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1 **Seafood Dose parameters: updating ²¹⁰Po retention factors for cooking, decay loss and mariculture**

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22

23 Abstract

24 ^{210}Po has been identified as one of the main contributors to ingestion doses to humans, particularly
25 from the consumption of seafood. The amount of ^{210}Po activity concentration data for various types
26 of seafood has increased greatly in recent times. However, to provide realistic seafood dose
27 assessments, most ^{210}Po data requires correction to account for losses that can occur before the
28 seafood is actually consumed. Here we develop generic correction factors for the main processes
29 associated with reduction of ^{210}Po in seafood – leaching during cooking, radioactive decay between
30 harvest and consumption, and sourcing from mariculture versus wild-caught.

31 When seafood is cooked, the overall mean fraction of ^{210}Po retained is 0.74 for all cooking and
32 seafood types, with the means for various seafood types and cooking categories ranging from 0.56
33 to 1.03. When considering radioactive decay during the period between harvest and consumption,
34 the overall mean fraction remaining is 0.81 across all seafood processing/packaging types, with
35 estimates ranging from 0.50 (canned seafood) to 0.98 (fresh seafood). Regarding mariculture
36 influence, the available data suggest marine fish and crustaceans raised with processed feed have
37 about one order of magnitude lower (0.10) ^{210}Po muscle content than wild-caught seafood of the
38 same or similar species.

39 Overall, this study concludes that ^{210}Po activity concentrations in seafood at the time of ingestion are
40 reduced to only about 55% compared to when it was harvested. Therefore, correction factors must
41 be applied to any data derived from environmental monitoring in order to achieve realistic dose
42 estimates. The data also suggest lower ^{210}Po ingestion doses for consumers who routinely favour
43 cooked, long shelf-life and farmed fish/crustaceans. However, more data is needed in some
44 categories, especially for cooking of molluscs and seaweed, and for the ^{210}Po content in all farmed
45 seafood.

46

47

48 Keywords

49 Polonium, farmed seafood, aquaculture, ingestion dose, loss of ^{210}Po , marine monitoring

50

51 1. Introduction

52 In marine waters, ^{210}Po is constantly being replenished via atmospheric deposition of its parent
53 radionuclides as well as dissolution from sediments (Fowler, 2011; IAEA, 2017; Jeffree et al., 1997). It
54 is therefore ubiquitous in world ocean and coastal waters and is readily available for uptake by
55 marine organisms (Carvalho, 2011, 2018; IAEA, 2017). Seafood typically has much higher ^{210}Po
56 activity concentrations than foods from terrestrial sources (IAEA, 2021). As ^{210}Po also has a relatively
57 high ingestion dose conversion factor due to its 5.3 MeV alpha emission (Adult DCF=1.2x10⁻⁶; ICRP,
58 2012), the consumption of seafood has been recognised as an important dose pathway for humans
59 (IAEA, 1995, 2021; UNSCEAR, 2008).

60 Given the importance of this radionuclide to ingestion dose, the ^{210}Po activity concentrations used in
61 seafood dose assessments must be accurate to achieve realistic results. Most of the available ^{210}Po
62 data comes from environmental monitoring studies which report the Bq kg⁻¹ present when the
63 marine organism is harvested. However, between harvest and consumption, some of this ^{210}Po is
64 typically lost. It may leach during cooking when tissue protein structures are altered or denatured by

65 heating (Kondjoyan et al., 2013). In addition, ^{210}Po is lost due to radioactive decay in the period
66 between harvest and consumption, and these losses can be substantial given the relatively short
67 ^{210}Po half-life of 138 days (Delacroix et al., 2002).

68 A further factor that should be considered is the difference in the ^{210}Po content of wild-caught
69 seafood as opposed to that from mariculture (farmed or aquaculture in the marine environment as
70 opposed to freshwater aquaculture). Mariculture-raised fish may have markedly different
71 radionuclide content as compared with wild-caught fish depending on the type of rearing conditions
72 such as the use of processed feed types. However, as most available ^{210}Po data are derived from
73 environmental monitoring studies that report on wild-caught specimens (e.g., 99.4% of marine fish,
74 MARIS database accessed 2022; IAEA, 2022), the use of such data without applying the necessary
75 correction factors may overestimate the ingestion dose contribution from ^{210}Po . Such correction is
76 important as finfish mariculture currently provides a substantial proportion of the total marine fish
77 supply, approximately 22% in Europe and 11% globally (EUMOFA, 2020; 2018 FOA data summarised
78 in NOAA, 2021), with future global supply projections predicted to increase (e.g., 17-27% by 2050:
79 Costello et al., 2020; Naylor et al., 2021).

80 The need to factor for the effects of cooking, decay, and mariculture has been recognised in previous
81 key publications (Fowler, 2011; IAEA, 1995, 2021; UNSCEAR, 2008); and some of these publications
82 have provided parameters for correcting the raw ^{210}Po data (at harvest) for use in dose assessments.
83 For example, Aarkrog et al. (1997) proposed the use of 0.6 as a generic decay factor for seafood
84 which corresponded to a typical Harvest-to-Consumption delay period of about 90 days. However,
85 since the 1997 Aarkrog et al. study, no substantive update to this parameter has been made even
86 though there have been major changes in seafood diet patterns (Hallström et al., 2019), in the
87 transportation and distribution networks that deliver seafood (Guillen et al., 2019) and in processing
88 and packaging technologies (Kontominas et al., 2021). Because of these changes, updated ^{210}Po
89 loss/retention correction factors are needed to support current and future seafood dose
90 assessments.

91 In this paper, we develop generic seafood ^{210}Po correction factors for the:

- 92 • ^{210}Po content change during cooking
- 93 • Loss of ^{210}Po from radioactive decay during the period from Harvest-to-Consumption
- 94 • ^{210}Po content differences between mariculture vs wild-caught seafood

95 We address these three factors in the order of their relative impact on typical seafood ingestion
96 dose. This paper makes use of global data to provide for broad applicability. However, dose
97 assessments are typically conducted on smaller-scale population groups (e.g., national, sub-national
98 and localised). Therefore, a further aim of this publication is to clarify best-practice methods for
99 deriving ^{210}Po loss/retention correction factors so that a consistent approach can be adopted in
100 these smaller-scale evaluations as well as to update the generic parameters over time as more global
101 data become available.

102 2. Methods

103 The ^{210}Po activity concentration data available for seafood dose assessments are typically gathered
104 from environmental monitoring studies on wild marine organisms and are typically reported for the
105 uncooked tissues at the time of harvest (removal from marine waters). However, for calculating
106 ingestion dose, the following should be considered: ^{210}Po losses due to cooking, physical decay
107 between harvest and consumption, and the effect of consuming mariculture seafood (“farmed”
108 seafood is also used and in this paper always refers to marine conditions). The corrected ^{210}Po
109 activity concentration at the time of ingestion can be represented as:

$$110 AC_{\text{ingest}} = AC_0 \cdot \sum_c f_c (R_{\text{cooking}})_c \cdot \sum_d f_d (R_{\text{decay}})_d \cdot \sum_f f_f (R_{\text{farmed}})_f \quad (1)$$

111 Where:

112	AC_{ingest}	activity concentration at the time of ingestion.
113	AC_0	activity concentration at the time of harvest (removal from marine waters).
114	f_c	fraction of seafood consumed using cooking method c .
115	R_{cooking}	fraction of ^{210}Po activity concentration retained after cooking method c .
116	f_d	fraction of seafood consumed for preservation method d .
117	R_{decay}	fraction of ^{210}Po activity concentration remaining after preservation method d .
118	f_f	fraction of seafood from source type f (farmed w various feed types, wild-caught).
119	R_{farmed}	^{210}Po activity concentration ratio of source type f (source: wild-caught, section 3.3).

120

121 When considering the application of the above equation, the R factors used in any assessment
122 should match the habits of the population being assessed (or the “representative person” of that
123 population; ICRP, 2006). If assessment-specific information is available, it should supersede the use
124 of any generic factors. For example, if the period between harvest and consumption is known for a
125 specific seafood being assessed, then the standard radioactive decay equation for ^{210}Po should be
126 used instead of the R_{decay} factors presented here.

127 This paper presents broadly applicable factors calculated from available global data. For example,
128 the f_d values used here are world medians of Fresh=44%, Frozen=34%, Canned=11%, Dried=7%,
129 Smoked=3%, (NOAA publication (Sun et al., 2022). based on FAO 2018 data). For the R_{farmed}
130 component, the intent is to provide a more accurate estimate of the ^{210}Po content of that portion of
131 fish and crustaceans sourced from mariculture (e.g., 11% (global) and 22% (Europe) of fish are
132 sourced from mariculture (EUMOFA 2020).

133 The ^{210}Po R_{cooking} , R_{decay} and R_{farmed} factors presented in this paper are generic values that have been
134 assembled using the following process: data search on global sources, quality assurance on the
135 source study, categorisation and statistical analysis as described in the following sections and
136 supplementary material, followed by reduction by summary statistics and comparison with
137 previously published values. The parameters are derived from data that often represent stochastic
138 processes (e.g., durations from seafood purchase to ingestion for a population of consumers). Data
139 distribution tests are used as indicated (e.g., Kolmogorov-Smirnov test for normality). However, for
140 some categories where there was little available data and the distributions were indeterminate, the
141 non-parametric Kruskal-Wallis test was used for comparison among data groups. The results tables
142 provide a range of indicators where the data allow (arithmetic mean (AM), standard deviation (SD),
143 geometric mean (GM), geometric standard deviation (GSD), median, minimum, maximum, number
144 of data (N)).

145 *2.1 Methods for determining ^{210}Po activity concentration changes during cooking*

146 The change in ^{210}Po content during cooking is determined by comparing the measured Bq kg^{-1}
 147 content of cooked samples with that of the corresponding raw samples and can be expressed as a
 148 retention factor (R_{cooking}). While cooking effects on the radionuclide content of foods were identified
 149 early in the nuclear age (Forrester, 1962; Whicker, 1982), most of the usable data on seafood have
 150 emerged from research published in recent decades. Data were gathered by searching global
 151 sources (1992 to 2022) focused on scientific journals, science conference proceedings, industry
 152 reports, government documents and websites. Studies were assessed for quality assurance of
 153 methods. Data were grouped by seafood and cooking categories appropriate for dose assessment
 154 (details in section 3.1.1 and S.1). Some sources reported directly on retention (or loss) of
 155 radionuclides from cooking, while other sources reported raw vs cooked activity concentrations
 156 from which retention values were calculated.

157 The R_{cooking} values were developed using a total of $N=63$ experimental data, the largest amount of
 158 which was for the cooking of fish ($N=42$), followed by crustaceans ($N=16$) and bivalves ($N=5$). No data
 159 were found for ^{210}Po loss during the cooking of gastropods, cephalopods and seaweed. Key
 160 references for ^{210}Po retention were (in order of the amount of data provided): Uddin et al. (2019),
 161 Díaz-Francés et al. (2017), Roselli et al. (2020), Štok and Smodiš (2011), Medley and Patterson (2022)
 162 , Kristan et al. (2015) and the Radioactive Waste Management Center (RWMC), Japan, (1994). When
 163 compiling data on the effects of cooking, additional reference data were found for the seafood
 164 cooking losses of other radionuclides that are often important to dose (e.g., ^{90}Sr , ^{137}Cs , ^{210}Pb ,
 165 $^{226,228}\text{Ra}$) which are briefly summarized here as they may also be of benefit during dose assessments.
 166 Unless specifically noted, all activity concentration data are in Bq kg^{-1} fresh mass (wet weight).

167 The R_{cooking} factors are grouped relative to cooking methods with grilling and frying methods
 168 combined as they have higher heat potential and are applied as a so-called “dry heat.” Boiling and
 169 steaming data are grouped as they share similar heat levels (assumed at standard pressure) and are
 170 “wet” cooking methods. This categorisation is consistent with past reports (IAEA 1992, 2009). Dry vs
 171 wet methods may differ in their effectiveness of fragmenting molecules and subsequent dissolution
 172 and leaching from tissues.

173

174 2.2 Methods for determining ^{210}Po retention after radioactive decay from Harvest-to-Consumption

175 The standard decay equation for ^{210}Po decay and ingrowth (from ^{210}Pb) is:

$$176 \quad AC_{t, \text{Po}} = AC_{0, \text{Po}} e^{-\lambda_2 t} + AC_{0, \text{Pb}} \frac{\lambda_2}{(\lambda_2 - \lambda_1)} (e^{-\lambda_1 t} - e^{-\lambda_2 t}) \quad (2)$$

177 Where:

- 178 $AC_{t, \text{Po}}$ activity concentration of ^{210}Po at the time of ingestion.
 179 $AC_{0, \text{Po}}$ initial activity concentration of ^{210}Po (e.g., at the time of harvest).
 180 $AC_{0, \text{Pb}}$ initial activity concentration of ^{210}Pb (e.g., at the time of harvest).
 181 λ radionuclide decay constants; λ_1 (^{210}Pb) = $8.52 \times 10^{-5} \text{ d}^{-1}$, λ_2 (^{210}Po) = 0.005 d^{-1} .
 182 t time duration over which decay and ingrowth is being calculated.

183

184 The above equation can be used directly if the delay period between harvest and ingestion is
 185 known. However, in a typical seafood dose assessment, t may vary substantially across the
 186 assessment population according to the varied types of seafood preservation methods (e.g., fresh,
 187 frozen, canned, etc.), each of which can have differing durations for transport, processing, and
 188 shelf-lives. Delay times within categories are also influenced by consumer behaviour, with some

189 consumers eating seafood soon after purchase and others waiting until the “use by” date.
 190 Therefore, when representing populations, delay times for seafood are inherently imprecise and
 191 can best be estimated stochastically.

192
 193 The component of the equation (2) for the ingrowth of ^{210}Po (from ^{210}Pb) may be relatively minor,
 194 and may add only an incremental amount, especially for products with short production/storage
 195 durations. The ingrowth component requires input of the initial activity concentration ^{210}Pb relative
 196 to ^{210}Po (the ratio of ^{210}Pb to ^{210}Po activity concentrations at the time of harvest). For this study, a
 197 generic $^{210}\text{Pb}/^{210}\text{Po}$ ratio of 0.16 was used ($^{210}\text{Po}/^{210}\text{Pb}$ ratio of 6.3) which was obtained from 770
 198 paired ^{210}Po and ^{210}Pb data after filtering data for edible tissues and considering the seafood types
 199 and proportions consumed globally (fish=56.8%, Crustacean=14.4%, Bivalve=17.0%,
 200 Gastropod=2.4%, Cephalopod=3.9% and seaweed=5.4%; Cai and Leung, 2017).

201
 202 Data on the delay durations for seafood were gathered using a search on global sources (through
 203 2022) focused on scientific journals, industry reports and government documents. Data were sought
 204 for five generic categories of seafood preservation (Table 1). While these categories are highly
 205 simplified relative to the numerous types of processing and packaging methods that are available
 206 (Kontominas 2021), they are fit-for-purpose for dose assessment in that cumulatively they
 207 represent almost all seafood types available for purchase and that consumption information on
 208 these generic categories is often available. For dose calculation, a more complex categorisation of
 209 methods is currently not justified given that more detailed consumption data are typically not
 210 available (e.g., the diet proportions from different kinds of freezing techniques such as pressure-
 211 shift vs isochoric freezing).

212 Table 1. For calculating typical delay durations, data were grouped into five generic categories:

Category	Key descriptors/assumptions
Fresh	Refrigerated/chilled but not frozen or otherwise preserved.
Frozen	Frozen until thawed for consumption.
Canned	Sterilised and packaged for room-temperature storage, includes cans, retort pouches, glass jars and similar packaging that can be sterilised.
Dried	Dehydrated & packaged for room-temperature storage, includes dried, cured and similar products.
Smoked	Refrigerated, cold & hot-smoked processing. Does not include sterilized seafood packaged for long-term room-temperature storage (included in Canned category).

213

214 The detailed procedure for compiling Harvest-to-Consumption duration data and estimating the
 215 ^{210}Po retention factors (R_{decay}) is presented in the supplemental (S.2). In brief, for each seafood
 216 preservation category, available reference data were compiled on the chain of events between
 217 harvest and consumption. Data were grouped into pre-market termed here “Harvest-to-Market”
 218 (e.g., harvest, transport to processing location, processing, storage, transport to market), and market
 219 plus post-market events (storage at market/display, consumer storage) termed here “Market-to-
 220 Consumption.” This grouping is necessary because Harvest-to-Market events are dominated by
 221 industrial-type production processes while the Market-to-Consumption events are dominated by
 222 retail and consumer behaviours. Where necessary, bounding data (minimum and maximums) are
 223 used along with the stochastic distributions indicated by reference studies. For example, for fresh

224 seafood, an exponential distribution best represents the Market-to-Consumption delay times as
225 retailers desire to sell fresh seafood quickly and most consumers tend to eat fresh seafood within
226 two days of purchase (Hicks, 2016; Østli et al., 2013; Roccato et al., 2017). The estimates for total
227 delay times (t) combine the duration data distributions across the entire Harvest-to-Consumption
228 period via Monte Carlo methods (used here via Goldsim™ software, <https://www.goldsim.com>).
229 Total delay durations were rounded to the nearest day as more precision is not warranted by the
230 available data. See Supplemental for details of each seafood category.

231 The above process yielded generic delay times for the five seafood processing types, which, in turn,
232 provide ^{210}Po retention factors R_{decay} ($R_{\text{decay}} = AC_{t,\text{Po}} / AC_{0,\text{Po}}$ using equation 2). They are stochastic
233 estimates based on limited data and are intended to be updated over time as more data become
234 available. These new factors are compared with available previously published values.

235 *2.3 Methods for determining ^{210}Po differences between farmed and wild-caught seafood*

236 Differences in activity concentrations between mariculture-sourced vs wild-caught seafood are
237 determined through the straight-forward comparison of measurements in comparative samples. A
238 search was conducted focused on scientific journals, science conference proceedings, industry
239 reports, government documents and websites (through 2022). In this study, the ^{210}Po activity
240 concentrations of the mariculture vs wild-caught were compared for the same or similar species
241 from the same region.

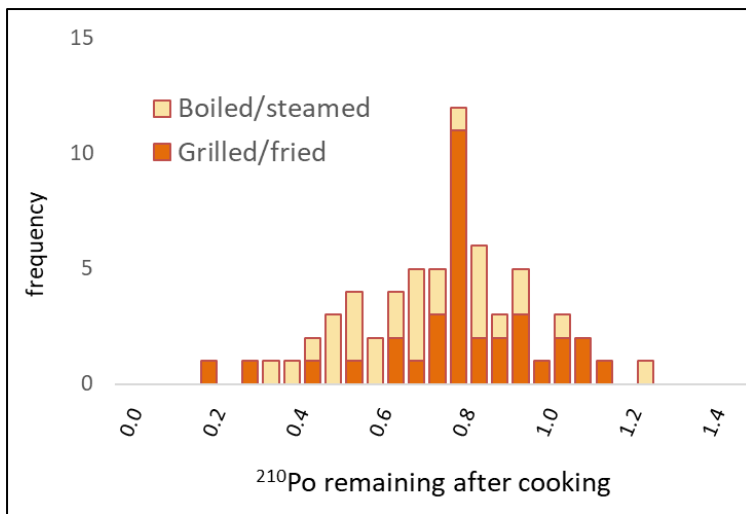
242 The available data on ^{210}Po activity concentrations in the edible tissues of mariculture seafood were
243 few ($N=16$) and limited to fish and crustaceans. The primary publications for fish were: Heldal et al.
244 (2019), Kong et al. (2021) Jalili et al. (2009), Smith (2004). Only limited data were found from one
245 study on changes in ^{210}Po in mariculture vs wild-caught crustaceans. More data are needed for this
246 category as they are a major seafood source with approximately 9.4 million tonnes of crustaceans
247 harvested from mariculture each year (2018 FAO data reported by (2018 FAO data reported by
248 Albalat et al., 2022). Data from bivalve mariculture is not included as processed feeds are mainly
249 used only for broodstock/larval stages and not for the period of primary bivalve growth which
250 typically is carried out in natural marine settings (Smaal et al., 2018). Similarly, there is no need for
251 correction of data for seaweed mariculture where this occurs in natural settings.

252 **3. Results and discussion**

253 *3.1 ^{210}Po change during cooking*

254 *3.1.1 Data and recommended R_{cooking} factors*

255 Recommended cooking correction factors (R_{cooking}) have been developed for fish, crustaceans and
256 bivalves (Table 2) but not for other seafood categories due to lack of data. The mean overall
257 retention of ^{210}Po for all cooking methods and all seafood types is 0.74 (AM; SD=0.21 for combined
258 fish, crustaceans and bivalves). When comparing cooking methods across all data, the grilled/fried
259 (dry) retention is somewhat higher (AM=0.78, SD=0.21, N=34) than boiled/steamed retention
260 (AM=0.68, GSD=0.20, N=29) which is consistent with a conceptual understanding of greater leaching
261 of metals from ‘wet’ cooking methods (e.g., greater loss of Pb in shrimp meat from boiling vs grilling;
262 Abd-Elghany et al., 2020). However, the retention difference between the grilled/fried vs
263 boiled/steamed groups is not strong ($p=0.02$, Kruskal-Wallis test), and one substantive study
264 reported no significant ^{210}Po retention difference between grilled and boiled methods (Uddin et al.,
265 2019). Additional data are needed to clarify any difference between these cooking methods.



267

268 Figure 1. Histogram of published values of the fraction of ²¹⁰Po activity concentration retained after
 269 cooking. Data include marine fish, crustaceans, and bivalves (cephalopod, gastropod and seaweed
 270 data not available). Data are for the edible tissues, without stock, broth or other leached liquid (see
 271 text). See Table 2 and Table S1.1 for source data summaries and references.

272

273 The variation in ²¹⁰Po retention data examining the impact of cooking is substantial. The means of
 274 the various categories range from 0.56 to 1.03 and the source individual data range from 0.19 –
 275 1.24). In particular, significant variation may result from whether and how the digestive tract is
 276 included or treated during preparation, cooking and consumption. Higher ²¹⁰Po activity
 277 concentrations occur in seafood where the digestive tract is included compared to the muscle alone
 278 (Table S1.1).

279

280 Table 2. R_{cooking} fractions of ^{210}Po activity concentrations retained after cooking (ratios of Bq kg^{-1}
 281 cooked mass / Bq kg^{-1} fresh mass). AM= arithmetic mean, SD= standard deviation, GM= geometric
 282 mean, GSD= geometric standard deviation, Med=median, Min= minimum, Max=maximum. See Table
 283 S1.1 for source data.

	AM	SD	GM	GSD	Med	Min	Max	N
All cooking methods: (Fish, Crustacean, Bivalve)	0.74	0.21	0.70	1.2	0.76	0.19	1.24	63
Fish ^{1,2,3,6}	0.75	0.21	0.72	1.4	0.79	0.19	1.24	42
Crustacean ^{1,4,6,7}	0.68	0.20	0.65	1.3	0.69	0.35	1.06	16
Bivalve ^{2,5,7}	0.75	0.26	0.71	1.41	0.62	0.49	1.03	5
Grilled, Fried								
All grilled/fried seafood	0.78	0.21	0.74	1.4	0.78	0.19	1.12	34
Fish ^{1,2,3}	0.76	0.21	0.72	1.4	0.79	0.19	1.13	25
Crustacean ^{1,4}	0.81	0.12	0.80	1.2	0.78	0.75	1.06	7
Bivalve ⁵	1.03	0.01				1.02	1.03	2
Boiled, Steamed								
All boiled/steamed seafood	0.68	0.20	0.66	1.3	0.69	0.38	1.27	29
Fish ^{1,6}	0.75	0.21	0.66	1.4	0.66	0.38	1.24	17
Crustacean ^{1,4,6,7}	0.58	0.20	0.55	1.4	0.54	0.35	1.24	9
Bivalve ^{2,7}	0.56	0.07	0.56	1.1	0.57	0.49	0.62	3

284 ¹Uddin et al. (2019) (N=42), ²Díaz-Francés et al. (2017) (N=9), ³Štok and Smodiš (2011) (N=2), ⁴Medley and
 285 Patterson (2022) (N=2), ⁵Kristan et al. (2015) (N=2), ⁶Roselli et al. (2020) (N=2), ⁷Radioactive Waste
 286 Management Center (RWMC), Japan, (1994), (N=2).

287 Overall, the retention data are approximately normally distributed (Kolmogorov-Smirnov test; $D(63)$
 288 = 0.09, $p=0.05$) and therefore the following recommendations are based on the arithmetic means
 289 (AMs) of Table 2:

290 When considering different cooking methods (all seafoods; stock/leachate/broth is discarded):

- 291 • R_{cooking} (all grilled/fried/boiled/steamed) = 0.74 ± 0.21
- 292 • R_{cooking} (grilled/fried) = 0.78 ± 0.21
- 293 • R_{cooking} (boiled/steamed) = 0.68 ± 0.20

294 When the seafood and stock/leachate/broth are both fully consumed (no loss):

- 295 • $R_{\text{cooking}} = 1.0$

296 In practice, some of the ^{210}Po can be lost to deposition on the dish/cooking implements or otherwise
 297 may not be eaten, and when data on such losses are known the above generic estimate could be
 298 refined.

299 In some instances, it may be useful to estimate cooking losses by seafood type and recommended
 300 fractional retention values for three different types of seafood (fish, crustacean and bivalve; Table 2)
 301 were calculated from the data for all cooking methods and when the stock/leachate/broth is
 302 discarded:

- 303 • R_{cooking} (fish) = 0.75 ± 0.21
- 304 • R_{cooking} (crustacean) = 0.68 ± 0.20

305 • $R_{\text{cooking}}(\text{bivalve}) = 0.75 \pm 0.26$

306 No previous comprehensive summary reference on cooking loss/retention was found for
307 comparison of these retention values.

308 *3.1.2 Variation in cooking correction factors and the need for more data*

309 Of the highest retention values in this compilation, the majority were in the crustacean and bivalve
310 categories, where the hepatopancreas was included during cooking. In crustaceans, the
311 hepatopancreas alone typically has 1-2 orders of magnitude higher ^{210}Po than muscle tissues
312 ((Carvalho, 2018; Fowler, 2011; Medley and Patterson, 2022). Uddin found 84% less ^{210}Po activity
313 concentration in shrimps with all of the digestive tract removed vs. whole uncooked shrimp. In some
314 cooking methods, the digestive tract/hepatopancreas are included during cooking but are not
315 consumed (e.g., a shrimp is cooked whole, then the tail meat alone is consumed). In such situations,
316 cross-contamination of the consumed portions may occur when they are cooked along with tissues
317 containing higher activity concentrations of ^{210}Po , which can result in retention values > 1.0 relative
318 to the edible portion (Medley and Patterson, 2022; Uddin et al., 2019).

319 In some seafood cooking methods, the liquid leached from the seafood tissues is retained in the
320 stock (broth, gravy). This stock may receive concentrated ^{210}Po if the digestive tract/hepatopancreas
321 are included. For example, 42-110 Bq kg⁻¹ leached into the stock/broth after one-hour boiling of
322 whole prawn samples including digestive tract organs (Medley and Patterson, 2022). Similarly, 20-36
323 Bq kg⁻¹ leached into the stock from shrimp samples with the digestive tract included (Uddin et al.,
324 2019). Consumption of such stock will therefore result in higher levels of ^{210}Po ingestion compared
325 with muscle tissues alone.

326 Further variation in the cooking effect on ^{210}Po activity concentrations may derive from differences
327 in the methods used by individual studies including differing approaches to compositing samples
328 (combined samples vs individual specimens) as well as use of differing heating levels and cooking
329 durations (e.g., 20 vs 60 minute boiling durations respectively in (e.g., 20 vs 60 minute boiling
330 durations respectively in; Medley and Patterson, 2022; Uddin et al., 2019).

331 Overall, more data are needed to better understand the effect of different cooking methods and the
332 aforementioned variables, particularly for crustaceans and bivalves where fewer (N=21) studies have
333 been published than for fish (N=42). We found no data on the effect of cooking on ^{210}Po in
334 gastropods, cephalopods and seaweed.

335

336

337 3.1.3 Retention/loss during cooking of other important radionuclides

338 While this paper focuses on ^{210}Po , some comparative data were found for other radionuclides that
339 can be important contributors to seafood ingestion dose. The anthropogenic radionuclides ^{90}Sr and
340 ^{137}Cs become important during and after nuclear accidents or other heightened release scenarios
341 (Aoyama et al., 2016; Johansen et al., 2015; Takata et al., 2019; Tateda et al., 2015). Studies on the
342 change of ^{137}Cs content during frying, baking or grilling of marine fish indicate post-cooking retention
343 values of: 0.84 (Rantavaara, 1989), 0.72-1.05 (Nabeshi et al., 2013) and 0.8-0.9 (IAEA, 2009).
344 Reported retention values after boiling or steaming of marine fish were: 0.35-0.68 (RWMC, 1994)
345 and 0.2-0.9 (IAEA, 2009). Similar studies on bivalves indicated post-cooking retention values of: 0.8
346 (steamed, Quinault, 1989), 0.64-1.30 (boiling) and 0.49 (sautéed) (Masson et al. 1989). For ^{90}Sr , a
347 single retention value of 0.9 was found for “fish: boiling flesh” (IAEA, 2009)).

348 For seaweeds, no conventional cooking effects data were found. However, Maro et al. (2002)
349 reported on radionuclide loss during the extraction of gelling/thickener products (alginic acid, high
350 milk reactive, satigum) from seaweed for use in various foods. For ^{137}Cs and ^{90}Sr , about 75% and
351 44% were eliminated respectively. The extractions include acid leaching, among other steps, and the
352 degree of radionuclide elimination exceeded 90% for $^{106}\text{Ru-Rh}$, ^{60}Co , ^{129}I , ^{238}Pu , $^{239+240}\text{Pu}$, ^{241}Am and
353 ^{244}Cm .

354 Other natural radionuclides such as ^{210}Pb , ^{228}Ra and ^{226}Ra also typically contribute to ingestion dose
355 (IAEA 2021). Concentrations of stable Pb decreased in crabs and shrimp after grilling (0.72) and
356 boiling (0.59) (Abd-Elghany et al., 2020), while increases and decreases (0.77-1.7) were observed in
357 coastal fish of Nigeria after grilling, frying and boiling (Bassey et al., 2014). The retention values from
358 these studies are higher than the values published by the IAEA for Pb retention in shrimp (0.4) and
359 for “lower sea organisms” (0.4-0.5) (IAEA, 2009). For $^{226,228}\text{Ra}$, no data on the loss/retention during
360 cooking were readily available.

361

362 3.2 ^{210}Po loss from radioactive decay during Harvest-to-Consumption

363 Given the relatively short 138-day half-life of ^{210}Po , seafood dose calculations should correct for the
364 loss of ^{210}Po due to radioactive decay between the time seafood is harvested to when it is consumed
365 (Harvest-to-Consumption). During this period, substantial decreases in ^{210}Po activity concentrations
366 can occur, especially for preserved seafood with longer processing times and shelf lives. If the delay
367 between harvest and consumption is known, then the standard decay equation for ^{210}Po should be
368 used. However, most dose assessments are for a varied population of consumers who consume
369 varied types of seafood and therefore a stochastic approach may be used. The recommended R_{decay}
370 factors represent the fraction of ^{210}Po remaining (retained) after the radioactive decay that occurs
371 between harvest and consumption for various seafood processing/preservation types using global
372 reference data (through 2022).

373 3.2.1 R_{decay} factors for ^{210}Po in fresh, frozen, canned, dried and smoked seafood

374 For fresh seafood, an R_{decay} correction factor of 0.98 is recommended (Table 3, Table S2.1) which
375 corresponds to a mean Harvest-to-Consumption duration of approximately 5 days (rounded from
376 5.2). As used here, “fresh” seafood includes chilled products, but does not include frozen-thawed
377 products (included in the frozen category). Key data references include (Baptista et al., 2020;
378 McManus et al., 2014; Østli et al., 2013; Roccato et al., 2017; Simpson et al., 2012). As a reference

379 example of Harvest-to-Market timing, fresh farmed salmon were shipped from Chile to the US in 2.7
 380 days in a study simulating typical transport of fresh seafood (Simpson et al., 2012). After purchase,
 381 most consumers (>50%) reported a preference for consuming fresh seafood within two days, but
 382 with refrigerated shelf lives of up to 11-14 days possible (McManus et al., 2014; Østli et al., 2013).
 383 Such Market-to-Consumption duration data for fresh seafood (from multiple studies) were best fit
 384 by an exponential distribution (Hicks, 2016; Østli et al., 2013; Roccato et al., 2017).

385 For, frozen, canned, dried and smoked seafood, the respective mean Harvest-to-Market durations
 386 are 89, 177, 51 and 13 days (Table 3). These correspond to R_{decay} factors of 0.70 for frozen, 0.50 for
 387 canned, 0.81 for dried and 0.95 for smoked (Table 3 and Tables S2.1, S2.2 for uncertainties and
 388 reference information). As an example of frozen seafood Harvest-to-Market information, in China,
 389 Xiao et al. (2016) reported a duration of 22 days for a typical transport/storage (cold chain)
 390 sequence of events, with the longest link being the transport from processing to market (14 days).
 391 As an example of current production of canned seafood, Boerder et al. (2018) provided quantitative
 392 data on tuna captured in the southern Indian Ocean, canned in Texas, US, and then distributed to
 393 various markets. They estimated that it took about six months on average (18 to 35 weeks) from the
 394 catch until the canned tuna finally appeared on the shelf for sale. See Table S2.2 for references and
 395 information summaries.

396 Where possible, the above specific factors for fresh, smoked, frozen, canned and dried categories
 397 should be used proportionally to reflect the diet of the consumer populations being evaluated.
 398 When it is necessary to calculate the radioactive decay of ^{210}Po in generic seafood (all combined), a
 399 mean R_{decay} factor of 0.81 is recommended for use when considering the typical global seafood
 400 consumer diet (the weighted mean using consumption percentages of 44% fresh, 34% frozen, 11%
 401 canned, 7% dried, and 3% smoked (based on 2018 FAO data and reported in NOAA, 2021)

402 Table 3. Recommended R_{decay} factors representing the fractions of ^{210}Po remaining after typical
 403 Harvest-to-Consumption durations for various seafood processing/preservation types (2022
 404 estimates). See Tables S2, S3 for supporting information.

	Total delay, Harvest-to-Consumption ¹	Recommended R_{decay} factors	References ²
	50 th (range) ³ (days)	Recommended (range)	
Fresh	5 (0-17)	0.98 (0.93-1.0)	1-5
Frozen	89 (1-540)	0.70 (0.21-1.0)	6-10
Canned	177 (10-2070)	0.50 (0.14-0.96)	9-11
Dried	51 (10-410)	0.81 (0.14-0.96)	12-15
Smoked	13 (2-62)	0.95 (0.78-0.99)	6,16-22
All seafood (weighted) ⁴	57 (0-2070)	0.81 (0.14-0.1.0)	

405 ¹ Harvest-to-Consumption includes Harvest-to-Market (transport, processing and storage times from the time
 406 of removal from the ocean until arrival at retail marketplace) and Market-to-Consumption (warehouse, display
 407 and consumer storage times from the time of arrival at the market until consumption).

408 ² References: 1 (USDA, 2022), 2 (Østli et al., 2013), 3 (Simpson et al., 2012), 4 (McManus et al., 2014), 5
 409 (Baptista et al., 2020), 6 (Roccato et al., 2017), 7 (Tingman, 2010), 8 (Xiao et al., 2016), 9 (Limbo et al., 2009),
 410 10 (Kontominas et al., 2021), 11 (Tsironi et al., 2016), 12 (Boerder et al., 2018), 13 (Immaculate et al., 2013), 14
 411 (Obluchinskaya and Daurtseva, 2020), 15 (Foscarini and Prakash, 1990), Various sources (seaveg.com), 168
 412 (Bienkiewicz et al., 2022), 17 (Afchain et al., 2005), 18 (Chardon and Swart, 2016), 19 (Daelman et al., 2013), 20
 413 (Pouillot et al., 2007), 21 (Pouillot et al., 2010), 22 (Erkan et al., 2011)

414 ³ranges are minimum – maximum for distributions used in this study’s Monte Carlo analysis.

415 ⁴Percentage weighting is world median consumption proportions of: Fresh=44%, Frozen=34%, Canned=11%,
416 Dried=7%, Smoked=3%, (NOAA publication (Sun et al., 2022). based on FAO 2018 data).

417 The data compiled for this work are drawn from many studies, including review/summary studies.
418 Some studies considered various types of seafood (fish, crustaceans, bivalves, etc.) and many studies
419 focus on marine fish which is consistent with fish contributing the largest proportion to world
420 consumption (Cai and Leung, 2017). However, the available duration data are limited in some
421 categories and further data would better define the stochastic distributions of Harvest-to-
422 Consumption timings for various seafood processing/packaging products. Such data may emerge
423 from source-certification and ecolabelling trends (<https://www.fao.org/in-action/globefish>), as well
424 as advances in technologies, such as Radio Frequency Identification (RFID) on food packages which
425 has the potential to generate large datasets that document seafood consumer preferences and shelf
426 times (Bibi et al., 2017), Furthermore, such data would allow for a better definition of the
427 proportions of processing/packaging types for specific seafood categories (fish, crustaceans, etc.).

428 *3.2.2 Comparison with previously published information on ²¹⁰Po delay times loss during Harvest-to- 429 Consumption*

430 Comparing the derived time durations of this study (Table 3) with previous estimates (Table S2.3),
431 the five days for fresh seafood used in this study is similar to the three days used in (Aarkrog et al.,
432 1997). For frozen seafood, the 89 days of this study is comparable to the 90 days value for wild-
433 caught frozen seafood in Jones and Sherwood (2009) but higher than the 60 days value for general
434 frozen seafood in Aarkrog et al. (1997) (Table S2.3 for more reference information). That the current
435 estimate for frozen seafood has a slightly longer delay duration than the 1997 Aarkrog value may
436 reflect technological improvements, increased varieties of freezing methods and more complex
437 global processing/business arrangements (Kontominas et al., 2021).

438 For canned seafood, the recommended delay period in this work (177 days) reflects shorter
439 durations than the previous estimate of 365 days in Aarkrog et al. (1997) which may reflect
440 improvements in distribution systems (Anderson et al., 2018) and shorter transport times such as
441 the air transport as described in Boerder et al. (2018) and Simpson et al. (2012). For smoked
442 seafood, Jones and Sherwood (2009) include smoked marine fish in with “fresh” with a
443 representative delay estimate of 8-10 days which is slightly shorter, but not substantially different
444 than the 13-day recommended estimate of this study. The recommended R_{decay} in this work (0.50;
445 177 days) also includes the ingrowth of ²¹⁰Po (from ²¹⁰Pb) which increases the recommended R_{decay}
446 value of this work (compared with 0.16 in Aarkrog et al. (1997).

447 For overall generic seafood, the recommended R_{decay} estimate from this work (0.81) includes the
448 ingrowth of ²¹⁰Po (from ²¹⁰Pb) which results in a slightly higher value than if the ingrowth was not
449 included as is the case for past estimates. The overall R_{decay} =0.81 estimate (as compared with
450 previous dominantly used value of 0.6 (90 days) from Aarkrog et al. (1997)) is also consistent with
451 changing consumer patterns which show a greater proportion of fresh seafood consumed currently
452 (44%, FAO 2018 data) compared with 30% value used by Aarkrog et al. in 1997). Concurrently,
453 canned seafood consumption has decreased to 11% today from 20% used in 1997 (Aarkrog et al.,
454 1997). In addition to these changes in consumption patterns, distribution systems have improved
455 allowing faster harvest to market delivery times (e.g., via air transport vs ground transport). The
456 combination of these factors has contributed to shorter overall Harvest-to-Consumption timings
457 resulting in radioactive decay factors (R_{decay}) closer to unity (i.e., less loss of ²¹⁰Po as a result of
458 radioactive decay).

460 3.3 Differences in the ^{210}Po activity concentrations in farmed vs wild-caught marine fish

461 3.3.1 Available data and recommended R_{farmed} factors

462 Reported measurements on ^{210}Po content in the muscle tissues of mariculture fish are few (total
 463 summary data $N=16$ based on $N=54$ samples) and highly varied (0.003 to 10.4 Bq kg^{-1} ; Table 4). While
 464 few, the data indicate the ^{210}Po activity concentrations in the muscle tissues of some mariculture fish
 465 are very low as compared with wild-caught fish. This difference is clearly indicated when considering
 466 farm-raised Atlantic salmon (*Salmo salar*), with a mean ^{210}Po activity concentration ((GM=0.02,
 467 GMSD=3.7; Heldal et al., 2019; Smith, 2004) of about one order of magnitude lower than that of
 468 wild-caught fish from the same region (0.14 - 0.17 Bq/kg ; Komperød et al., 2020). Consistent with this,
 469 the mean $^{210}\text{Po}/^{210}\text{Pb}$ ratio of 0.24 for the maricultured salmon as reported in Heldal et al. (2019) is
 470 very low (^{210}Po -depleted) compared with wild seafood (mean ratio of 6.3 from 770 paired ^{210}Po and
 471 ^{210}Pb data after filtering data for edible tissues as described above and in S2).

472 In addition to salmon, which are prominent in commercial mariculture production (EUMOFA, 2020),
 473 other data from similar industrial-scale operations is available for Gilthead seabream (*Sparus*
 474 *aurata*)(Jalili et al., 2009), and the mean for the combined fish raised on processed feed (GM=0.03
 475 Bq kg^{-1} , GSD=4.2) is nearly three orders of magnitude lower than the generic global value for wild-
 476 caught fish (GM=2.1 Bq kg^{-1} , GSD=5.1; global summary, MARIS 2022)($p < 0.01$, Kruskal-Wallis test).

477 The main reason for such differences appears to be the use of processed feed in mariculture
 478 production facilities. The processed feeds can have lower ^{210}Po content (compared to natural marine
 479 food webs) due to decay during processing/storage time intervals, and the nature of the feed mix
 480 sources. The feeds that are typically used in industrial scale mariculture are mainly derived from
 481 terrestrial-origin vegetable material (e.g., soy, sunflowers, rapeseed, corn, broad beans and wheat)
 482 augmented by smaller proportions of terrestrial animal products (e.g., poultry meal, feather meal,
 483 blood meal), as well as smaller amounts of marine animal products (e.g., fish meal, crustacean meal,
 484 fish oil and salmon oil) and micro-ingredients (e.g., vitamins, mineral mixtures)(Skretting, 2022). In
 485 salmon feed, marine protein and oils accounted for only about 14% and 10% by mass, respectively
 486 (2016 data; NOFIMA, 2022).

487 In contrast, other mariculture fish have been reported to have higher ^{210}Po activity concentrations in
 488 muscle tissues (GM=2.4 Bq kg^{-1} , GSD=3.6) (Kong, 2021), that were not distinguishable from generic
 489 wild-caught fish (GM=2.1 Bq kg^{-1} , GSD=5.1); global summary, MARIS 2022)($p > 0.05$, Kruskal-Wallis
 490 test). In these cases, the fish were raised on “small fish and shrimp” which were marine-sourced
 491 (personal communication Yanqin Ji, 24 January 2023), and thus can accumulate ^{210}Po to levels that
 492 are similar to those that feed on natural marine food webs.

493 For crustaceans, a similar decrease in the ^{210}Po content in the muscle tissues of mariculture vs wild-
 494 caught is indicated although the data are few and limited to one study (Table 4; Dong et al. 2018).
 495 The R_{farmed} factors in Table 4 group into distinct categories that are distinguished by the type of feed
 496 used to raise the fish and crustaceans. The mariculture fish and crustaceans raised on processed
 497 feed mixtures that are mainly derived from of terrestrial plant sources have lower ^{210}Po content than
 498 those raised on natural marine-sourced products. Although the data are sparse (and a controlled
 499 study has yet to be reported) they suggest an approximate one order of magnitude decrease (R_{farmed}
 500 of 0.1). This outcome is consistent with previously reported findings that ^{210}Po is mainly taken up by
 501 marine organisms via their dietary sources (IAEA, 2017, 2021; Komperød et al., 2020).

502

503 Table 4. Summary ²¹⁰Po activity concentrations (Bq kg⁻¹ fresh mass) in the muscle tissues of
 504 mariculture fish. Also shown are the recommended R_{farmed} values (ratio of ²¹⁰Po activity
 505 concentrations in muscle of farm-raised vs wild-caught). GM= geometric mean, GSD= geometric
 506 standard deviation, AM= arithmetic mean, SD= standard deviation, Min= minimum, Max=maximum.

Species and reference	Common name	GM ¹ Bq kg ⁻¹	GSD	AM Bq kg ⁻¹	SD Bq kg ⁻¹	Min Bq kg ⁻¹	Max Bq kg ⁻¹	Recommended R _{farmed}
Fish raised with processed feed		0.03	4.20	0.064	0.070	0.003	0.181	0.1²
<i>Salmo salar</i> ³	Atlantic Salmon	0.010	2.31	0.013	0.009	0.003	0.023	
<i>Salmo salar</i> ⁴	Atlantic Salmon	0.072	2.75	0.094	0.05	0.016	0.13	
<i>Sparus aurata</i> ⁵	Gilthead seabream			0.181	0.022			
Fish raised with natural marine-sourced feed		2.42	4.1	4.26	5.3	0.99	10.4	1.0⁶
<i>Larimichthys polyactis</i> , <i>Pagrus major</i> , <i>Lateolabrax japonicus</i> ⁷	Yellow croaker, Red sea bream, Common sea perch	2.28	2.71	3.92	4.22	0.99	10.4	
Crustaceans raised with processed feed		0.88	9.80	3.72	5.87	0.12	10.5	0.1⁸
<i>Litopenaeus vannamei</i> , <i>Penaeus monodon</i> ⁹	Whiteleg shrimp, Tiger prawn	0.88	9.80	3.72	5.87	0.12	10.5	
All Data⁸		0.1	8.7	1.3	3.2	0.003	10.5	0.2¹⁰

507 ¹ The geometric mean values are used as the combined data appear to be log normally distributed and
 508 consistent with general practice for environmental activity concentrations.

509 ² The ratio (0.1 rounded from 0.13) is relative to the geometric means for farm-raised vs wild-caught *Salmo*
 510 *salar* data (muscle) from the same region (Komperød et al., 2020)).

511 ³ Heldal 2019, N=7. ⁴ Smith 2006, N=4. ⁵ Jalili 2009, N=2.

512 ⁶ The ratio reflects that there is no statistical difference between the Kong et al 2018 farm-raised fish (marine
 513 based feed) vs the global estimate on wild-caught fish data (muscle; GM=2.1 Bq kg⁻¹: MARIS 2022).

514 ⁷ Kong 2021, N=3 species summary data based on 41 samples.

515 ⁸ The ratio (0.1 rounded from 0.07) is relative to the geometric means for farm-raised vs wild-caught shrimp
 516 from the same study (similar species and from the same region (Dong et al., 2018)).

517 ⁹ Dong et al., 2018. N=3 (mariculture), N=5 (wild-caught).

518 ¹⁰ The ratio (0.2 rounded from 0.21) is the geometric mean of the individual R_{farmed} data from the above
519 categories.

520

521 The lowest ²¹⁰Po activity concentrations in mariculture fish muscle are for salmon and there may be
522 species-specific influences that contribute to lower ²¹⁰Po accumulation (e.g., 12-16 months of
523 juvenile growth in fresh water). However, there is a need for more data for other species in order to
524 make any meaningful species-specific comparisons. Much of the available data on non-salmon
525 species comes from a single study with marine-sourced natural feed (Kong 2021). Any species
526 differences in the Table 4 values are more likely as a result of differences in mariculture methods
527 (e.g., feed types) rather than underlying differences between species. Support for this is seen in the
528 data on rainbow trout (*Oncorhynchus mykiss*), a freshwater species that is sometimes farm-raised in
529 marine waters. This species is distinct from *Salmo salar*, but when raised in similar marine
530 processed-feed fed operations the reported ²¹⁰Po contents were similar to farmed Atlantic salmon
531 ($0.020 \pm 0.007 \text{ Bq kg}^{-1}$) (reported by Komperød et al., 2020). The same study attributed differences
532 between mariculture and wild-caught fish as likely due to differing diets (Komperød et al., 2020)

533 When compiling fish and crustacean ²¹⁰Po activity concentration data generally (e.g., for use in
534 calculating ingestion doses), the ²¹⁰Po content of the edible muscle of any mariculture seafood
535 would ideally be known from measurements and used directly in the dose assessment. Where such
536 data is not available, an alternative approach is to use available wild-caught data, ideally from the
537 same/similar species, and estimate the ²¹⁰Po in that portion sourced from mariculture by applying
538 correction factors as follows:

- 539 • Where mariculture fish and crustaceans have been raised using processed feed, the
540 available data suggest an R_{farmed} factor of 0.1 should be applied to wild-caught data of similar
541 species.
- 542 • Where the feed types used for mariculture fish and crustaceans are varied or not known, the
543 available data suggests an R_{farmed} factor of 0.2 be applied for the correction of generic wild-
544 caught data.
- 545 • Where fish or crustaceans are raised using exclusively marine-derived feed, no correction is
546 recommended ($R_{\text{farmed}} = 1.0$).
- 547 • Where seafood is wild-caught, no correction is needed, ($R_{\text{farmed}} = 1.0$).

548 The intent of applying these factors in Eqn 1 is to provide a more accurate estimate of the ²¹⁰Po
549 content of that portion of seafood sourced from mariculture (e.g., 11% globally).

550 3.3.2 Variation in ²¹⁰Po in farmed fish and crustaceans and the need for more data

551 The above correction factors have typical variation when considering the same feed type and species
552 (e.g., salmon raised on processed feed GSDs are 2.3-2.7), but have high variation when considering
553 data that includes both processed and natural-feed methods. Such mixed data can vary over four
554 orders of magnitude (0.003-10.5 Bq kg^{-1} range in Table 4) which give rise to elevated GSDs in some
555 Table 4 categories. The amount of ²¹⁰Po in such processed feeds can vary depending on:

- 556 • The percentage of marine-derived ingredients in the feed (e.g., fishmeal and other
557 components that contain marine-derived ²¹⁰Po are typically only 15-30% of the feed mass
558 (NOAA, 2022; NOFIMA, 2022).

- 559
- Feed is tailored to certain species, and even for the same species, variation in feed could occur in processed batches from either the same supplier or different suppliers operating across various global regions (Glencross et al., 2020).
 - The time delay from when any marine-derived ingredients were extracted from the marine environment until their use as feed. During such delays, the amount of unsupported ^{210}Po decreases through natural decay (x2.6 decrease with each year of storage).
 - Potential processing losses (e.g., leaching or volatilisation when heated).
 - The additional amount of ^{210}Po in the feed mix due to terrestrial sources, including any mineral additives. Teien (2022) reported uranium-series radionuclides (hence ^{210}Po progeny) in commercial fish feed for Atlantic salmon (*Salmo salar*) that are associated with the phosphate compounds added to enhance P nutrient content. Smith (2004) measured substantially elevated ^{210}Po levels in fish feed for Atlantic salmon (GM=10.3 Bq kg⁻¹, GSD=2.8, range of 2.8-25 Bq kg⁻¹). However, despite this added source, the ^{210}Po content remained relatively low in the salmon muscle measured in the same study (GM=0.7 Bq kg⁻¹, range of 0.02 to 0.16).

574 Given the potential for large variation of ^{210}Po in processed feeds, more data is needed to
575 refine/improve the summary in Table 4 which have relatively few data in all categories (N=19). In
576 particular, more data are needed on mariculture vs wild-caught crustaceans as a greater proportion
577 of shrimp/prawn seafood is produced by mariculture than for fish (43% in Europe, EUMOFA, 2020).

578

579 **4. Conclusions**

580 Global data through 2022 were used to develop factors to correct for the ^{210}Po change in seafood
581 during cooking (R_{cooking}), the ^{210}Po loss from radioactive decay during the period between harvest and
582 seafood consumption (R_{decay}) and differences in ^{210}Po content of farmed vs wild-caught fish and
583 crustaceans (R_{farmed}). The mean retention factor (R_{cooking}) of ^{210}Po in seafood after cooking was 0.74
584 with a range of 0.56 to 1.03 depending on the seafood categories and cooking methods used (these
585 values do not include the consumption of the stock/broth). For the fraction of ^{210}Po remaining in
586 seafood following radioactive decay during the period from Harvest-to-Consumption (R_{decay}), our
587 recommended estimate for generic seafood is 0.81 with a range of 0.50 for long-storage seafood
588 (e.g., canned) to 0.98 for fresh seafood. These R_{decay} values are slightly higher than previously
589 published values due to inclusion of ^{210}Po ingrowth (from ^{210}Pb) and are consistent with the changes
590 in seafood processing and distribution systems in recent times.

591 When considering seafood from mariculture, the available data suggest marine fish and crustaceans
592 raised with processed feed have about one order of magnitude lower ^{210}Po muscle content than wild
593 fish of the same species (R_{farmed} of 0.10). However, mariculture practices vary, and fish raised with
594 marine-sourced feed (e.g., small marine fish) have ^{210}Po content similar to wild-caught fish. When
595 feed types vary or are unknown, the limited data available suggest a generic R_{farmed} of 0.2 that would
596 take into account the variation in mariculture operations and practices around the world.

597 The potential losses of ^{210}Po associated with the cooking, decay and mariculture influences can be
598 significant. Overall, the data suggest that, at the time of ingestion, seafood often has only about 55%
599 of ^{210}Po content as compared to when it was harvested (using the means/recommended values of
600 $R_{\text{cooking}}= 0.75$, $R_{\text{decay}}= 0.81$, and $R_{\text{farmed}}= 0.2$ for 11% of data; see supplement S.4). Given the
601 importance of ^{210}Po to ingestion dose, if these factors are ignored, any calculated doses for seafood
602 ingestion may be substantially overestimated. The data also suggest that lower ^{210}Po seafood

603 ingestion doses will occur for consumers who routinely favour farmed fish, long shelf-life products
604 and cooked seafood without stock/broth. Conversely, higher ^{210}Po seafood doses are implied to
605 those who favour fresh, wild-caught and uncooked seafoods.

606 This paper utilised global data to provide broad applicability. However, the amount of supporting
607 data varied, and more data is required, particularly with regard to the loss/retention of ^{210}Po when
608 cooking molluscs (bivalves, gastropods and cephalopods) and on the ^{210}Po content of seafood from
609 the varied range of world mariculture practices, especially for crustaceans.

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618

619 **References**

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890 **Supplemental**

891 S.1 ²¹⁰Po change during cooking

892 S.2 ²¹⁰Po loss from radioactive decay during Harvest-to-Consumption

893 S.3 ²¹⁰Po differences in farm-raised vs wild-caught marine fish

894 S.4 Example of typical ²¹⁰Po reduction using the recommended correction factors

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896 S.1 ²¹⁰Po change during cooking

897 The change in ²¹⁰Po content during cooking is determined by comparing the measured Bq kg⁻¹ of
 898 cooked samples with that of the corresponding pre-cooked raw samples and can be expressed as a
 899 correction factor (R_{cooking}). While cooking effects on the radionuclide content of foods were identified
 900 early in the nuclear age (Forrester, 1962; Whicker, 1982), most of the usable data on seafood have
 901 emerged from research published in recent decades. Data were gathered by searching global
 902 sources (1992 to 2022) focused on scientific journals, science conference proceedings, industry
 903 reports, government documents and websites. In gathering data on ²¹⁰Po change from cooking,
 904 various search terms were used: seafood (marine fish, crustacean, bivalve, gastropod, cephalopod,
 905 seaweed), cooked seafood, heat leaching from tissues, radionuclide loss from cooking, radionuclides,
 906 dose, radioactive polonium, ²¹⁰Po. Studies were assessed for quality assurance of methods. Data
 907 were grouped by seafood and cooking categories appropriate for dose assessment (details in section
 908 3.1.1 and S.1). Some sources reported directly on retention (or loss) of radionuclides from cooking,
 909 while other sources reported raw vs cooked activity concentrations from which retention values
 910 were calculated.

911

912 Table S1.1. Fractions of ²¹⁰Po activity concentration retained after cooking (relative to the raw
 913 tissues) including summarised source data.

	AM	SD	GM	GSD	Median	Min	Max	N	
All cooked Seafood (Fish, Crustacean, Bivalve)	0.74	0.21	0.70	1.2	0.76	0.19	1.24	63	This study
Fish	0.75	0.21	0.72	1.4	0.79	0.19	1.24	42	This study
Crustacean	0.68	0.20	0.65	1.3	0.69	0.35	1.06	16	This study
Bivalve	0.75	0.26	0.71	1.41	0.62	0.49	1.03	5	This study
Grilled, Fried									
All grilled/fried seafood	0.78	0.21	0.74	1.4	0.78	0.19	1.12	34	This study
Fish	0.76	0.21	0.72	1.4	0.79	0.19	1.13	25	This study
	0.74	0.14	0.73	1.2	0.78	0.45	0.94	16	Uddin 2019
	0.73	0.36	0.62	2.0	0.80	0.19	1.13	7	Díaz-Francés 2017
	0.93	0.05				0.89	0.96	2	Strok 2011

Crustacean	0.81	0.12	0.80	1.2	0.78	0.75	1.06	7	This study
Shrimp (various)	0.78	0.03	0.78	1.0	0.78	0.75	0.82	5	Uddin 2019
Prawn (whole)	0.88	0.25				0.70	1.06	2	Medley 2022 ¹
Bivalve	1.03	0.01				1.02	1.03	2	Krystan 2015
Boiled, Steamed									
All boiled/steamed seafood	0.68	0.20	0.66	1.3	0.69	0.38	1.27	29	This study
Fish									
	0.75	0.21	0.66	1.4	0.66	0.38	1.24	17	This study
	0.73	0.15	0.71	1.3	0.75	0.38	0.92	16	Uddin 2019
	1.24							1	Roselli 2020
Crustacean	0.58	0.20	0.55	1.4	0.54	0.35	1.24	9	This study
Shrimp (various)	0.50	0.08	0.49	1.2	0.46	0.41	0.62	5	Uddin 2019
Prawn (whole)	1.04					0.82	1.03	2	Medley 2022 ¹
Mantis shrimp (meat)	0.66							1	Roselli 2020
Small shrimp	0.35							1	RWMC 1994
Bivalve	0.56	0.07	0.56	1.1	0.57	0.49	0.62	3	This study
	0.55	0.09				0.49	0.62	2	Díaz-Francés 2017
	0.57							1	RWMC 1994

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919 S.2 ²¹⁰Po loss from radioactive decay during Harvest-to-Consumption

920 Within each seafood production category, there exists a chain of events (e.g., harvest, transport,
921 processing, transport to market, market storage, home storage consumption). In this study, the
922 duration data for these events are combined into two groups termed here “Harvest-to-Market” and
923 “Market-to-Consumption”. This is necessary because Harvest-to-Market events are dominated by
924 industrial-type production processes while the Market-to-Consumption events are dominated by
925 retail and consumer behaviours. These two groups of events are therefore expected to have
926 differing data sources, data ranges and potentially differing data distributions. The following process
927 was used to estimate delay durations:

- 928 • Seafood categories of fresh, frozen, canned, dried and smoked are considered separately
929 given their potentially different storage delay times. These simplified categories serve the
930 purpose for use in typical dose assessments. More detailed categorisation is not currently
931 justified given that most dose assessments do not have access to more detailed data on
932 receptor preferences.
- 933 • For each category, duration data are gathered and grouped into the two types of Harvest-to-
934 Market and Market-to-Consumption. In gathering duration data, various combinations of
935 the following search terms were used: seafood, fresh seafood, marine fish,
936 chilled/refrigerated, smoked, frozen, canned, retort pouch, dried, cured, “use by” date, shelf
937 life, storage time, radionuclides, dose, radioactive polonium, ²¹⁰Po.
- 938 • The Harvest-to-Market duration ranges (from harvest until arrival at market) are typically
939 sourced from industry data (e.g., harvest, production and process studies), science
940 publications (e.g., minimum and maximum observed data for various seafoods).
- 941 • The Market-to-Consumption duration ranges (from arrival at market until consumption.
942 Includes warehouse, display/shelf time, transport, home storage) are typically sourced from
943 industry data, science publications and government reports.
- 944 • Within each of the above ranges, data distributions are applied that are consistent with
945 observed data and reference information. Distributions may vary depending on the
946 category. See Table S2.1 and text on distributions for specific seafoods.
- 947 • The overall delay estimates for each seafood category are calculated by combining the
948 Harvest-to-Market and Market-to-Consumption distributions using Monte Carlo analysis
949 (used here via Goldsim™ software). The Monte Carlo methods used common parameters
950 (e.g., latin hypercube sampling over 10,000 realisations) and, where appropriate, utilised
951 distributions that were truncated to the minimum and maximum data (Table S2.1).

952 Applying the above procedure to fresh seafood, using the available data up through 2022, the range
953 of Harvest-to-Market durations is typically 0-6 days (Table S2.1). Within this range, it is assumed the
954 durations can be approximated by a normal distribution (mean=3.0 days), consistent with typical
955 production-transport supply chains (e.g., Tyworth and O'Neill, 1997). After the fresh seafood is
956 purchased, data reflect a preference for consumption with 1-3 days, but some durations ranged up
957 to 12 days (Baptista et al., 2020; McManus et al., 2014; Østli et al., 2013; Roccato et al., 2017;
958 Simpson et al., 2012). These durations are consistent with the desire of producers to sell fresh
959 products quickly and the preferences of consumers to for seafood products that are fresh, appealing

960 and considered to be safe (Newsome et al., 2014). The data on Market-to-Consumption durations of
961 fresh seafood (from multiple studies) were best fit by an exponential distribution (Roccatto et al.,
962 2017). This same study reported that the mean storage time was approximated by dividing the use-
963 by date by four (Roccatto et al., 2017). The two separate data distributions, Harvest-to-Market
964 (normal) and Market-to-Consumption (exponential), were then combined using Monte Carlo
965 methods to arrive at an overall distribution of Harvest-to-Consumption durations (total delay
966 estimates, Table S2.1).

967 Applying the above procedure to packaged seafood (frozen, , frozen, canned, dried and smoked), the
968 typical Harvest-to-Market duration ranges are provided in Table S2.1 based on reported data
969 (Bienkiewicz et al., 2022; Boerder et al., 2018; Immaculate et al., 2013); Kontominas et al. (2021);
970 (Limbo et al., 2009; Obluchinskaya and Daurtseva, 2020; Østli et al., 2013; Roccatto et al., 2017;
971 Tingman, 2010; Tsironi et al., 2016; USDA, 2022; Xiao et al., 2016). The distributions within these
972 Harvest-to-Market ranges were approximated using normal distributions (e.g., Tyworth and O'Neill,
973 1997). For the Market-to-Consumption period, the durations ranged up to more than 5 years for
974 canned seafood in reference publications (Boerder et al., 2018; Kontominas et al., 2021; Tsironi et
975 al., 2016). Within the Market-to-Consumption ranges for seafood packaged/preserved for longer
976 shelf lives (frozen, , frozen, canned, dried), the reported quantitative reports and qualitative
977 observations suggest the data are best represented by lognormal distributions. Compared with fresh
978 seafood, there is less urgency for quick sale of the packaged/preserved products. However, retailers
979 tend to avoid long storage times and, after purchase, much of the packaged seafood is consumed in
980 a timely manner as many consumers are aware of the potential for degradation of quality and tastes
981 over time and also have a perception of increased risk with delayed usage (Newsome et al., 2014). A
982 small percentage of products may have long shelf storage delays before use consistent with a
983 lognormal distribution. As with fresh seafood, the overall estimated distribution of Harvest-to-
984 Consumption durations for packaged/preserved seafood were derived using Monte Carlo (Goldsim™
985 software; Ref) to combine the Harvest-to-Market (normal distributions) and Market-to-Consumption
986 (log-normal distributions) estimates. Total delay durations were rounded to the nearest day as more
987 precision is not warranted by the scarce data.

988 For smoked seafood, the Market-to-Consumption durations were, similar to fresh seafood,
989 approximated using an exponential distribution consistent with reference publications (Afchain et
990 al., 2005; Chardon and Swart, 2016; Pouillot et al., 2010) and using duration data from (Afchain et
991 al., 2005; Chardon and Swart, 2016; Daelman et al., 2013; Pouillot et al., 2010; Roccatto et al., 2017)

992

993 Table S2.1. Recommended R_{decay} ; correction factors (fraction ^{210}Po retained) derived from ^{210}Po delay
 994 times between harvest and consumption for various seafood processing/preservation types (2022
 995 estimates).

	Harvest-to-Market ¹	Market-to-Consumption ²	Total delay, Harvest-to-Consumption	R_{decay} ; correction factors	
	Distribution mean (range) (days)	Distribution mean (range) (days)	50 th (range) (days)	Recommended value (range)	
Fresh	Normal 3(0-6) ^{1,2}	Expon. 3(0-12) ¹⁻⁵	5 (0-17)	0.98 (0.93-1.0)	
Frozen	Normal 65.5(1-130) ⁶⁻⁹	LogNorm(t) 20.2(0-410) ⁶⁻¹⁰	89 (1-540)	0.70 (0.21-1.0)	
Canned	Normal 127.5(10-245) ^{9,10}	LogNorm(t) 42.7(0-1825) ^{10,11}	177 (10-2070)	0.50 (0.14-0.96)	
Dried	Normal 30.5(10-51) ¹²⁻¹⁴	LogNorm(t) 19.1(0-365) ¹²⁻¹⁵	51 (10-410)	0.81 (0.26-0.96)	
Smoked	Normal 5.5(2-9) ¹⁶	Expon. 11(0-53) ^{6,17-22}	13 (2-62)	0.95 (0.78-0.99)	
All seafood (weighted)				0.81 (0.14-0.1.0)	

996 ¹ Harvest-to-market includes all transport, processing and storage times from the time of removal from the
 997 ocean until arrival at retail marketplace.

998 ² Market-to-Consumption includes all warehouse, display and consumer storage times from the time of arrival
 999 at the market until consumption.

1000 Table S2.2. Expanded reference descriptions for Table S2.1.

1	(USDA, 2022). US Department of Agriculture (https://www.fsis.usda.gov/food-safety/safe-food-handling-and-preparation/food-safety-basics/shelf-stable-food)
2	(Østli et al., 2013). How fresh is fresh? Perceptions and experience when buying and consuming fresh cod fillets (Norway). Summarizing, when elder respondents were asked which was the last day they would be willing to buy cod after capture, there was a 75% probability that this would be approximately 3 days(Fig. 2); for young respondents this time was approximately 5 days. There was a 75% probability that these consumers would have the fish approximately 1 day at home before cooking and eating it. Using a rejection probability of 25% results in a shelf life of approximately 11 days when no capture date information was given.
3	(Simpson et al., 2012). Time-temperature indicator to monitor cold chain distribution of fresh salmon (<i>Salmo Salar</i>). Fresh salmon (farmed) were shipped from Chile to the US in 65 hours total time (truck transport, air flight, final transport) in a TTI study simulating typical durations for fresh fish Harvest-to-Market.
4	(McManus et al., 2014). Perceptions and preference for fresh seafood in an Australian context. 91.3% of respondents reported storing thawed seafood in the refrigerator for 3 days or less with 2 weeks being the maximum storage period reported." (Australia). 57.8% of respondents stating that 'fresh' meant that the seafood or fish displayed in retail outlets was caught the same day as displayed for sale. Four percent (n = 7) thought 'fresh' meant caught within a few days.
5	(Baptista et al., 2020). Consumption, knowledge, and food safety practices of Brazilian seafood.
6	(Roccatto et al., 2017). Analysis of domestic refrigerator temperatures and home storage time distributions for shelf-life studies and food safety risk assessment. The storage time was described by an exponential distribution corresponding to the use-by date period divided by 4.
7	(Tingman, 2010). Fish product quality evaluation based on temperature monitoring in cold chain Maximum recommended total time from Harvest-to-Consumption of 330 days (shorter durations if temperatures not maintained throughout cold chain).
8	(Xiao et al., 2016). Typical frozen cold-chain from Harvest-to-Market for farmed fish in China was

	approximately 22 days total (Harvest-to processing 1.4 d, processing 1.3 d, transport to market 15 d, market 4.3 d).
9	(Limbo et al., 2009). Freshness decay and shelf life predictive modelling of European sea bass (<i>Dicentrarchus labrax</i>) applying chemical methods and electronic nose. Maximum recommended total time from Harvest-to-Consumption of 393 days.
10	(Kontominas et al., 2021). Recent Developments in Seafood Packaging Technologies.
11	(Tsironi et al., 2016). Evaluation of Time Temperature Integrators for shelf-life monitoring of frozen seafood under real cold chain conditions (i.e. production warehouse, distribution centre, retail and domestic storage).
12	(Boerder et al., 2018). "It thus takes about half a year on average (18 to 35 weeks) from the Harvest of albacore tuna to the canned final product on the shelf. Along the entire supply chain, the fish have travelled an average 17,000 km"
13	(Immaculate et al., 2013). Quality and shelf life status of salted and sun dried fishes of fishing villages in different seasons dried fish is that if properly stored, the product can maintain quality for up to 3-6 months
14	(Obluchinskaya and Daurtseva, 2020). Effects of air drying and freezing and long-term storage on phytochemical composition of brown seaweeds. In the course of the experiment on long-term storage of samples of these algae, the similarity in phytochemical composition in dry and frozen states remained up to 365 days of storage.
15	(Foscarini and Prakash, 1990), Various sources (seaveg.com) Storage times vary depending on residual moisture content, treatments and storage conditions. In one example (FAO 199) "Well dried seaweed with salt crystals on its surface can be stored for a long time; up to 2 years without getting spoiled. The salt covering the seaweed prevents the spoilage of the carrageenan. Of course it is important that seaweed is stored properly." However, many products will not be salt encrusted. For most commercial products, we estimated a practical shelf life limit of about one year.
16	(Bienkiewicz et al., 2022) The available literature contains a lot of information on microbiological safety or freshness level indicators, such as TVB-N. This experiment showed that the 28-day storage period of the hot and cold smoked product did not result in exceeding the TVB-N limits. However, in the case of raw salmon, on day 21 of storage, a TVB-N content limit was found.
17	(Afchain et al., 2005) Proposes a statistical approach that utilises an approximate 12-day total storage time (retail + consumer) for smoked salmon.
18	(Chardon and Swart, 2016) Consumer survey data. The smoked fish consumer storage data were represented by an exponential distribution with a mean of 3.29 days (home refrigerated storage).
19	(Daelman et al., 2013) One fifth (19.8%) of the REPFEDs (chilled goods including smoked fish) were consumed on the day of purchase, little over half of the products (52.9%) were estimated as consumed within the 2 days after purchase and 93.7% was estimated as consumed within the first week after purchase.
20	(Pouillot et al., 2007) Utilises/updates estimates in Afchain et al., 2005. Proposes a statistical approach that utilises an approximate 12-day total storage time (retail + consumer) for smoked fish. Proposes exponential distributions for various components of the retail and consumer storage times.
21	(Pouillot et al., 2010) Proposed a Fitted distribution of time to first consumption of smoked seafood, exponential with mean of 4 days.
22	(Erkan et al., 2011) Based on the sensory and microbiological results, the control samples were acceptable only up to 6 weeks, compared to 8 weeks in HP treatment cold smoked salmon samples, extending the shelf-life by 2 weeks.

1001

1002

1003 Table S2.3. Results from this study (bolded) compared with previously published estimates on ²¹⁰Po
 1004 delay times between harvest and consumption for various seafoods.

		Total duration Harvest-to- Consumption (days)	R _{decay} ; correction factors ¹	Reference
Fresh				
	Seafood	5 (0-17)	0.98 (0.93-1.0) ¹	This study (Table S3)
	Seafood	3	0.99	Aarkrog et al. (1997)
	Wild-caught fish	8 (2-12)	0.96	Jones and Sherwood (2009)
	Farm-raised fish	2 (1-5)	0.99	Jones and Sherwood (2009)
	Bivalve/crustacean	7 (1-9)	0.97	Jones and Sherwood (2009)
Frozen				
	Seafood	89 (1-540)	0.70 (0.21-1.0) ¹	This study (Table S3)
	Seafood	60	0.74	Aarkrog et al. (1997)
	Wild-caught fish	90 (60-365)	0.64	Jones and Sherwood (2009)
	Farm-raised fish	14 (2-60) ²	0.93	Jones and Sherwood (2009)
	Bivalve/crustacean	7 (4-548) ²	0.97	Jones and Sherwood (2009)
Canned				
	Seafood	177 (10-2070)	0.50 (0.14-0.96) ¹	This study (Table S3)
	Seafood (canned)	365	0.16	Aarkrog et al. (1997)
Dried				
	Seafood	51 (10-410)	0.81 (0.26-0.96) ¹	This study (Table S3)
Smoked				
	Marine fish	13 (2-62)	0.95 (0.78-0.99) ¹	This study (Table S3)
All types				
	Seafood ³		0.81 (0.14-0.1.0) ^{1,3}	This study (Table S3)
	Seafood	90	0.6	Aarkrog et al. (1997) ⁴

1005 ¹ For reference data, the correction factors are calculated here from the published delay estimates using a
 1006 standard decay equation without ingrowth of ²¹⁰Po from ²¹⁰Pb, as is consistent with past approaches. For
 1007 this study, the R_{decay} factors include the ingrowth of ²¹⁰Po from ²¹⁰Pb and are therefore slightly higher
 1008 even when considering similar delay durations.
 1009 ² The reference does not explain or support this comparatively short duration.
 1010 ³ Percentage consumption weighting is world median Fresh=44%, Frozen=34%, Canned=11%, Dried=7%,
 1011 Smoked=3%, (based on FAO 2018, (Sun et al., 2022)).
 1012 ⁴ Aarkrog et al., 1997 report correction factors of 0.6 in the text (results section) and also reported use of a
 1013 value of 0.5 in calculations.

1014 Part of the difference in R_{decay} factors from this study vs previous is that the values presented here
 1015 include the ²¹⁰Po ingrowth from the ²¹⁰Pb that is in the seafood (as measured at the time of harvest;
 1016 Eqn (2)). This ingrowth is relatively minor because the ²¹⁰Pb activity concentrations in seafood are
 1017 typically relatively low compared to ²¹⁰Po which is mainly derived via the diet of the organism. In
 1018 addition, the ²¹⁰Po ingrowth is relatively slow (about 2.3 years to equilibrate). For Fresh and Smoked
 1019 categories, the ingrowth adds only 0.01 to the fraction retained. For the longest category of Canned,
 1020 the ingrowth adds 0.09 to the fraction estimate. These are minor, but not insignificant increases in
 1021 ²¹⁰Po,

1022 The ingrowth component of equation (2) requires input of the initial activity concentration ²¹⁰Pb
 1023 relative to ²¹⁰Po (the ratio of ²¹⁰Pb to ²¹⁰Po activity concentrations at the time of harvest). For this
 1024 study, a generic ²¹⁰Pb/²¹⁰Po ratio of 0.16 was used (²¹⁰Po/²¹⁰Pb ratio of 6.3) which was obtained from

1025 770 paired ^{210}Po and ^{210}Pb data after filtering data for edible tissues and considering the seafood
 1026 types and proportions consumed globally (fish=56.8%, Crustacean=14.4%, Bivalve=17.0%,
 1027 Gastropod=2.4%, Cephalopod=3.9% and seaweed=5.4%; Cai and Leung, 2017). In deriving the
 1028 generic $^{210}\text{Pb}/^{210}\text{Po}$ ratio of 0.16, the ^{210}Pb and ^{210}Po activity concentration data were screened for
 1029 relatively high \pm uncertainties, and removed if their \pm uncertainty values were greater than 50% of
 1030 the reported activity concentrations. The same test was applied to the propagated uncertainties on
 1031 the $^{210}\text{Pb}/^{210}\text{Po}$ activity concentration ratios. The application of these screens did not introduce
 1032 substantive bias across the distribution ranges (e.g., data were removed relatively evenly across the
 1033 entire range of activity concentrations) and therefore the estimates on the distribution means did
 1034 not change substantially. This screening provided greater confidence in the $^{210}\text{Pb}/^{210}\text{Po}$ ratio used in
 1035 equation (2).

1036

1037 S.3 ^{210}Po differences in farm-raised vs wild-caught marine fish

1038 Differences in the activity concentrations between mariculture-sourced vs wild-caught seafood are
 1039 determined through the straight-forward comparison of measurements in comparative samples. A
 1040 search was conducted focused on scientific journals, science conference proceedings, industry
 1041 reports, government documents and websites (through 2022). Various search terms were used:
 1042 mariculture, aquaculture, seafood, marine fish, fish, crustaceans, cephalopods, farmed, farm-raised,
 1043 pen-raised, , artificial feed, radionuclides, radiological dose, polonium, ^{210}Po . In this study, the ^{210}Po
 1044 activity concentrations of the mariculture vs wild-caught were compared for the same or similar
 1045 species from the same region.

1046 Table S3.1. Summary ^{210}Po activity concentrations in the muscle tissues of farm-raised marine fish
 1047 grouped by species. Note that the feed types are different among studies (see main text).

Species and reference	Common name	^{210}Po Bq kg ⁻¹ (ww)	\pm	N	Reference
Fish raised with processed feed					
<i>Salmo salar</i> ¹	Atlantic Salmon				
		0.003	0.001	1	Heldal et al., 2019)
		0.004	0.001	1	"
		0.013	0.003	1	"
		0.02	0.008	1	"
		0.022	0.007	1	"
		0.008	0.002	1	"
		0.023	0.008	1	"
		0.016	NA		(Smith, 2006) ²
		0.13	NA		"
		0.1	NA		"
		0.13	NA		"
<i>Sparus aurata</i>	Gilthead seabream	0.181	0.022	2	(Jalili et al., 2009)
Fish raised with					

natural marine-sourced feed					
<i>Larimichthys polyactis</i> ,	Yellow croaker	1.39	0.15	18	(Kong et al., 2021)
<i>Pagrus major</i>	Red sea bream	10.4	1.2	12	"
<i>Lateolabrax japonicus</i>	Common sea perch	0.99	0.12	11	"
Crustaceans raised with processed feed					
<i>Litopenaeus vannamei</i> ,	Whiteleg shrimp	0.117	0.019	1	(Dong et al., 2018)
<i>Litopenaeus vannamei</i> ,	Whiteleg shrimp	0.562	0.099	1	"
<i>Penaeus monodon</i>	Tiger prawn	10.5	0.4	1	"

1048 ¹. From commercial/industrial-scale operations.

1049 ²The available data from Smith 2006 were the minimum and maximums for two time/sampling periods.

1050 The available data on ²¹⁰Po activity concentrations in the edible tissues of mariculture seafood were
1051 few (N=19) and limited to fish and crustaceans. The primary publications were: Heldal et al. (2019),
1052 Kong et al. (2021) Jalili et al. (2009), Smith (2004). Data from bivalve aquaculture is not included as
1053 processed feeds are mainly used for broodstock/larval stages and not for the period of primary
1054 bivalve growth which typically is carried out in natural marine settings (Smaal et al., 2018). Only
1055 limited data were found from one study on changes in ²¹⁰Po in mariculture vs wild-caught
1056 crustaceans. More data are needed for this category as they are a major seafood source with
1057 approximately 9.4 million tonnes of crustaceans harvested from mariculture each year (2018 FAO
1058 data reported by (2018 FAO data reported by Albalat et al., 2022).

1059

1060 S.4 Example of typical ²¹⁰Po reduction using the recommended correction factors

1061 The potential losses of ²¹⁰Po associated with the cooking, decay and mariculture influences can be
1062 significant. If for example, when the mean (or recommended) correction factors are used, the data
1063 suggest that, at the time of ingestion, seafood often has only about 55% of ²¹⁰Po content as
1064 compared to when it was harvested. The example calculation is:

1065 Overall generic correction factor = (1 X 0.74) * (1 X 0.81) * ((0.89 X 1) + (0.11 X 0.1)) = 0.55.

1066 Table S4.1 Recommended typical correction factors.

Factor	Value	Section reference
F _c (all cooking)	1	3.1.1
R _{cooking} (all seafood)	0.74	
F _d (all methods)	1	3.2.1
R _{decay}	0.81	
F _f (wild caught)	0.89	3.3.1
R _{farmed} (wild caught)	1	
F _f (mariculture)	0.11	
R _{farmed} (mariculture)	0.2	
Generic Global correction factor that considers cooking,	0.55	

delay-decay and mariculture corrections.		
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