125}I
674 distribution coefficients Kd in the studied soils (based on the data from Kashparov et al.
675 (2005a)). Solid and dotted lines represent the approximating trends and the associated
676 95% confidence intervals.

677

678 Fig. 3. ^{125}I CR in lettuce leaves (a), bean pods (b), wheat straw (c) and grain (d) vs
679 stable iodine concentrations in the studied soils A'_{soil} (based on the data from
680 Kashparov et al. (2005a)). Solid and dotted lines represent the approximating trends
681 and the associated 95% confidence intervals.

682

Table 1. Average agrochemical characteristics of soils (mean±2σ) and size class distribution parameters (from Kashparov et al., 2005a).

| Characteristics of soils | Soil type | | | | |
|--|--|--------------------------|------------------------|--------------------------|--------------------------|
| | FAO-WRB classification (IUSS, 2006) | Podzoluvisol | Greyzem | Phaeozem | Chernozem |
| CIS countries classification (Arynushkina, 1970) | | Soddy-podzolic | Grey forest | Meadow Chernozem | Typical Chernozem |
| IAEA (2010) classification | | Sand | Loam | Clay | Clay |
| Coordinates of soil origin | | 51.0126° N 30.0009° E | 50.294° N 29.744° E | 50.3038° N 29.7407° E | 47.9279° N 30.5382° E |
| Stable iodine concentration before ¹²⁵ I injection, mg kg ⁻¹ | | 0.4±0.3 | 1.0±0.4 | 2.3±0.5 | 5.3±0.8 |
| Soil moisture at injection, % | | 11 | 14 | 18 | 23 |
| Exchangeable calcium (Ca), mg-eq kg ⁻¹ | | 0.16±0.01 | 0.59±0.03 | 1.20±0.04 | 2.2±0.1 |
| Exchangeable magnesium, mg-eq kg ⁻¹ | | 0.016±0.001 | 0.062±0.002 | 0.103±0.005 | 0.17±0.01 |
| Sum of exchangeable bases, mg-eq kg ⁻¹ | | 0.30±0.05 | 0.92±0.02 | 2.54±0.05 | not determined |
| Cation exchange capacity, mg-eq kg ⁻¹ | | 0.58±0.06 | 1.4±0.1 | 2.6±0.01 | 3.5±0.2 |
| Hydrolytic acidity | | 1.5±0.5 | 0.46±0.04 | 0.5±0.1 | 0.37±0.04 |
| The water extract, pH _{H2O} | | 6.3±0.3 | 7.9±0.1 | 8.2±0.2 | 8.6±0.1 |
| The salt extract, pH _{KCl} | | 5.2±0.6 | 6.9±0.3 | 7.0±0.3 | 7.3±0.1 |
| Humus (H), % | | 0.8±0.2 | 1.1±0.1 | 2.8±0.2 | 4.0±0.2 |
| Total nitrogen (N _{total}), % | | 0.058±0.004 | 0.056±0.005 | 0.18±0.02 | 0.27±0.01 |
| Alkaline-hydrolyzed nitrogen (N _{hydr}), mg kg ⁻¹ | | 0.55±0.03 | 0.72±0.05 | 0.96±0.05 | 1.1±0.1 |
| Size class distribution parameters | | | | | |
| Median diameter, μm | | 141.2 | 48.9 | 23.2 | 11.6 |
| 10% mass, μm | | <22.4 | <3.0 | <3.8 | <1.7 |
| 90% mass, μm | | <513 | <462 | <43.6 | <31.6 |
| >500 μm, % mass | | 8 | 6 | 0 | 0 |

Table 2. ^{125}I activity concentrations and stable iodine (I_{st}) concentrations in the soil samples, and soil moisture contents.

| Parameter | Sampling date (days after ^{125}I injection into the soil) | | | | | | | | mean \pm 2SD | mean \pm SD ¹ |
|---|---|-------------------|-------------------|------------------|------------------|-------------------|--------------------|------------------|--------------------------------|---------------------------------|
| | June, 3 (46) | July, 10* (83) | Aug, 15* (119) | Oct, 2* (167) | Jan, 30 (287) | May, 23* (400) | June, 27* (435) | Aug, 14 (483) | | |
| Podzoluvisol | | | | | | | | | | |
| Mean I_{st} concentration (A'_{soil}), mg kg ⁻¹ DW (N=8) | | | | | | | | | 0.5\pm0.1 | |
| ^{125}I activity concentration at the injection, kBq kg ⁻¹ DW | | | | | | | | | 1560\pm80 | |
| Mean ^{125}I activity concentration in soil in the period 46-483 days after the injection (A_{soil}), kBq kg ⁻¹ DW (N=8) | | | | | | | | | 1190\pm60 | |
| Mean ^{125}I activity fraction remaining in soil in the period 46-483 days after the injection, % (N=8) | | | | | | | | | 76\pm7 | |
| ^{125}I in soil solution (A_{sol}), kBq L ⁻¹ | 163 \pm 8 | 178 \pm 18 | 167 \pm 8 | 78 \pm 4 | 11 \pm 3 | 19 \pm 4 | 101 \pm 6 | 51 \pm 9 | | 108\pm53 |
| I_{st} in soil solution (A'_{sol}), mg L ⁻¹ | - | 0.05 \pm 0.02 | - | 0.02 \pm 0.01 | 0.04 \pm 0.03 | 0.01 \pm 0.01 | 0.05 \pm 0.01 | 0.03 \pm 0.01 | | 0.03\pm0.02 |
| Soil moisture, % | 11.6 | 11.9 | 7.8 | 14.6 | 8.3 | 16.3 | 13.4 | 16.3 | | 13\pm3 |
| Greyzem | | | | | | | | | | |
| Mean I_{st} concentration (A'_{soil}), mg kg ⁻¹ DW (N=8) | | | | | | | | | 1.4\pm0.3 | |
| ^{125}I activity concentration at the injection, kBq kg ⁻¹ DW | | | | | | | | | 1650\pm80 | |
| Mean ^{125}I activity concentration in soil in the period 46-483 days after the injection (A_{soil}), kBq kg ⁻¹ DW (N=8) | | | | | | | | | 1240\pm140 | |
| Mean ^{125}I activity fraction remaining in soil in the period 46-483 days after the injection, % (N=8) | | | | | | | | | 75\pm10 | |
| ^{125}I in soil solution (A_{sol}), kBq L ⁻¹ | 20 \pm 1 | 12 \pm 1 | 34 \pm 2 | 28 \pm 2 | 8 \pm 4 | 18 \pm 8 | 29 \pm 5 | 16 \pm 8 | | 22\pm8 |
| I_{st} in soil solution (A'_{sol}), mg L ⁻¹ | - | 0.08 \pm 0.05 | - | 0.07 \pm 0.03 | 0.05 \pm 0.04 | 0.04 \pm 0.01 | 0.04 \pm 0.01 | 0.2 \pm 0.1 | | 0.09\pm0.07 |
| Soil moisture, % | 17.4 | 11.9 | 10.2 | 14.8 | 14.5 | 14.6 | 13.6 | 15.3 | | 14\pm2 |

¹ Without the Jan, 30 data (winter period with the temperature below 0°C)

| Phaeozem | | | | | | | | | | |
|--|----------|-----------|------|-----------|-----------|-----------|-----------|-----------|------------------|-----------------|
| Mean I_{st} concentration (A'_{soil}), mg kg ⁻¹ DW (N=8) | | | | | | | | | | 2.9±1.1 |
| ¹²⁵ I activity concentration at the injection, kBq kg ⁻¹ DW | | | | | | | | | | 1740±90 |
| Mean ¹²⁵ I activity concentration in soil in the period 46-483 days after the injection (A_{soil}), kBq kg ⁻¹ DW (N=8) | | | | | | | | | | 1470±120 |
| Mean ¹²⁵ I activity fraction remaining in soil in the period 46-483 days after the injection, % (N=8) | | | | | | | | | | 84±9 |
| ¹²⁵ I in soil solution (A_{sol}), kBq L ⁻¹ | 11.7±0.6 | 31±3 | 17±2 | 11.5±0.6 | 8±4 | 10±4 | 15±5 | 10±4 | 15±8 | |
| | 6 | | | | | | | | | |
| I_{st} in soil solution (A'_{sol}), mg L ⁻¹ | - | 0.10±0.07 | - | 0.03±0.02 | 0.05±0.07 | 0.08±0.01 | 0.03±0.01 | 0.03±0.01 | 0.05±0.03 | |
| Soil moisture, % | 19 | 16.2 | 12.5 | 19.3 | 18.9 | 19.5 | 18.5 | 19.9 | 18±3 | |
| Chernozem | | | | | | | | | | |
| Mean I_{st} concentration (A'_{soil}), mg kg ⁻¹ DW (N=8) | | | | | | | | | | 6.2±1.3 |
| ¹²⁵ I activity concentration at the injection, kBq kg ⁻¹ DW | | | | | | | | | | 1850±90 |
| Mean ¹²⁵ I activity concentration in soil in the period 46-483 days after the injection (A_{soil}), kBq kg ⁻¹ DW (N=8) | | | | | | | | | | 1510±120 |
| Mean ¹²⁵ I activity fraction remaining in soil in the period 46-483 days after the injection, % (N=8) | | | | | | | | | | 82±8 |
| ¹²⁵ I in soil solution (A_{sol}), kBq L ⁻¹ | 20±1 | 7±1 | 21±6 | 11±2 | 10±8 | 14±13 | 14±10 | 22±7 | 15±6 | |
| I_{st} in soil solution (A'_{sol}), mg L ⁻¹ | - | 0.18±0.11 | - | 0.06±0.04 | 0.14±0.10 | 0.09±0.02 | 0.06±0.02 | 0.04±0.02 | 0.09±0.06 | |
| Soil moisture, % | 25.1 | 22.2 | 15.2 | 22.3 | 22.4 | 24.3 | 21.8 | 28.5 | 23±4 | |

* Radish roots harvest

Table 3. ^{125}I activity concentrations and stable iodine (I_{st}) concentrations in the radish root samples.

| Parameter | Sampling date (days after ^{125}I injection into the soil) | | | | | mean \pm SD |
|---|---|----------------|----------------|-----------------|-----------------|---------------------------------|
| | July, 10 (83) | Aug, 15 (119) | Oct, 2 (167) | May, 23 (400) | June, 27 (435) | |
| Podzoluvisol | | | | | | |
| ^{125}I in radish roots (A_{radish}), kBq kg $^{-1}$ FW | 25 \pm 6 | 44 \pm 23 | 12.3 \pm 0.6 | 37 \pm 22 | 12 \pm 6 | 26\pm14 |
| I_{st} in radish roots (A'_{radish}), mg kg $^{-1}$ FW | 0.03 \pm 0.02 | - | - | 0.03 \pm 0.02 | 0.02 \pm 0.01 | 0.03\pm0.02 |
| Greyzem | | | | | | |
| ^{125}I in radish roots (A_{radish}), kBq kg $^{-1}$ FW | 19 \pm 2 | 10.1 \pm 0.5 | 5.4 \pm 0.4 | 7 \pm 4 | 5 \pm 0.5 | 9\pm6 |
| I_{st} in radish roots (A'_{radish}), mg kg $^{-1}$ FW | 0.02 \pm 0.01 | - | - | 0.03 \pm 0.03 | 0.02 \pm 0.01 | 0.02\pm0.01 |
| Phaeozem | | | | | | |
| ^{125}I in radish roots (A_{radish}), kBq kg $^{-1}$ FW | 7 \pm 5 | 9.6 \pm 0.5 | 2.7 \pm 0.4 | 13 \pm 4 | 3 \pm 2 | 7\pm4 |
| I_{st} in radish roots (A'_{radish}), mg kg $^{-1}$ FW | 0.03 \pm 0.02 | - | - | 0.01 \pm 0.01 | 0.02 \pm 0.01 | 0.02\pm0.01 |
| Chernozem | | | | | | |
| ^{125}I in radish roots (A_{radish}), kBq kg $^{-1}$ FW | 6 \pm 3 | 5.8 \pm 0.3 | 2.4 \pm 0.3 | 4 \pm 3 | 5 \pm 3 | 5\pm2 |
| I_{st} in radish roots (A'_{radish}), mg kg $^{-1}$ FW | 0.02 \pm 0.01 | - | - | 0.01 \pm 0.01 | 0.03 \pm 0.01 | 0.03\pm0.01 |

Table 4. Distribution coefficients (Kd) and concentration ratios (CR) for ^{125}I and stable iodine (^{127}I) in radish roots.

| Parameter | Sampling date (days after ^{125}I injection into the soil) | | | | | | | | mean \pm SD ¹ |
|--|---|-------------------|-------------------|-------------------|---------------|-------------------|-------------------|---------------|----------------------------|
| | June, 3 (46) | July, 10 (83) | Aug, 15 (119) | Oct, 2 (167) | Jan, 30 (287) | May, 23 (400) | June, 27 (435) | Aug, 14 (483) | |
| Podzoluvisol | | | | | | | | | |
| ^{125}I Kd , L kg ⁻¹ | 7.2 \pm 0.5 | 6.5 \pm 0.7 | 7.0 \pm 0.5 | 15 \pm 1 | 109 \pm 27 | 62 \pm 21 | 12 \pm 1 | 23 \pm 4 | 19 \pm 9 |
| I_{st} Kd' , L kg ⁻¹ | | 9 \pm 5 | | 20 \pm 12 | 13 \pm 13 | 36 \pm 22 | 9 \pm 4 | 19 \pm 13 | 19 \pm 11 |
| ^{125}I CR | | 0.021 \pm 0.005 | 0.04 \pm 0.02 | 0.010 \pm 0.005 | | 0.03 \pm 0.02 | 0.010 \pm 0.005 | | 0.022 \pm 0.012* |
| I_{st} CR' | | 0.06 \pm 0.04 | | | | 0.06 \pm 0.04 | 0.04 \pm 0.02 | | 0.05 \pm 0.03 |
| Greyzem | | | | | | | | | |
| ^{125}I Kd , L kg ⁻¹ | 63 \pm 8 | 103 \pm 14 | 37 \pm 5 | 45 \pm 6 | 162 \pm 87 | 70 \pm 31 | 42 \pm 8 | 77 \pm 39 | 62 \pm 23* |
| I_{st} Kd' , L kg ⁻¹ | | 18 \pm 12 | | 19 \pm 10 | 32 \pm 30 | 36 \pm 14 | 41 \pm 16 | 7 \pm 4 | 24 \pm 14 |
| ^{125}I CR | | 0.015 \pm 0.002 | 0.008 \pm 0.001 | 0.004 \pm 0.001 | | 0.006 \pm 0.003 | 0.004 \pm 0.001 | | 0.008 \pm 0.005* |
| I_{st} CR' | | 0.014 \pm 0.007 | | | | 0.02 \pm 0.02 | 0.014 \pm 0.007 | | 0.017 \pm 0.012 |
| Phaeozem | | | | | | | | | |
| ^{125}I Kd , L kg ⁻¹ | 125 \pm 12 | 47 \pm 6 | 86 \pm 11 | 127 \pm 12 | 174 \pm 80 | 147 \pm 57 | 96 \pm 30 | 147 \pm 60 | 111 \pm 36* |
| I_{st} Kd' , L kg ⁻¹ | | 29 \pm 23 | | 91 \pm 58 | 60 \pm 91 | 36 \pm 15 | 91 \pm 45 | 97 \pm 50 | 69 \pm 33 |
| ^{125}I CR | | 0.005 \pm 0.003 | 0.007 \pm 0.001 | 0.002 \pm 0.001 | | 0.009 \pm 0.003 | 0.002 \pm 0.001 | | 0.005 \pm 0.003 |
| I_{st} CR' | | 0.010 \pm 0.007 | | | | 0.003 \pm 0.003 | 0.007 \pm 0.004 | | 0.007 \pm 0.005 |

¹ Without the Jan, 30 data (winter period with the temperature below 0°C)

| Chernozem | | | | | | | | | |
|---|------|-------------|-------------|-------------|---------|-------------|-------------|--------|-------------|
| $^{125}\text{I } Kd, \text{ L kg}^{-1}$ | 76±7 | 203±32 | 73±21 | 142±24 | 147±113 | 111±105 | 108±78 | 68±22 | 112±48 |
| $I_{st} Kd', \text{ L kg}^{-1}$ | | 34±22 | | 103±72 | 44±32 | 69±21 | 103±38 | 155±83 | 93±45 |
| $^{125}\text{I } CR$ | | 0.004±0.002 | 0.004±0.001 | 0.002±0.001 | | 0.003±0.002 | 0.003±0.002 | | 0.003±0.001 |
| $I_{st} CR'$ | | 0.003±0.002 | | | | 0.002±0.002 | 0.005±0.002 | | 0.003±0.002 |

* Significant difference between the values for ^{125}I and I_{st} ($p < 0.05$).

Table 5. Parameters of relationships between ^{125}I CR for crops and main characteristics of the studied soils, and associated coefficients of determination (R^2).

| ^{125}I CR | $CR=k/Kd$ | | $CR=k'/Kd'$ | | $CR=C_l/A'_{soil}$ | | $CR=C_H/H$ | |
|---------------------|-------------|-------|-------------|-------|--------------------|-------|---------------|-------|
| | k | R^2 | k' | R^2 | C_l | R^2 | C_H | R^2 |
| Radish roots* | 0.4±0.1 | 0.97 | 0.3±0.1 | 0.74 | 0.014±0.004 | 0.71 | 0.013±0.004 | 0.78 |
| Lettuce leaves** | 0.5±0.2 | 0.76 | 0.5±0.3 | 0.46 | 0.02±0.01 | 0.86 | 0.02±0.01 | 0.51 |
| Bean pods** | 0.034±0.005 | 0.61 | 0.03±0.02 | 0.43 | 0.0012±0.0004 | 0.87 | 0.0013±0.0009 | 0.47 |
| Wheat straw** | 1.0±0.2 | 0.56 | 1.0±0.7 | 0.45 | 0.04±0.02 | 0.88 | 0.04±0.03 | 0.44 |
| Wheat grain** | 0.016±0.005 | 0.94 | 0.013±0.006 | 0.66 | 0.0006±0.0004 | 0.78 | 0.0006±0.0002 | 0.72 |

* this study; ** based on the data from Kashparov et al. (2005a).

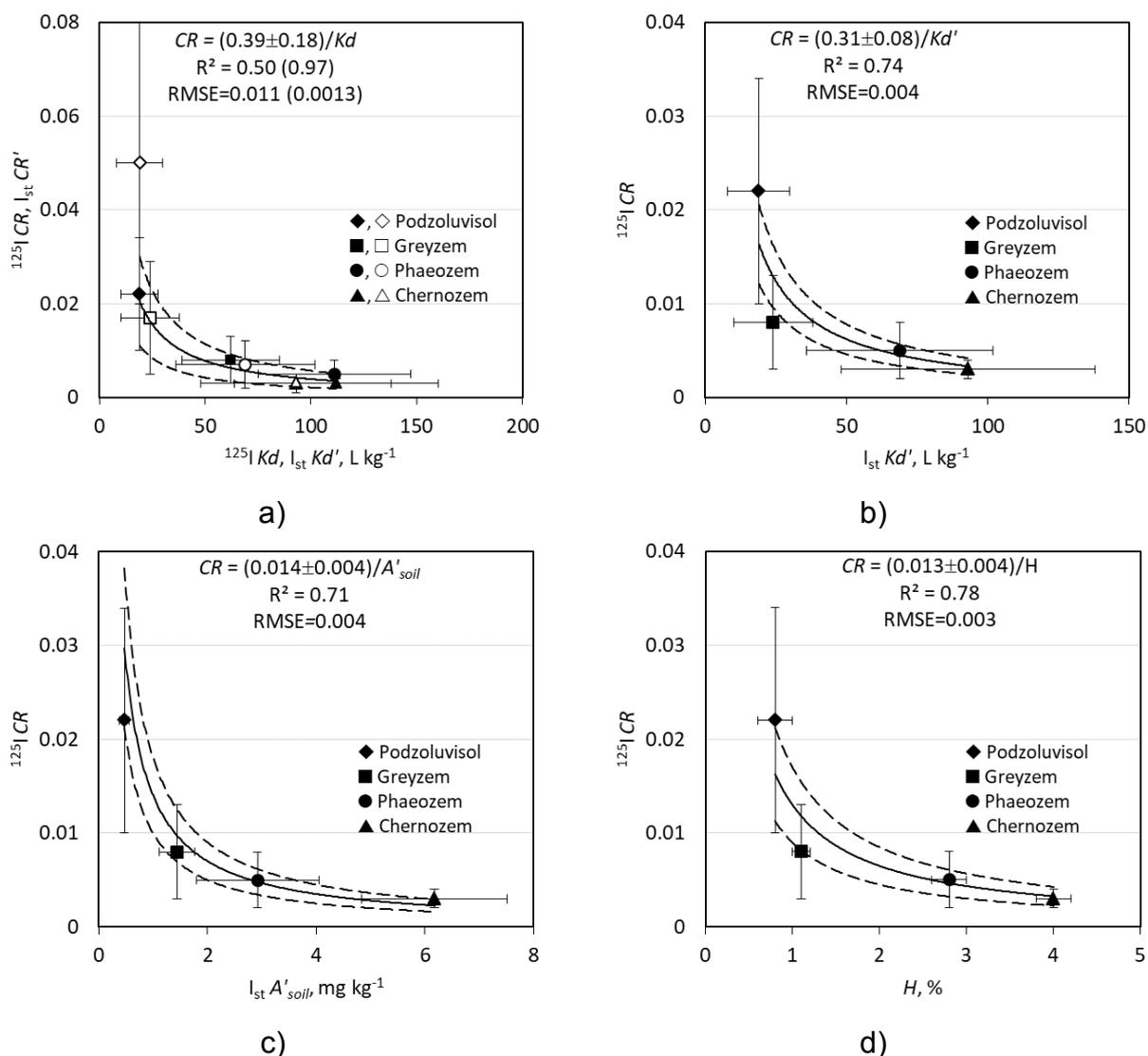


Fig.1. Correlations between concentration ratios of iodine isotopes in radish roots and soil properties: (a) CR and CR' vs distribution coefficients Kd (^{125}I) and Kd' (I_{st}), (b) CR vs Kd' , (c) CR vs A'_{soil} , and (d) CR vs humus content H . Open and shaded symbols indicate the mean values for I_{st} and ^{125}I , respectively, and vertical and horizontal bars show standard deviations. R^2 and $RMSE$ denote the coefficient of determination and root mean square error $RMSE$ of approximation, respectively. In (a), the values in parentheses are R^2 and $RMSE$ calculated without considering the data for stable iodine in Podzoluvisol. Solid and dotted lines represent the approximating trends and the associated 95% confidence intervals.

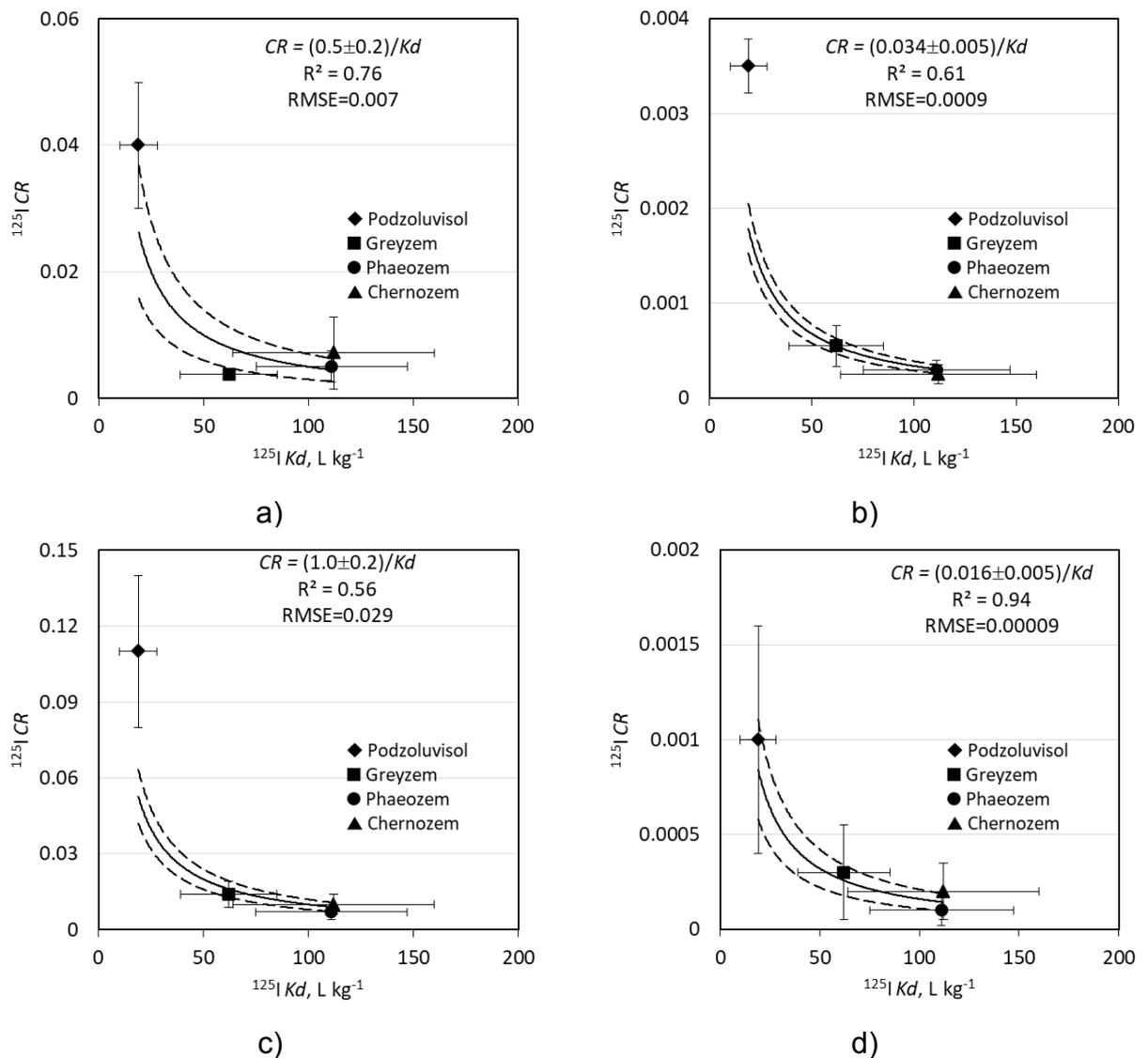


Fig.2 $^{125}\text{I} CR$ in lettuce leaves (a), bean pods (b), wheat straw (c) and grain (d) vs ^{125}I distribution coefficients K_d in the studied soils (based on the data from Kashparov et al. (2005a)). Solid and dotted lines represent the approximating trends and the associated 95% confidence intervals.

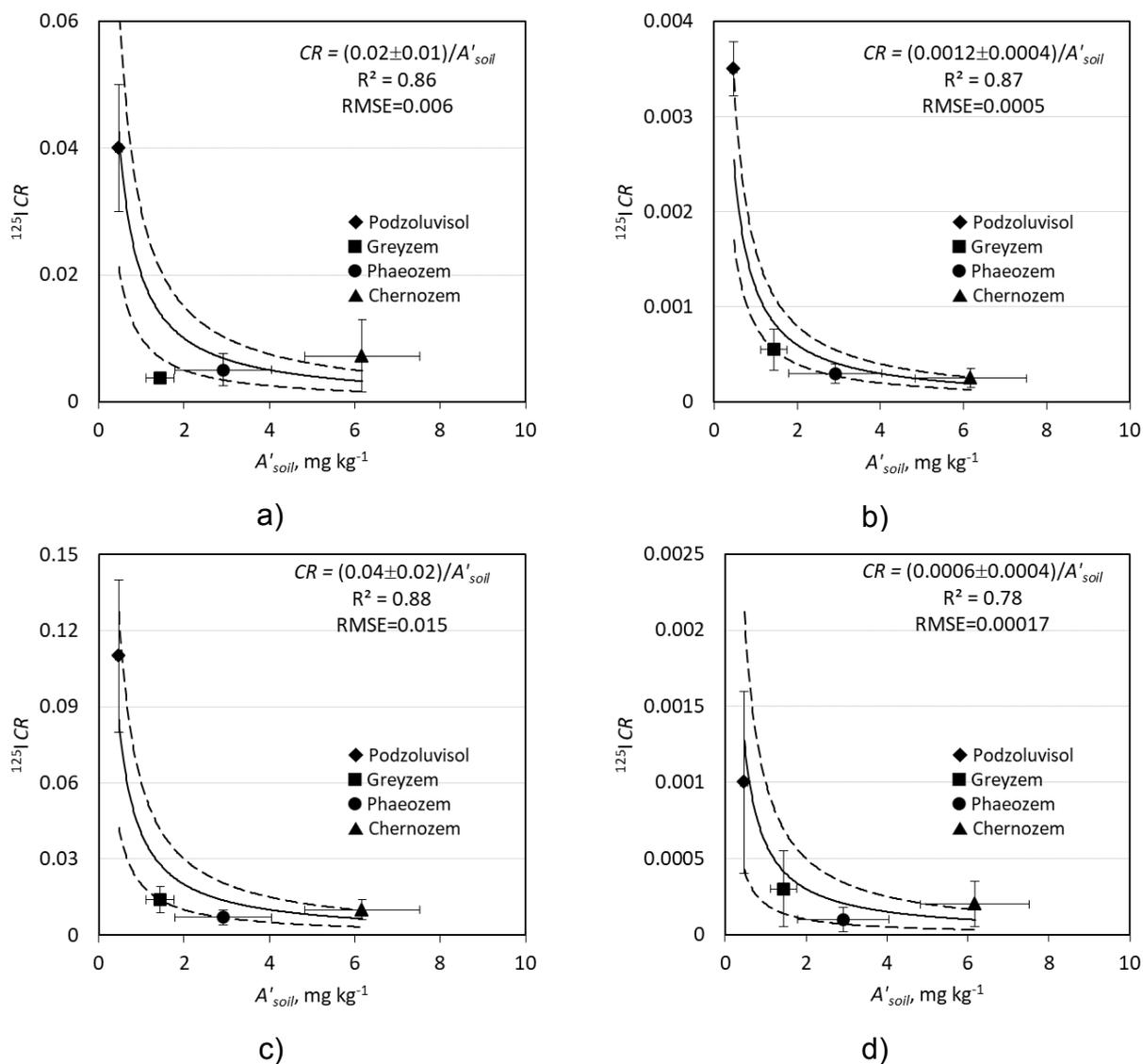


Fig. 3. ^{125}I CR in lettuce leaves (a), bean pods (b), wheat straw (c) and grain (d) vs stable iodine concentrations in the studied soils A'_{soil} (based on the data from Kashparov et al. (2005a)). Solid and dotted lines represent the approximating trends and the associated 95% confidence intervals.