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Radiocesium concentration ratios and radiation dose to wild rodents in Fukushima Prefecture

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Abstract

Radiocesium was dispersed from the Fukushima Dai-ichi disaster in March 2011, causing comparatively high radioactive contamination in nearby environments. Radionuclide concentrations in wild rodents (*Apodemus argenteus*, and *Apodemus speciosus)* within these areas were monitored from 2012-2016. However, whole-organism to soil transfer parameters (i.e., concentration ratio, $CR_{wo\text{-}soil}$) for wild rodents at Fukushima were not determined and hence were lacking from the international transfer databases. We augmented the 2012-2016 data by collecting soil activity concentrations (Bq/kg, dry mass) from five rodent sampling sites in Fukushima Prefecture, and developed corresponding $CR_{wo\text{-}soil}$ values for radiocesium (^{134}Cs and ^{137}Cs) based on rodent radioactivity concentrations (Bq/kg, fresh mass). The $CR_{wo\text{-}soil}$ were added to the Wildlife Transfer Database (WTD; http://www.wildlifetransferdatabase.org/), supporting the development of the International Commission on Radiological Protection's (ICRP) environmental protection framework, and increasing the WTD from 84 to 477 entries for cesium and *Muridae* ('Reference Rat'). Significant variation occurred in $CR_{wo\text{-}soil}$ values between study sites within Fukushima Prefecture. The geometric mean $CR_{wo\text{-}soil}$, in this paper, was higher than that reported for *Muridae* species for Chernobyl.

Radiocaesium absorbed dose rates were also estimated for wild rodents inhabiting the five Fukushima study sites and ranged from 1.3-33 μGy h^{-1}. Absorbed dose rates decreased by a factor of two from 2012-2016. Dose rates in highly contaminated areas were within the ICRP derived consideration reference level for Reference Rat (0.1-1 mGy d^{-1}), suggesting the possible occurrence of deleterious effects and need for radiological effect studies in the Fukushima area.

Keywords: Reference Rat; internal dose; external dose; ERICA Tool; concentration ratio

1. Introduction

Research quantifying the radiation dose received by wildlife has increased as the scientific community tries to assess the impact of radiation on the environment (Hinton et al., 2013) and support the development of environmental radiation protection (ICRP, 2008; IAEA, 2014a). Better understanding the environmental transfer of radionuclides will improve estimates of radiation doses received by wildlife from radionuclide releases (Whicker et al., 1999), and reduce the uncertainties associated with environmental impact assessments (Beresford et al. 2008a).

Simplified compartmental models are often used to estimate radionuclide uptake by wildlife (e.g. Brown et al., 2008). Radionuclide activity concentration data from open source monitoring programs and studies in radioactively contaminated environments can improve such compartmental models. A commonly used compartmental model for radiological assessments of terrestrial wildlife is the whole-organism to soil concentration ratio ($CR_{wo\text{-}soil}$, (IAEA, 2014a)). The $CR_{wo\text{-}soil}$ is the equilibrium ratio of radionuclide activity concentration in a whole-organism (Bq kg^{-1} fresh mass; fm) to the radionuclide concentration in soil (Bq kg^{-1} dry mass; dm; IAEA, 2014b; ICRP, 2009b). $CR_{wo\text{-}soil}$ values provide a pragmatic approach to estimate radioactivity concentrations in organisms for screening assessments, without the need to measure radioactivity levels in organisms. $CR_{wo\text{-}soil}$ values, or some other predictive approach, are a necessity in planned exposure assessments where radioactive releases have not yet occurred.

$CR_{wo\text{-}soil}$ values are used to estimate radionuclide activity concentrations in organisms, which in-turn are used to estimate internal doses. The estimated doses can be compared to benchmark dose rates suggested as being protective of wildlife populations (see Howard et al., 2010), such as the Derived Consideration Reference Levels (DCRLs) suggested by the

International Commission for Radiological Protection (ICRP) (ICRP, 2008). The ICRP has proposed a list of Reference Animals and Plants (RAPs) to support their radiological assessment framework (ICRP, 2009a, 2008). One of the RAPs is a small terrestrial mammal, 'Reference Rat' (defined as a generic representative of the *Muridae* family), which has a DCRL of 0.1-1 mGy d^{-1} (ICRP, 2008). $CR_{wo\text{-}soil}$ values for Reference Rat have been collated into the Wildlife Transfer Database (WTD, (Copplestone et al., 2013)) to support the development of radiological assessments (IAEA, 2014b; ICRP, 2009b).

Large variations exist in the WTD $CR_{wo\text{-}soil}$ data, including those for Reference Rat-cesium (Cs) (i.e. coefficient of variation, CV = 445%), which greatly increase the uncertainties of any predictions from which they are derived. Such large variation in Reference Rat $CR_{wo\text{-}soil}$ data is likely due to aggregating across sites and rodent species that have different life history characteristics, such as diet. Additionally, in versions of the WTD used to support activities of the assessment model development (Brown et al., 2016; IAEA, 2014b; ICRP, 2009b), the WTD Reference Rat-Cs data were heavily biased towards $CR_{wo\text{-}soil}$ studies from the Chernobyl Exclusion Zone (Howard et al., 2013), hereafter referred to as 'Chernobyl'. Regionally biased data may increase the uncertainty of estimates when extrapolating to other areas. It is logical to speculate that more credible radionuclide transfer predictions can likely be obtained by using site- and circumstance-specific data.

Herein, we report on radiocesium (^{134}Cs and ^{137}Cs) $CR_{wo\text{-}soil}$ for 393 wild rodents inhabiting five Japanese forest sites within Fukushima Prefecture and contaminated following the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) accident of 2011 (Chino et al., 2011). The rodent radioactivity concentration data were published in an open source data paper (Ishiniwa et al., 2019). Subsequently, we visited the five sites and collected soil samples for radionuclide analyses. The radiocesium concentrations in wild rodents and soil samples were then used to derive radiocesium $CR_{wo\text{-}soil}$ values, and to estimate absorbed radiation dose rates to the species at each site.

2. Materials and Methods

2.1 Study area

Due to radioactive material dispersed from the FDNPP accident in 2011, the Japanese Government evacuated people over an area of approximately 1150 km^2. The evacuated zone was comprised mainly of forest (75%), rice paddies (10%), other agricultural fields (10%), and urban areas (5%) (Steinhauser et al., 2014). Rodent sampling sites were within the forested terrain of the evacuation zone, which has an annual average temperature of 11°C and average annual precipitation of 1300 mm. Additional site information can be found in Ishiniwa et al. (2019).

2.2 Rodent radiocesium data

We used radiocaesium activity concentration data from Ishiniwa et al. (2019), collected at five trapping grids (each with a 1 km radius) in different forests within Fukushima Prefecture between August 2012 and August 2016 (Fig. 1). Their data consisted of radiocaesium activity concentrations in 393 samples of *Apodemus speciosus* (large Japanese field mouse) and *Apodemus argenteus* (small Japanese field mouse), which are within the definition of the ICRP's Reference Rat. Relevant life-history information for each species is provided in Table 1. Small mammal monitoring protocols, and individual animal radiocesium activity concentration are provided in Ishiniwa et al., (2019). In brief, captured rodents were euthanized, and the head and internal organs (stomach, intestine, liver, spleen, and reproductive organs) removed. The remaining carcasses were homogenized individually and transferred to polystyrene containers (U8; diameter = 50 mm; height = 62 mm). ^{134}Cs and ^{137}Cs activity concentrations were measured using high-purity germanium (HpGe) detectors (GMX45P4-76, ORTEC, TN, or GCW7023, Canberra industries Inc., TN) calibrated with a standard source (MX033U8PP, the Japan Radioisotope Association). Gamma Studio (SEIKO EG&G CO., LTD., Tokyo, Japan) and Spectrum Explorer (Canberra Industries Inc.) software were used to analyze the γ-ray spectra. Radiocaesium activity concentrations were decay corrected to the day of capture.

2.3 Soils

Three, 9 cm deep soil cores (5 cm diameter) were collected from randomly selected points within each of the five trapping grids during July 2018. Ambient dose rates (μSv h^{-1}) were measured using a NaI scintillation survey meter (Hitachi TCS-172), at a height of 1 m above the ground surface at each soil sampling location. The survey meter was calibrated with a standard source. Soil sampling and preparation was conducted according to Onda et al. (2015). Samples were dried at 80°C, homogenized and placed into polystyrene containers (U8; diameter = 50 mm; height = 62 mm). All soils were analyzed for radiocesium activity concentrations using HpGe detectors (GC3018, Canberra Industries Inc., Japan, Tokyo). The gamma-spectra obtained were analyzed with Gamma Explorer (Canberra Industries Inc.) with coincidence summing correction applied. Samples were assayed until gamma-ray emissions of 604.7 and 661.6 keV, for ^{134}Cs and ^{137}Cs respectively, had standard deviations from counting statistics below 10%. Results were subsequently decay corrected to the rodent sampling dates (2012-2016) to enable the derivation of $CR_{wo\text{-}soil}$ values.

2.4 Calculation of $CR_{wo\text{-}soil}$ *values*

$CR_{wo\text{-}soil}$ values were calculated from the fresh mass radiocesium activity concentrations determined in rodent carcasses collected at each study site by Ishiniwa et al. (2019), and the corresponding mean soil concentrations specific to each trapping grid. Activity concentrations in rodents were considered to be whole-body values because radiocesium is relatively uniformly distributed. Removing the internal organs prior to measurement was not considered a bias in the whole-body estimations (Beresford et al., 2008b; Kubota et al., 2015). All measurement data (^{134}Cs and ^{137}Cs activity concentrations in soil and $CR_{wo\text{-}soil}$ values) are provided in the supplementary information file.

2.5 Dose Assessment using the ERICA Tool

The ERICA Tool (version 1.3, Tier 3 probabilistic assessment; Brown et al., 2016, 2008) was used to estimate absorbed dose rates to both rodent species at all five study sites using the available soil and whole-body ^{134}Cs and ^{137}Cs activity concentrations. Other radionuclides had decayed to undetectable levels at the time of this study (Steinhauser et al., 2014). Due to yearly variations in sufficiency of rodent sample sizes, absorbed dose rates were estimated for 2012 and 2016 at sites N1 and N2; 2012 at site N3; and 2014 at sites N4 and N5.

To estimate external dose, we compared three different occupancy scenarios: (1) an "on-soil" occupancy factor of 1.0 was used within the ERICA Tool for both species (i.e. the rodents were assumed to spend all of their time on the soil surface); (2) *A. argenteus* has a tendency to be arboreal, therefore another scenario was conducted with time spent in the air (10 m) set to 50% (i.e. mimicking time spent above ground in trees) and 50% "on-soil"; and (3) 50% of the time spent "in-soil" (i.e. representing underground nesting) and 50% "on-soil". Lognormal distributions for both soil and animal radiocaesium activity concentrations were assumed (in accordance with Brown et al. 2008). Each site's average percent soil dry matter content value was used (see Supplement material).

ERICA uses Dose Conversion Coefficients (DCCs; μGy h^{-1}per Bq kg^{-1}) that are radionuclide-specific. The DCCs convert activity concentrations in soils to external dose rate, and activity concentrations in organisms to internal dose rate. Organism-specific DCCs are calculated within the ERICA tool based on the geometry (shape and size) of the organism. We used the “new organism” option in the ERICA Tool and input specific sizes of 0.03 m, 0.03 m, 0.11 m, 0.040 kg (height, width, length and mass) and of 0.03 m, 0.03 m, 0.075 m, 0.020 kg for *A. speciosus and A. argenteus*, respectively, based on information provided in Table 1 and Kubota et al. (2015). The ERICA Tool default radiation weighting factors (10 for alpha, 3 for low energy beta, and 1 for other beta/gamma) were used.

2.6 Statistical analysis

All statistical analyses were performed using MINITAB version 18. A P-value of less than 0.05 was considered statistically significant. Prior to statistical analyses a log transformation was applied to the radiocesium activity concentration data and subsequent $CR_{wo\text{-}soil}$ values to satisfy the assumption of normality. A general linear model (GLM) with Tukey pairwise comparison was used to compare ^{137}Cs $CR_{wo\text{-}soil}$ values among species and sites. Additionally, Mann-Whitney u-test was used to compare $CR_{wo\text{-}soil}$ data from the WTD to this study. The ^{137}Cs $CR_{wo\text{-}soil}$ values were lognormal distributed (Kolomogorov-Smirnov test) and are summarized as geometric means (GM) and geometric standard deviations (GSD); arithmetic means (AM) and standard deviations (SD) are provided for comparative purposes to reported $CR_{wo\text{-}soil}$ studies and for application in the ERICA Tool as described above.

3. Results

Summarized (^{134}Cs and ^{137}Cs) soil activity concentrations for each study site and measured ambient dose rates are provided in Table 2. Ambient dose rates were highest in areas where soil radiocesium activity concentrations were greatest and decreased as activity concentrations decreased (r^2 = 0.92).

Wild rodent radiocesium (^{134}Cs and ^{137}Cs) activity concentrations are summarized by year in Table 3, for each site and species. The range of activity concentrations in rodents exceeded three orders of magnitude, with the highest radiocesium concentration (780 kBq kg^{-1}, site N1) observed in *A. speciosus* and the lowest (0.35 kBq kg^{-1}, N5) observed in *A. argenteus*.

3.1 $CR_{wo\text{-}soil}$ values

A total of 393 radiocesium $CR_{wo\text{-}soil}$ values were derived from collated data and are summarized in Table 4 by species and site. Paired t-tests indicated no statically significant difference in the $CR_{wo\text{-}soil}$ of ^{134}Cs and ^{137}Cs isotopes ($p > 0.05$). This agrees with other studies (e.g., Barnett et al., 2014; Copplestone et al., 2013; ICRP, 2009a; Tagami et al., 2018), which demonstrated $CR_{wo\text{-}soil}$ are the same for all isotopes. Because $CR_{wo\text{-}soil}$ values for ^{134}Cs and ^{137}Cs were similar, subsequent statistical comparisons were based only on ^{137}Cs data.

3.2 Contribution to the Wildlife Transfer Database

Our 393 $CR_{wo\text{-}soil}$ values for Reference Rat-Cs were added to values in the WTD. The added data now comprise 80% of the WTD values for ICRP Reference Rat-Cs (ICRP, 2009b), and 100% of the available $CR_{wo\text{-}soil}$ data for Reference Rat in Japan (Table 5). Integration of these data into the WTD reduced the variation (CV) of $CR_{wo\text{-}soil}$ for Reference Rat from 450% to 340%, and importantly provided Japanese-specific data for future regional screening assessments.

3.3 $CR_{wo\text{-}soil}$ values – Comparisons over time, between species and among locations

A. speciosus had a significantly higher $CR_{wo\text{-}soil}$ value than *A. argenteus* across our entire dataset ($p < 0.05$). However, further analysis showed there was a significant difference between the two species at only one site (N1) ($p < 0.05$). There was no trend with time in the $CR_{wo\text{-}soil}$ values for either species (Fig. 2, $p > 0.05$).

Site differences in $CR_{wo\text{-}soil}$ values within Fukushima Prefecture occurred for each species. For *A. specious,* $CR_{wo\text{-}soil}$ values were significantly higher at sites N2 and N3 than site N1 ($p < 0.05$). For *A. argenteus,* sites N2 and N4 had significantly higher $CR_{wo\text{-}soil}$ values than site N1 ($p < 0.05$).

3.4 Comparison of Fukushima and Chernobyl data

$CR_{wo\text{-}soil}$ data from Chernobyl and our study sites both had log normal distributions with significant variations indicating that the GM provides the most suitable measure of central tendency. The GM for our study was higher than the GM reported for Reference Rat species in Chernobyl studies (Table 5), which dominated the WTD. Additionally, there was a statistical difference ($p < 0.01$, Mann-Whitney u-test) between the $CR_{wo\text{-}soil}$ for Chernobyl and our Fukushima data.

3.5 ERICA Tool absorbed dose rates

Total absorbed dose rates (external and internal doses combined) for the Fukushima data ranged from 4.8-33 μGy h^{-1}, 1.3-17 μGy h^{-1}, and 2.3-9.6 μGy h^{-1}, in 2012, 2014, and 2016, respectively, assuming a 100% occupancy on the soil surface (Table 6). External irradiation accounted for the majority of the total radiation dose to both rodent species (about 66%). Similar contributions of internal dose rates to the total dose occurred in all years. Both external and internal dose rates declined by about 50% from 2012-2016, largely explained by the physical decay of ^{134}Cs.

Time spent in, on or above the soil altered the dose rates to rodents simulated by ERICA. Estimated absorbed dose rates to *A. argenteus* decreased by about 8% when time spent in trees was assumed to be 50% (Table 6). When below ground nesting was assumed to be 50% the external dose rates for *A. argenteus* increased by approximately 20% (Table 6).

4. Discussion

Simple models based on soil contamination levels (e.g. $CR_{wo\text{-}soil}$) are routinely used to estimate radioactivity concentrations in terrestrial biota and evaluate risks to humans and the environment (IAEA, 2014b). A large range in $CR_{wo\text{-}soil}$ values, with three to four orders of magnitude variation, is typically seen for the transfer of radionuclides to specific wildlife groups (IAEA, 2014b), including three orders of magnitude variation of the values in Cs for Reference Rat (Copplestone et al., 2013; ICRP, 2009a). Some progress is being made to develop alternative approaches that take into account the effect of site and possibly help address the lack of data for many radionuclides and organisms (Beresford et al., 2016; Beresford and Willey, 2019). However, most environmental assessment models used in regulatory screening assessments are currently reliant on the $CR_{wo\text{-}soil}$ approach (e.g. Beresford et al., 2008a; Brown et al., 2016; ICRP, 2009a; Oskolkov et al., 2011). Generic $CR_{wo\text{-}media}$ values (e.g. IAEA 2014) are only suitable for screening-level assessments (Wood et al., 2013). However, users of $CR_{wo\text{-}soil}$ values tend to ignore their large variations, which can be especially misleading when $CR_{wo\text{-}soil}$ values are used in more 'realistic' assessments, as opposed to conservative screening assessments. Consequently, assessment approaches generally suggest using site-specific data rather than generic $CR_{wo\text{-}soil}$ values for assessments (e.g Brown et al., 2008; Jones et al., 2003; Sheppard, 2005). But even $CR_{wo\text{-}soil}$ values derived from site-specific data demonstrate large variations, as evidenced by the Fukushima data reported herein (CV = 160%).

4.1 Reference Rat $CR_{wo\text{-}soil}$ values

The $CR_{wo\text{-}soil}$ values from this study are within the ranges reported for Reference Rat species (Table 5). The WTD collates data by element making no distinction for isotopes (i.e.

cesium $CR_{wo\text{-}soil}$ for ^{137}Cs, ^{134}Cs and stable Cs are amalgamated). However, Reference Rat-Cs $CR_{wo\text{-}soil}$ values from studies using stable-element concentrations (e.g. Barnett et al., 2014; Guillén et al., 2018) tend to be lower (by approximately an order of magnitude) than $CR_{wo\text{-}soil}$ values estimated here (Table 5). Lower $CR_{wo\text{-}soil}$ values for stable Cs have been reported by a number of authors for many organisms (Barnett et al., 2014; Beresford et al., 2020; Copplestone et al., 2013; Thørring et al., 2016). The lower $CR_{wo\text{-}soil}$ values of stable elements are most likely because radioisotopic fallout is a relatively recent addition to local soils, and has not had comparable time to bind to inert soil components that reduce biological uptake.

Our $CR_{wo\text{-}soil}$ values for *A. speciosus* can be compared to data from a highly contaminated site (47 ± 27 kBq m^{-2}) close to the FDNPP, where Kubota et al. (2015) measured ^{137}Cs activity concentrations in *A. speciosus* (n = 48). Using the Kubota et al. data, we calculated their AM ^{137}Cs $CR_{wo\text{-}soil}$ to be approximately 0.1 (range = 0.01 to 0.6). Their $CR_{wo\text{-}soil}$ was lower than our AM CR value of 0.5, but within our standard deviation (± 0.8). The lower AM $CR_{wo\text{-}soil}$ derived from Kubota et al. (2015) could merely reflect the large variation in $CR_{wo\text{-}soil}$, or may be due to the reduced bioavailability of Cs isotopes locked into glassy particles found in highly contaminated areas closer to the FDNPP (Johansen et al., 2020; Reinoso-Maset et al., 2020).

4.2 $CR_{wo\text{-}soil}$ variation by species and location

Although there was a significant difference in $CR_{wo\text{-}soil}$ values for the two species of wild rodents across our entire data ($p < 0.05$), the significance was driven by just one of the five trapping grids (N1, the site with the largest sample size for both species). When analyzed separately by site, no difference in $CR_{wo\text{-}soil}$ values were observed between *A. speciosus* and *A. argenteus* $CR_{wo\text{-}soil}$ values at four of the five sites ($p > 0.05$). If the difference between species is real, it may be due to dietary factors between both species (Table 1). *A. speciosus* consumes roots, while *A. argenteus* consumes plant leaves, and radiocesium concentrations are often higher in roots than in leaves (Cline and Hungate, 1960; Zhu and Smolders, 2000). Root consumption would also enhance inadvertent ingestion of contaminated soil (Green and Dodd, 1988). Additionally, *A. argenteus* has a tendency to be arboreal, and therefore might consume arthropods in trees, such as spiders, which have significant differences in radiocesium concentrations based on trophic levels (Tanaka et al., 2016).

Our expansion of the WTD for $CR_{wo\text{-}soil}$ Reference Rat-Cs from 84 to 477 entries did not change the GM reported in the WTD, and counters the suggestion by Wood et al. (2013) that more $CR_{wo\text{-}soil}$ data will strengthen the $CR_{wo\text{-}soil}$ construct; combined Chernobyl and Fukushima $CR_{wo\text{-}soil}$ value for Reference Rat-Cs still range over two orders of magnitude. It is our opinion that soil contamination levels are poor predictors of biota activity concentrations and that $CR_{wo\text{-}soil}$ should only be used in screening level assessments. Conclusions from dose-effect research that rely on generic $CR_{wo\text{-}soil}$ values (e.g. Beaugelin-Seiller et al. 2020; Garnier-Laplace et al., 2015) should be viewed cautiously.

4.3 Estimated external dose rates

External irradiation accounted for the majority of the estimated absorbed dose rates for wild rodents in our study when assuming a 100% 'on-soil' occupancy (60%, 73%, and 67%, in 2012, 2014, and 2016, respectively). However, our estimated external doses using the ERICA Tool show that species-specific behaviors, such as the time an animal spends on the soil surface versus underground (in-soil) or in trees (arboreal), can significantly influence external dose rates for wild rodents (Table 6). Similar changes in external dose due to time spent in sub-habitats (e.g. trees vs underground) was also documented for snakes wearing GPS-coupled dosimeters at Fukushima (Gerke et al., 2020). We used the default assumption of homogenous contamination of soil with burrows located at a depth of 25 cm, which may not reflect the actual situation and result in uncertainty in our estimated dose rates (Beaugelin-Seiller, 2014). Although we defined species-specific geometries approximating the size of *A. speciosus* and *A. argenteus* in this study, the absorbed dose rates estimated using those geometries differed little from those estimated using the ERICA Tool default 'Mammal – small burrowing' geometry (e.g. less than 1% difference in the external dose rate estimates).

Ishiniwa et al. (2019) measured ambient dose rates (μSv h^{-1}) at all trapping sites (one measurement at all five sites in 2012, and five measurements at all sites in 2013-2016) during the rodent sampling program in which this paper is based. Estimated external absorbed dose rates using the ERICA Tool, tended to be similar to ambient dose rates (Table 6).This is in agreement with comparisons of ambient measurements to TLDs attached to small mammals in contaminated areas of Chernobyl (Beresford et al., 2008b; Chesser et al., 2000); the conversion factor for ambient dose rates (μSv h^{-1}) to absorbed dose (uGy) via specific air kerma being relatively small for Cs isotopes (e.g. 1.1, Kubota et al. 2015). Pragmatically, taken together, this suggests that ambient dose rate measurements (μSv h^{-1}) may be changed directly to external absorbed dose rates (μGy h^{-1}) for estimating external absorbed dose rates for wild rodents. This is also likely because of wild rodent's small home ranges, whereas recent studies of wolves, with more complex use of their much larger home ranges, showed that the spatial-temporal aspects of an animal's position within a contaminated environment dominated the differences in external dose among animals within the population (Hinton et al., 2019), and that spatial-temporal aspects of contamination should be better considered to improve external dose estimations.

4.4 Uncertainty due to soil sampling strategy

Radiocesium from FDNPP accident was distributed heterogeneously across the impacted areas and large spatial variation has been observed (Kato et al., 2018; Mikami et al., 2015). Soil concentrations tended to vary across relatively small distances, as shown by our sampling sites and other studies over similar sampling areas using larger sampling campaigns (Anderson et al., 2019; Kubota et al., 2015a). We acknowledge that three soil concentration measurements at each rodent trapping grid, used for deriving $CR_{wo\text{-}soil}$ values and external absorbed dose rate estimates, may not fully represent the wild rodents' environment. More field samples and interpolation of contaminant levels (e.g. kringing method) across the habitat of the target biota would reduce variation seen in our trapping grids. Additionally, variation seen in $CR_{wo\text{-}soil}$ values may also be caused by the soil radiocesium concentration back calculation. The decay correction from the soil sampling campaign date to the respective rodent capture date ignores potential radiocesium vertical migration that could have occurred between 2012 and 2016 (Konoplev et al., 2018; Yoschenko et al., 2018). Radiocesium may have been more bioavailable to wild rodents 1-2 years after the FDNPP accident and surface contamination of vegetation would have been higher than a simple decay correction implies.

4.5 Estimated absorbed dose rates in context with the ICRP DCRLs

The ICRP DCRLs are order of magnitude ranges in absorbed dose rates within, which there is likely to be some chance of deleterious radiation induced effects occurring to individuals (ICRP, 2008). For Reference Rat, the DCRL is approximated at 4-40 μGy h^{-1} (0.1 – 1 mGy d^{-1}). In 2012, the estimated absorbed dose rates to sampled wild rodents were within this benchmark range (e.g. 33 μGy h^{-1} for *A. speciosus* at N1; assuming a 100% occupancy on-soil surface). In 2014, absorbed dose rates to wild rodents were within the DCRL range at N4 (17 μGy h^{-1}). In 2016, average absorbed dose rates to wild rodents had decreased approximately 50% from 2012, but some were still within the ICRP DCRL (e.g. 9.6 μGy h^{-1} for *A. speciosus* at N1). Our ERICA simulated dose rates assumed 100% on-soil occupancy, but real dose rates could be higher because both species of rodents are known to spend time underground (Ohdachi et al., 2009).

Some field studies have reported radiation effects on wild rodents, such as chromosomal aberrations (Fujishima et al., 2020; Kubota et al., 2015b) and altered spermatogenesis (Takino et al., 2017) in the severely contaminated areas of Fukushima. Given that our estimated absorbed dose rates are within the DCRLs, additional studies of chronic effects on populations of exposed wild rodents in areas of Japan receiving high levels of contamination are warranted. This recommendation supports that from other studies of wild rodents sampled from Fukushima impacted areas where the estimated total absorbed dose was 50 μGy h^{-1} in 2014 (Kubota et al., 2015a) and 13-23 μGy hr^{-1} from 2012-2016 (Onuma et al., 2020).

5. Conclusion

The $CR_{wo\text{-}soil}$ values presented in this paper are the largest reported data set for Reference Rat-Cs from FDNPP contaminated sites. Although several studies have estimated absorbed dose rates for wild rodents using various methodologies, to our knowledge no radiocesium $CR_{wo\text{-}soil}$ values have previously been published for species falling within the definition of Reference Rat in Japan. The 393 $CR_{wo\text{-}soil}$ values for Reference Rat-Cs have now been integrated into the WTD (the data are entered as Reference ID 572 in the WTD (http://www.wildlifetransferdatabase.org/) and comprise 80% of the data currently (February 2020) available for Reference Rat-Cs (ICRP, 2009b). The addition of our data has reduced the coefficient of variation by about 100%. The revised WTD database is being used for the development of environmental protection frameworks (e.g. by the ICRP, https://www.icrp.org/icrp_group.asp?id=92).

$CR_{wo\text{-}soil}$ values in this paper were within the range of other reported Reference Rat-Cs $CR_{wo\text{-}soil}$ values with the exception of $CR_{wo\text{-}soil}$ values derived from stable-Cs. Generally, variation in $CR_{wo\text{-}soil}$ values, and their use to estimate internal dose, may have little impact on the estimation of total dose, because external dose will likely dominate in situations similar to the FDNPP accident (see also Howard et al., 2013).

Estimated absorbed dose rates for wild rodents dropped by about 50% from 2012-2016, largely due to ^{134}Cs decay, but the absorbed dose rates in highly contaminated sites in 2016 were still within the DCRL proposed by ICRP for Reference Rat. Thus, there is the possibility of deleterious effects, and additional studies on potential impacts of chronic exposures to small mammals and other species in the Fukushima impacted areas are warranted.

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Additional Information

Supplementary information accompanies this manuscript as a downloadable MS Excel (.xlsx) file.

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Figure legends

Figure 1. Wild rodents were captured at five sites in Fukushima Prefecture, Japan (N1, N2, N3, N4, and N5). The Fukushima Dai-ichi Nuclear Power Plant is represented by a red X, with a 20 km radius (grey line in inset map). Provided are airborne ambient dose rate (μSv h^{-1}) measurements in November 2018 provided by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Nuclear Regulation Authority (NSR) airborne monitoring project. Presented map is sourced from Extension Site of Distribution Map of Radiation Dose (MEXT/NSR) site (https://ramap.jmc.or.jp/map).

Figure 2. Box-whisker plots of annual ^{137}Cs CR$_{wo\text{-}soil}$ values for (A) *Apodemus speciosus* and (B) *A. argenteus* collected in Fukushima prefecture. Whiskers show -1.5 IQR of lower quartile and

+1.5 IQR of upper quartile, and each box shows lower and upper quartiles. Open circles represent outliers in the data.

Table 1: Life-history information for *Apodemus speciosus* and *Apodemus argenteus* in Japan.

Name	Adult size[a]	Habitat[a]	Adult diet[a]	Home range[a,b]
Apodemus speciosus	Medium or large sized mouse-like appearance, 80-140 mm head and body length, 20-60 g body weight.	Forests, plantations, riverside fields, dense grasses, paddy fields, ground dweller, little tendency to climb trees.	Root and stems of plants, seeds, berries, and insects.	304 – 1853 m^2
Apodemus argenteus	Small sized mouse-like appearance, 65-100 mm head to body length, 10-20 g body weight.	Wooded areas, lowlands to alpine zones, plantations and scrublands, preference to mature tree forests. Nests are below ground and occasionally in trees above ground.	Seeds, green plants, fruits, insects.	200 – 1325 m^2

[a]Ohdachi et al., 2009; [b]Oka, 1992

Table 2. Summarized data on ambient dose rate (μSv hr^{-1}) and radiocesium activity concentrations (kBq kg^{-1} dm) in soil samples (n = 3) at each site in 2018.

Site	Arithmetic mean ± SD		
	Ambient dose rate (μSv hr^{-1})	^{134}Cs (kBq kg^{-1} dm)	^{137}Cs (kBq kg^{-1} dm)
N1	3.9 ± 0.40	5.5 ± 3.5	53 ± 35
N2	1.7 ± 0.06	1.1 ± 0.71	11 ± 6.2
N3	4.3 ± 0.25	4.2 ± 1.5	41 ± 14
N4	6.3 ± 0.46	6.9 ± 0.76	65 ± 4.3
N5	0.47 ± 0.06	0.64 ± 0.48	5.8 ± 4.3

Table 3: Summarized data on radiocesium activity concentrations (kBq kg^{-1}, fm) for wild rodents in Fukushima Prefecture at five sites, from 2012 to 2016. All the individual data is available in Ishiniwa et al. 2019.

Species	Site	Capture year	Number of samples	^{134}Cs activity concentration (kBq kg^{-1}, fm)			^{137}Cs activity concentration (kBq kg^{-1}, fm)		
				Geometric mean [GSD]	Arithmetic mean ± SD	Range	Geometric mean [GSD]	Arithmetic mean ± SD	Range
A. speciosus	N1	2012	20	21 [4.2]	51 ± 74	0.68 – 310	32 [4.2]	78 ± 110	1.0 – 470
		2013	27	2.1 [1.8]	2.6 ± 1.8	0.84 – 8.5	4.2 [1.8]	5.2 ± 3.8	1.7 – 18
		2014	25	2.4 [2.5]	4.0 ± 5.0	0.81 – 22	6.5 [2.5]	11 ± 14	2.2 – 61
		2015	14	2.7 [2.2]	3.8 ± 3.7	1.0 – 12	10. [2.2]	14 ± 13	3.7 – 46
		2016	19	2.0 [2.1]	2.6 ± 1.8	0.39 – 7.4	11 [2.1]	14 ± 9.7	2.1 – 39
	N2	2012	18	3.2 [2.7]	5.1 ± 6.3	0.84 – 27	4.9 [2.6]	7.9 ± 9.8	1.4 – 43
		2013	11	2.1 [2.0]	2.6 ± 2.0	0.88 – 6.8	3.9 [1.9]	4.9 ± 3.4	1.6 – 13
		2014	19	2.2 [2.0]	2.8 ± 2.0	0.41 – 8.5	6.0 [2.0]	7.5 ± 5.2	1.1 – 22
		2015	17	2.7 [2.3]	3.9 ± 4.6	0.57 – 20	10. [2.2]	14 ± 17	2.6 – 74
		2016	23	0.69 [2.2]	0.93 ± 0.87	0.13 – 4.2	3.7 [2.2]	5.0 ± 4.7	0.71 – 23
	N3	2012	11	20 [3.2]	32 ± 27	3.2 – 74	31 [3.2]	49 ± 41	5.0 – 110
	N4	2014	10	7.9[2.2]	11 ± 11	2.5 – 39	21 [2.3]	30 ± 29	6.3 – 100.
	N5	2014	9	0.50 [2.9]	0.90 ± 1.3	0.10 – 4.1	1.3 [2.9]	2.3 ± 3.3	0.26 – 11
A. argenteus	N1	2012	30	5.7 [2.1]	8.1 ± 11	1.2 – 61	12 [2.0]	12 ± 16	3.8 – 89
		2013	20	2.2 [1.6]	2.4 ± 2.2	1.0 – 5.5	4.2 [1.6]	4.6 ± 2.4	2.0 – 11
		2014	16	1.3 [1.9]	1.6 ± 1.2	0.62 – 5.0	3.4 [1.9]	4.1 ± 3.1	1.7 – 13
		2015	7	0.69 [1.5]	0.73 ± 0.20	0.36 – 1.1	2.5 [1.5]	2.7 ± 0.90	1.3 – 3.9
		2016	7	1.1 [3.2]	2.1 ± 3.0	0.36 – 8.6	5.5 [3.2]	11 ± 16	1.9 – 46
	N2	2012	16	4.0 [2.0]	4.9 ± 3.2	0.90 – 13	5.9 [2.1]	7.4 ± 5.2	1.3 – 21
		2013	29	1.8 [2.7]	3.2 ± 4.7	0.36 – 23	3.5 [2.7]	6.3 ± 9.2	0.63 – 44
		2014	15	1.9 [2.3]	2.7 ± 2.5	0.44 – 9.5	5.4 [2.3]	7.6 ± 7.1	1.3 – 21
		2015	2	0.41 [3.3]	0.56 ± 0.50	0.18 – 0.95	1.4 [3.4]	2.0 ± 2.0	0.59 – 3.4
		2016	6	0.82 [2.8]	1.2 ± 1.0	0.16 – 2.9	4.3 [2.7]	6.2 ± 5.4	0.86 – 15
	N4	2014	16	7.2 [2.3]	9.8 ± 8.0	1.8 – 28	19 [2.4]	26 ± 21	4.5 – 71
	N5	2014	16	0.30 [2.1]	0.36 ± 0.2	0.093 – 0.77	0.78 [2.0]	0.94 ± 0.61	0.26 – 2.0

Table 4. ^{137}Cs $CR_{wo\text{-}soil}$ data for rodents at all study sites in Fukushima Prefecture.

Species	Site	Number of $CR_{wo\text{-}soil}$ derived	$CR_{wo\text{-}soil}$		
			Geometric mean [GSD]	Arithmetic mean ± SD	Range
A. speciosus	N1	105	0.2 [3]	0.4 ± 0.9	0.02 – 8
	N2	88	0.5 [2]	0.7 ± 0.8	0.06 – 7
	N3	11	0.7 [3]	1 ± 0.9	0.1 – 2
	N4	10	0.3 [2]	0.4 ± 0.4	0.1 – 2
	N5	9	0.2 [3]	0.4 ± 0.5	0.04 – 2
	All	223	0.3 [3]	0.5 ± 0.9	0.02 – 8
A. argenteus	N1	80	0.1 [2]	0.1 ± 0.2	0.02 – 1
	N2	68	0.4 [3]	0.6 ± 0.6	0.05 – 4
	N4	16	0.3 [2]	0.4 ± 0.3	0.06 – 0.3
	N5	6	0.1 [2]	0.1 ± 0.1	0.04 – 0.3
	All	170	0.2 [3]	0.3 ± 0.5	0.02 – 4
All samples		393	0.2 [3]	0.5 ± 0.8	0.02 – 8

Table 5. Summarized Reference Rat-Cs $CR_{wo\text{-}soil}$ data from multiple studies (radio- and stable Cs). n/a - indicates the information is not available.

Reference Rat study locations	Number of $CR_{wo\text{-}soil}$ derived	Species	$CR_{wo\text{-}soil}$		
			Geometric mean [GSD]	Arithmetic mean ± SD [CV%]	Range
Radioisotope (^{134,137}Cs)					
Fukushima, Japan[a]	393	*A. argenteus*; *A. speciosus*	0.2 [3]	0.5 ± 0.8 [160]	0.02 – 8
Chernobyl, Ukraine[b,c]	94	*A. flavicollis, A. agrarius, Micromys minutes, A. sylvaticus*	0.1 [3]	0.3 ± 0.4 [133]	0.01 – 2
Stable isotope (^{133}Cs)					
Chernobyl, Ukraine[b]	3	*A. flavicollis*	0.07 [2]	0.08 ± 0.03 [38]	0.005 – 0.1
United Kingdom[d]	3	*A. sylvaticus*	n/a	0.01 ± 0.01 [100]	0.005 – 0.03
Spain[e]	12	*A. sylvaticus*	n/a	0.04 ± 0.04 [100]	0.003 – 0.08
Radio- and stable Cs					
WTD[f]	84	*Muridae*	0.2 [6]	1.0 ± 4 [445]	0.005 – 40
Japan data[a] plus WTD[f]	477	*Muridae*	0.2 [4]	0.5 ± 2 [341]	0.005 – 40

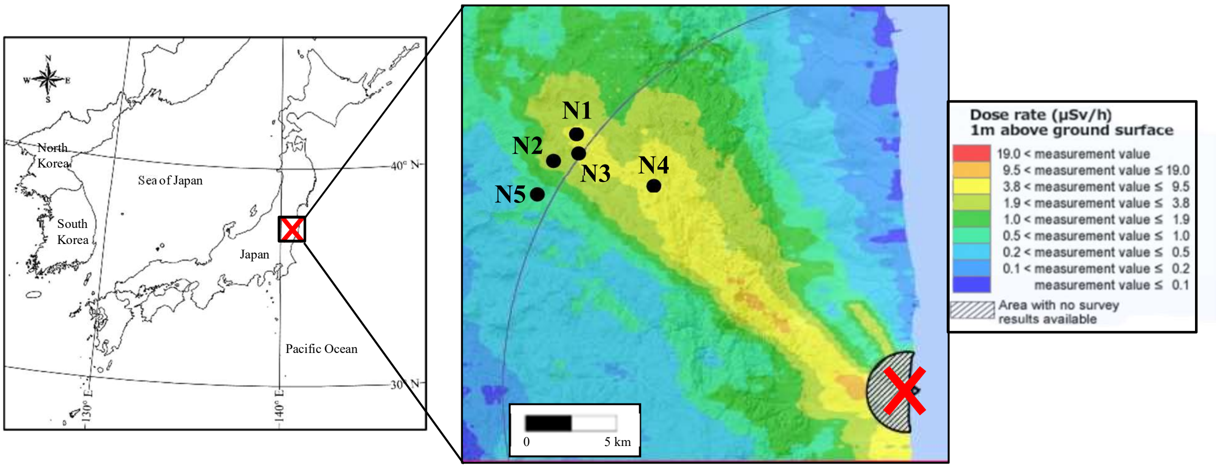
[a]This study; [b]Beresford et al., 2020, 2008b; [c]Oskolkov et al. 2011; [d]Barnett et al., 2014; [e]Guillien et al., 2018; [f]ICRP, 2009a (WTD as described by Copplestone et al. 2013).

Table 6. A comparison of estimated mean absorbed dose rates to *Apodemus speciosus* and *Apodemus argenteus* at N1 and N2 in 2012 and 2016; N3 in 2012; N4 and N5 in 2014.

Site	Year	Species	Ambient dose rate ($\mu Sv\ h^{-1}$)[a]	Absorbed dose rate ($\mu Gy\ h^{-1}$)					
				Internal	External			Total[b]	Range (5th – 95th percentile)
`					100% on-soil	50% in-air	50% in-soil		
N1	2012	*A. speciosus*	17	19	14			33	14 – 69
		A. argenteus		2.9	14	13	25	17	8.3 – 31
	2016	*A. speciosus*	7.6	2.5	7.1			9.6	4.9 – 17
		A. argenteus		1.9	7.1	6.5	13	9.0	4.2 – 17
N2	2012	*A. speciosus*	6.8	1.9	3.1			5.0	2.5 – 9.0
		A. argenteus		1.7	3.1	2.9	6.0	4.8	2.7 – 8.0
	2016	*A. speciosus*	2.8	0.90	1.4			2.3	1.0 – 4.2
		A. argenteus		1.1	1.4	1.3	2.5	2.5	1.2 – 4.5
N3	2012	*A. speciosus*	21	12	11			23	14 – 38
N4	2014	*A. speciosus*	18	6.1	11			17	12 – 26
		A. argenteus		5.2	11	10.	19	16	12 – 22
N5	2014	*A. speciosus*	1.5	0.44	1.1			1.5	0.65 – 3.1
		A. argenteus		0.19	1.1	1.0	2.0	1.3	0.60 – 2.4

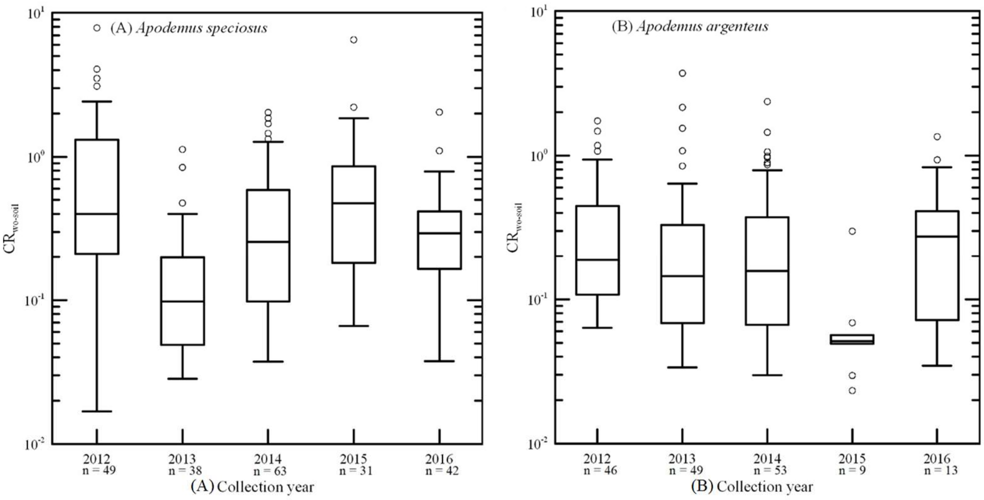
[a]From Ishiniwa et al. 2019 survey, based on ambient dose measurements taken at 1 m height. [b]Total absorbed dose rate provided is sum of internal absorbed dose rate and external dose rate assuming a 100% occupancy on the soil.

Figure 1



North Korea
South Korea
Sea of Japan
Japan
Pacific Ocean
40° N
30° N
130° E
140° E
N1
N2
N3
N4
N5
0
5 km
Dose rate (μSv/h)
1m above ground surface
19.0 < measurement value
9.5 < measurement value ≤ 19.0
3.8 < measurement value ≤ 9.5
1.9 < measurement value ≤ 3.8
1.0 < measurement value ≤ 1.9
0.5 < measurement value ≤ 1.0
0.2 < measurement value ≤ 0.5
0.1 < measurement value ≤ 0.2
measurement value ≤ 0.1
Area with no survey results available

Figure 2.



(A) Apodemus speciosus
(B) Apodemus argenteus
CR_{wo-soil}
2012
n = 49
2013
n = 38
2014
n = 63
2015
n = 31
2016
n = 42
(A) Collection year
2012
n = 46
2013
n = 49
2014
n = 53
2015
n = 9
2016
n = 13
(B) Collection year