Radioprotection 2023, 58(3), 181–195
© The Authors, published by EDP Sciences 2023
https://doi.org/10.1051/radiopro/2023017

Available online at:
www.radioprotection.org

ARTICLE OPEN ACCESS

Radiation doses to non-human species after the Fukushima accident and comparison with ICRP's DCRLs: A systematic qualitative review

M. Takada[1],* and T. Schneider[2]

[1] National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan.
[2] Nuclear Protection Evaluation Centre (CEPN), Fontenay-aux-Roses, France.

Received: 28 February 2023 / Accepted: 2 May 2023

Abstract – This study reviewed publications on radiation dose estimations for non-human species after the 2011 Fukushima nuclear power plant accident and discussed the accident's potential effects on the environment. Articles published from 2011 to December 2022 in online database were manually searched, and 27 eligible articles were identified. The estimated doses were summarized according to reference animals and plants and derived consideration reference levels (DCRLs) from ICRP Publication 108. Most estimated dose rates were on or below DCRL bands, but several greatly exceeded the DCRLs, mainly immediately after the accident. Half of the articles focused on dose estimation, but 13 also contained assessments of radiation effects. Effects such as chromosomal aberrations, morphological abnormalities, and population decline, were observed and the observed effects corresponding to estimated dose rates were implied in agreement with DCRL. Although a broader integration of knowledge is needed to obtain more robust data on environmental effects and improve environmental protection systems, our review contributes to refining the objectives of the environmental radiological protection approach.

Keywords: ^{134}Cs / ^{137}Cs / environmental radiological protection / nuclear accident / reference animals and plants

1 Introduction

The accident at the Fukushima Daiichi Nuclear Power Plant (FDNPP) in March 2011 led to the release of radioactive materials into the environment and exposure to ionizing radiation of humans and environment. Interest in environmental radiological protection has been growing recently, and the latest general recommendations by the International Commission on Radiological Protection (ICRP) highlight the importance of environmental protection (ICRP, 2007). Environmental radiological protection applies to all exposure situations, including emergency and post-accident situations, such as the FDNPP event.

The focus of environmental radiological protection is often on populations at the species or higher levels, although protection objectives depend on specific scenarios. In ICRP Publication 124 (2014), the protection objectives are species conservation, maintenance of biological diversity, and sustaining ecosystem health. Accordingly, the most relevant biological endpoints are those that could lead to changes in population size or structure. The ICRP (2008) introduced a practical approach to environmental radiological protection with its reference animals and plants (RAPs) and derived consideration reference levels (DCRLs). The RAPs are 12 animals and plants that are representative of the major taxonomic families inhabiting major ecosystem (terrestrial, freshwater, marine). The biological effects and risks of RAPs are assessed with doses by comparing with the DCRLs as benchmarks. DCRLs are bands of dose rates within which there is likely to be some chance of deleterious effects of radiation to individuals RAPs. These are derived from knowledge on biological effects. DCRLs can be used as reference points to optimize environmental protection. Under emergency exposure situations, the RAPs and DCRL frameworks may be useful when communicating with stakeholders about radiological situations. Similar approaches are also used by other international organizations (International Atomic Energy Agency (IAEA), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)), countries, and research projects, providing a series of benchmark values. The lowest benchmark values are broadly comparable among these organizations and publications (Real and Garnier-Laplace, 2020).

The benchmark values contain uncertainties. Data were obtained in various ways: studies examined high dose rates

---

*Corresponding author: `momo.takada@aist.go.jp`

over short periods of time, and lower dose rates over extended periods of time. Some data were obtained from field observations, others from experiments under controlled conditions. In the current DCRLs, some dose rate bands have insufficient or lacking information (ICRP, 2008). Further, as most data were from studies of small groups of individuals, the relevance of endpoints above the population level is debatable (Real and Garnier-Laplace, 2020). After the Chernobyl nuclear accident in 1986, many studies were conducted and knowledge has been summarized for acute/chronic effects, differences in effects by organism, and remaining issues (IAEA, 2006; Hinton *et al.*, 2007; Beresford and Copplestone, 2011). The consistency of knowledge between field data and laboratory experiments has been discussed, along with data from Fukushima (Real and Garnier-Laplace, 2020). Although UNSCEAR reported that regional impacts on wildlife populations with a clear causal link to radiation exposure were unlikely (UNSCEAR, 2013, 2021), studies are continuing in Fukushima. In addition to the knowledge gained from Chernobyl, new findings from Fukushima will improve the robustness of knowledge on environmental effects and the protection system. As a first step, we present a systematic review of studies conducted in Japan on dose and radiation effects on non-human species after the FDNPP accident. Our review contributes to refining the objectives of the environmental radiological protection approach. These are to identify:

1. target non-human species and methods of dose estimation;
2. distributions of doses and comparisons with DCRL;
3. observed radiation effects.

2 Materials and methods

We consulted the Web of Science database to select publications and completed a manual search. Keywords included “Fukushima,” “exposure,” and “environment or environmental or non-human biota” in varying combinations. We limited results to original articles published in 2011 or later. All references cited in the chapters of “assessment of doses and effects for non-human biota” in *Scientific Annexes of the UNSCEAR* 2013 and 2020/2021 reports, and in Appendix F of the 2013 report were included. A rater used the following screening criteria:

- survey was conducted in Japan;
- target(s) were non-human species;
- data included dose, not air dose rate or radioactivity;
- data were obtained in the field, not a laboratory.

After screening titles and abstracts, 51 studies were identified (Web of Science 31: UNSCEAR, 2013, 2: UNSCEAR, 2020/2021, 18). We excluded articles in languages other than English, book chapters, and sources that did not include a dose determination. After removing duplicates, the full text of 46 articles was evaluated against the eligibility criteria, and 27 articles remained (Tab. 1). The detailed study characteristics and main findings of the 27 articles are summarized in the Appendix A.

For each article, we summarized methods of dose estimation, study sites, and data collection periods. Estimated doses were compiled and compared with DCRLs according to RAPs. Finally, we summarized radiation effects, if provided, and estimated doses. We included data evaluated by the UNSCEAR (2013) report’s Appendix F.

3 Results

3.1 Characteristics of the articles included in the review

In all, 94 data points were included in the 27 eligible articles and UNSCEAR (2013) report. Figure 1a shows the number of data for each category of non-human species, (*i.e.*, RAPs) and organisms other than RAPs. When several species or different life stages of a species were evaluated in an article, we considered them as different data. If several sampling points were contained in an article, we considered it as one data. Accordingly, the total data number does not correspond to the number of eligible articles. To sort data into RAPs, we used the following procedures. When scientific names were identified and matched RAPs at the “family” level, as defined in ICRP, we assigned them to the corresponding RAP. When the targeted species did not match RAPs at the family level, but were close to the intent of the RAP definitions, we assigned them to the corresponding RAP. For example, data for “pelagic fish” in a freshwater lake were assigned to “trout (freshwater fish).” If author(s) compared the data to RAPs in the article, we applied the correspondence.

Among data about RAPs, the largest number corresponded to flatfish (marine fish) and frogs (amphibians), with 12 and 11 reported, respectively, about 12–13% of the total (Fig. 1a). The next-most frequent data were deer (large terrestrial mammals), rats (small terrestrial mammals), and crabs (marine crustaceans), each with 7 data (7%). Following them, brown seaweed (seaweed), wild grass (small terrestrial plant), and ducks (aquatic birds) accounted for 5 or 6 data, 5–6% of the total. Data for pine trees (large terrestrial plants), bees (terrestrial insects), earthworms (terrestrial annelids), and trout were the least common, with 3 or 4 data (3–4%) each. We noted 22 data reported that did not belong to any RAP, about 22% of the total. These included terrestrial reptiles and marine mollusks.

Figure 1b shows the data by period for data collection from 2011–2019. If a study for one species provided several data obtained in different years, we counted as data for each year. About 30% of data were obtained in 2011. Data gathered by 2012 accounted for about half of the total. The numbers of data tend to decrease with time, with the last collected in 2019. One from the UNSCEAR (2013) report did not identify the collection period; it was omitted from Figure 1b, we expect it was from 2011, 2012, or 2013.

Figure 1c shows each study’s location. All data were taken in Fukushima Prefecture and along the coast. We divided them into four categories: Hamadori, Nakadori, and Aizu (terrestrial areas), and the coast (Fig. 1d). The three terrestrial regions are divided by two mountain ranges, stretching from north to south. They feature topographical, natural, and cultural differences. As shown in Figure 1c, 63% of the data were obtained in Hamadori; 90% were from Hamadori and Nakadori. All marine data were obtained from the port of FDNPP and several kilometers offshore.

Table 1. Properties of the 27 eligible articles.

RAPs	Focus	References
Deer	Dose estimation	Toyoda *et al.* (2019)
	Dose estimation, assessment of radiation effects	Urushihara *et al.* (2016), Pederson *et al.* (2020), Anderson *et al.* (2022)
Rats	Dose estimation	Garnier-Laplace *et al.* (2011), Kubota *et al.* (2015a), Anderson *et al.* (2021, 2022)
	Dose estimation, assessment of radiation effects	Kubota *et al.* (2015b), Kawagoshi *et al.* (2017), Sproull *et al.* (2021)
Pine trees	Dose estimation	Garnier-Laplace *et al.* (2011)
	Dose estimation, assessment of radiation effects	Yoschenko *et al.* (2016)
Grasses	Dose estimation	Garnier-Laplace *et al.* (2011), Fuma *et al.* (2017), Fuma *et al.* (2019)
	Dose estimation, assessment of radiation effects	Horemans *et al.* (2018)
Bees	Dose estimation	Fuma *et al.* (2017)
	Dose estimation, assessment of radiation effects	Hancock *et al.* (2019)
Worms	Dose estimation	Garnier-Laplace *et al.* (2011), Fuma *et al.* (2015, 2017, 2019)
Ducks	Dose estimation	Garnier-Laplace *et al.* (2011)
	Dose estimation, assessment of radiation effects	Garnier-Laplace *et al.* (2015)
Trout	Dose estimation	Fuma *et al.* (2019)
Frogs	Dose estimation	Fuma *et al.* (2015), Fuma *et al.* (2019)
	Dose estimation, assessment of radiation effects	Giraudeau *et al.* (2018), Tagami *et al.* (2018), Gombeau *et al.* (2020)
Flatfish	Dose estimation	Garnier-Laplace *et al.* (2011), Kryshev *et al.* (2012), Keum *et al.* (2014), Vives i Batlle *et al.* (2014), Johansen *et al.* (2015), Keum *et al.* (2015), de With *et al.* (2021)
Crabs	Dose estimation	Garnier-Laplace *et al.* (2011), Keum *et al.* (2014), Vives i Batlle *et al.* (2014), Keum *et al.* (2015), Fuma *et al.* (2019)
	Dose estimation, assessment of radiation effects	Fuller *et al.* (2022)
Seaweed	Dose estimation	Garnier-Laplace *et al.* (2011), Kryshev *et al.* (2012), Vives i Batlle *et al.* (2014), Keum *et al.* (2015),
Others	Dose estimation	Kryshev *et al.* (2012), Vives i Batlle *et al.* (2014), Keum *et al.* (2015), Fuma *et al.* (2017), Fuma *et al.* (2019), de With *et al.* (2021)

3.2 Dose estimation

Dose determination methods were mainly classified into equilibrium or dynamic models based on direct measurements of environmental media (Appendix A). Of the eligible 27 articles, except for data from the UNSCEAR (2013) report, 21 used equilibrium models, 5 used dynamic models, and 1 applied electron spin resonance tooth enamel dosimetry. The highest doses were estimated using dynamic models under non-equilibrium conditions immediately after the accident, and in many cases corresponded to data from the marine environment.

Cs-134 and ^{137}Cs were targeted radionuclides for all articles; 16 focused on radiocesium only, but 8 articles also targeted ^{131}I. Four covered other trace radionuclides, such as ^{110m}Ag, ^{3}H, and ^{90}Sr. Twenty-six of the 27 articles provided figures of the estimated doses in the manuscripts, and 22 introduce the concept of dose rate (*e.g.*, μGy/h, mGy/h, μGy/d, mGy/d). Nine articles provided accumulated doses in Gy or mGy. Five used both units.

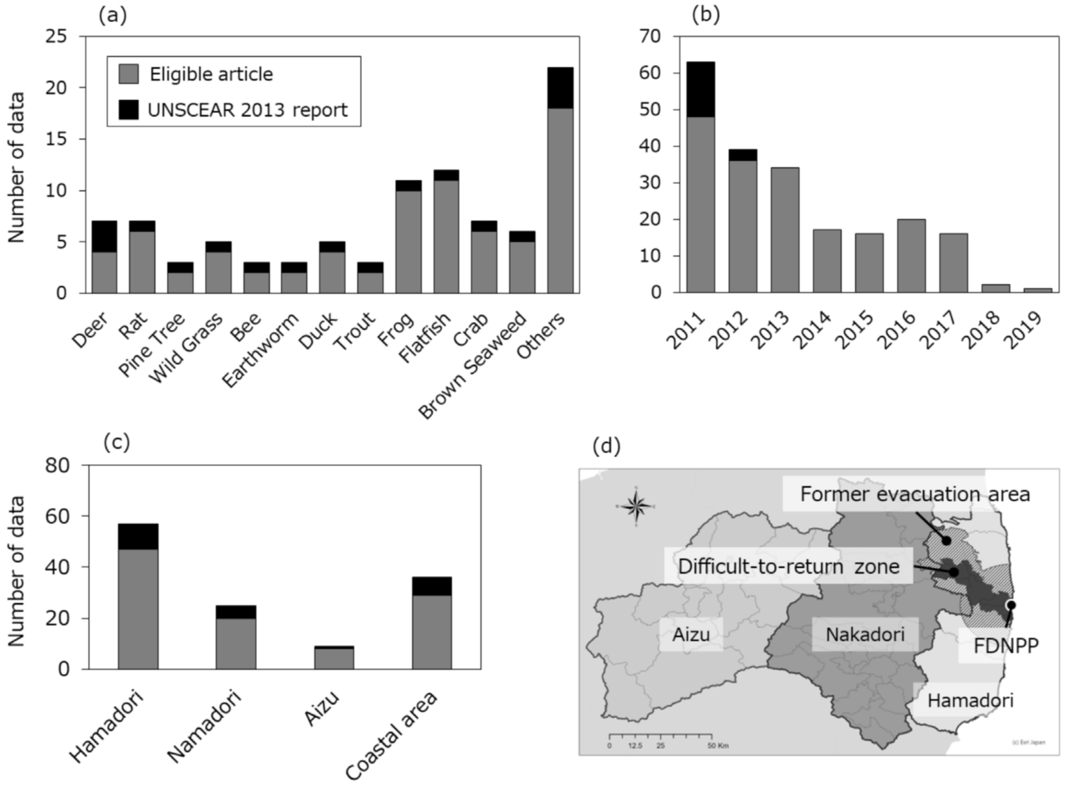

Fig. 1. Number of data (a) per RAP category and non-assimilated organisms (others), (b) per year in the period 2011–2019 and (c) per studied areas, as spatially distributed in the vicinity of the FDNPP (d).

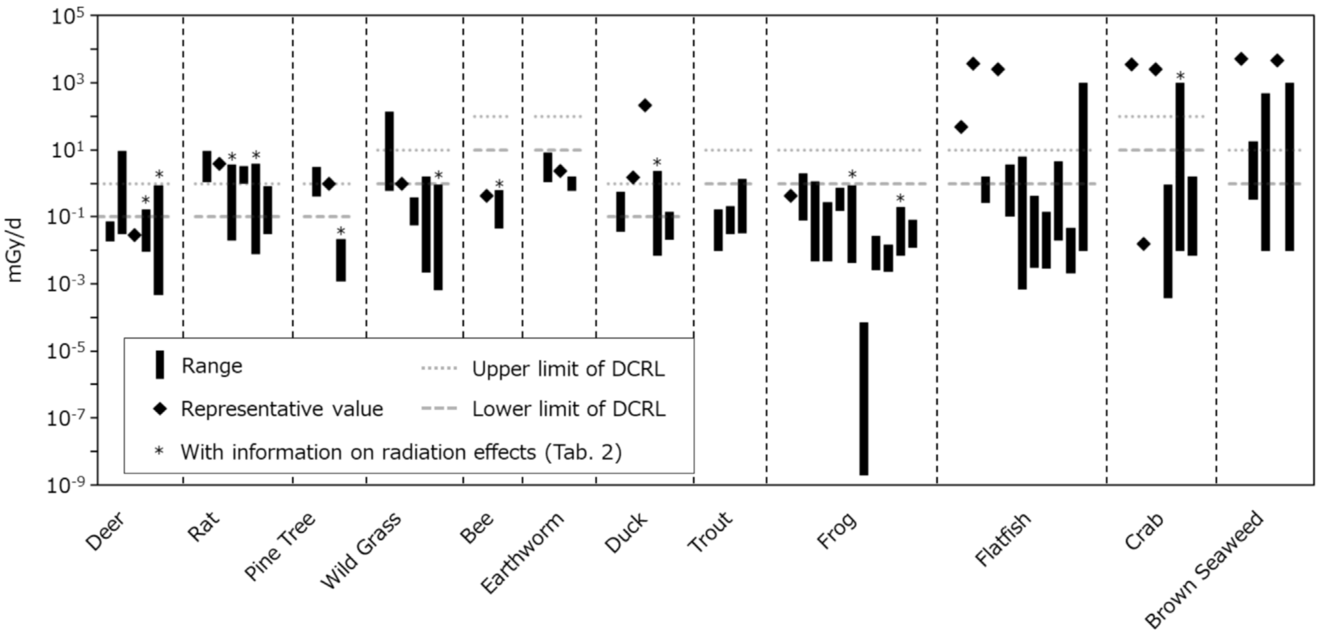

Fig. 2. Comparison between estimated dose rates and DCRLs by RAP types. Estimated dose rates providing a range of values are represented with a bar; those providing representative values are represented by points. Asterisks (*) indicate the availability of information on radiation effects (Tab. 2 and discussed in the following section). For each RAP, estimated dose rates on the left are those of the immediate aftermath of the accident.

Table 2. Summaries of articles examining dose and radiation effects.

RAPs	Reference	Animals and plants	Estimated dose range	Effect
Deer	Anderson *et al.* (2022)	Wild boars	0.02–36 μGy/h Lifetime doses: < 0.1–700 mGy	No elevated mutation rates in loci
	Pederson *et al.* (2020)	Wild boars	Upper-bound, lifetime radiation dose: 1–1596 mGy	No effect on cataract prevalence
	Urushihara *et al.* (2016)	Cattle	9.1–155.1 μGy/d Cumulative dose: 3.5–85.5 mGy	Chronic exposure to low-dose rate resulting in modified plasma protein and enzyme levels
Rats	Kawagoshi *et al.* (2017)	Wild rodents	0.008–3.67 mGy/d Cumulative dose: 1.3–1387 mGy	Increased chromosomal aberrations in splenic lymphocytes with increasing estimated dose rates
	Kubota *et al.* (2015b)	Wild rodents	0.02–3.5 mGy/d Cumulative dose: 2.1–1050 mGy	Increased chromosomal aberrations with increasing estimated dose rates
	Sproull *et al.* (2021)	Japanese field mice	Lifetime dose: 0.01–0.64 Gy	Increased expression of proteomic biomarkers in the serum with increasing estimated doses
Pine trees	Yoschenko *et al.* (2016)	Japanese red pine	1.2–20.2 μGy/d	Increase of canceling apical dominance with increasing estimated dose rates
Grasses	Horemans *et al.* (2018)	Shepherd's purse	0.027–38 μGy/h	No change in genome-wide methylation levels
Bees	Hancock *et al.* (2019)	Pale grass blue butterfly	0.0037–0.10 Gy (external dose)	Linearly increased mortality rates with increasing estimated historic radiation doses
Ducks	Garnier-Laplace *et al.* (2015)	Birds	0.3–97 μGy/h	Decreased abundance and species diversity with increasing estimated total dose
Frogs	Giraudeau *et al.* (2018)	Japanese tree frogs	0.18–34.20 μGy/h	No effects on tissue carotenoid levels
	Gombeau *et al.* (2020)	Japanese tree frogs	0.3–7.7 μGy/h	Increased DNA methylation and mitochondrial DNA damage with increasing estimated dose
Crabs	Fuller *et al.* (2022)	Japanese mitten crabs	0.016–37.7 μGy/h	No change in fluctuating asymmetry

3.3 Distribution of dose rates and comparison with DCRLs

Estimated dose rates corresponding to each RAP are summarized in Figure 2 (articles for each value are in the Appendix A). Data of the 9 articles providing only accumulated doses were not included in Figure 2. For each RAP, estimated dose rates on the left side are those of the immediate aftermath of the accident.

Estimated dose rates for bee and earthworm were below the lower limit of DCRLs. Several dose rates for trout and frog were located within the DCRL bands. The other eight organisms showed estimated doses above the upper limit of DCRLs. Most data correspond to 2011, but two data for rats are from 2012 and later assessments (Appendix A). Although most data above DCRLs were about one order of magnitude higher, one for marine birds (ducks) and several for flatfish, crabs, and brown seaweed in the marine environment exceeded the upper limit of the DCRL band by more than two orders of magnitude.

3.4 Radiation effects

Among the 27 eligible articles, 14 aimed at dose estimation and 13 articles also contained radiation effects assessments. There were three studies each on deer and rats; two on frogs; and one each on pine trees, wild grass, bees, ducks, and crabs. Eight of these concluded there were some impacts, and five found no effects (Tab. 2).

Nine articles included assessments of radiation effects focused on those at a subcellular level, such as chromosomal aberrations. Three examined individual impacts: Hancock *et al.* (2019) reported that morphological abnormality and mortality rates for pale grass blue butterflies (*Zizeeria maha*) increased with accumulation external doses. Yoschenko *et al.* (2016)

showed that canceling the apical dominance of Japanese red pine (*Pinus densiflora*) correlated with the dose rate. Pederson *et al.* (2020) did not confirm radiation's effect on cataract prevalence in wild boars (*Sus scrofa*) in the difficult-to-return zone. Garnier-Laplace *et al.* (2015) noted effects at above population levels; they revealed that abundance and species diversity for birds decreased with increasing total doses.

4 Discussion

4.1 Characteristics of data and methods

RAPs are generalized to the family level (ICRP, 2008), but few data in the present articles matched this. Some studies provided integrated results by general characteristics of a category, such as marine fish (*e.g.*, Keum *et al.*, 2014). Assignment according to RAP descriptions, such as deer as large terrestrial mammals, or matching at the class or higher taxonomic levels allowed for more data to be assigned to RAPs. If DCRLs were generalized at a higher taxonomic level than family (*e.g.*, order or class), it would be easier to apply for assessment, especially in such emergency situations.

Dose estimation methods were mostly classified into equilibrium or dynamic models. The equilibrium model assumes an equilibrium environment and is therefore suitable for situations after a certain period from a release. The dynamic model can be used to evaluate the situation immediately after the accident, in an emergency exposure situation. Comprehensive understanding of exposure circumstances and radiation effects after the accident spatiotemporally requires a holistic view of the results from these methods.

4.2 Radiation effect

Some studies assessed radiation effects and dose estimation, and a few identified impacts, but most were at a subcellular level, such as genetic abnormalities (Tab. 2). However, impacts at a subcellular level on the population level are still not well understood (ICRP, 2014; Real and Garnier-Laplace, 2020). Therefore, the effects at the subcellular level in the present review cannot conclude inducing immediate serious effects on population maintenance, one of the main objectives for environmental radiological protection. Further research needs to be developed on the relationship between radiation effects below the individual level and population dynamics of non-human species. Garnier-Laplace *et al.* (2015) showed that bird abundance in Fukushima decreased with increasing total doses, and the relationship was directly consistent with exposure levels to induce physiological effects in birds. The observed effects corresponding to the estimated doses in the present review agreed with knowledge leading to DCRLs (and other benchmark values).

Some studies gave necessary information by adding additional assessments to existing studies. Garnier-Laplace *et al.* (2015) examined the relationship between bird abundance and total doses using bird census data (Møller *et al.*, 2015) and air dose information. Hancock *et al.* (2019) focused on impacts on pale grass blue butterflies (*Zizeeria maha*) with accumulated dose, using butterfly data from Hiyama *et al.* (2012).

There were several studies on impact assessment without dose estimation except for the present eligible articles. Watanabe *et al.* (2015) founded that Japanese fir populations near the FDNPP showed a significantly increased number of morphological defects. Yoshioka *et al.* (2015) reported that the number of individuals of Apidae species *Xylocopa appendiculata* was low inside the evacuation zone. The response of non-human species to the Chernobyl accident was a complex interaction among radiation and indirect effects (Hinton *et al.*, 2007). The same would be true for Fukushima. Indeed, Yoshioka *et al.* (2015) noted that decreases in *Xylocopa appendiculata* may have been affected not by radiation but by the cessation of anthropogenic activities and the resulting disturbances due to evacuation. As obtaining data retroactively is impossible, examining relations with doses and effects by combining other published data would provide important findings.

4.3 Strengths and limitations

The present study reviewed studies performed in Fukushima after the accident focusing on dose estimation and the potential radiation effects, and we observed that most exposures of non-human species following the Fukushima accident are below the DCRLs (and other benchmarks) adopted for environmental protection. Only a few values were observed above the upper limit of DCRLs, but they were for a limited period. This suggests that there would be no significant impacts on species' biodiversity and reproduction. In the future, we should continue the surveillance or observation to confirm these results and consolidate the scientific knowledge used to derive DCRLs. The elements collected by our review contribute to refining the objective of an environmental radiological protection approach.

This review has some limitations. Some articles did not include dose rates and provided only cumulative doses, and thus these results were not included in the discussion of agreement with DCRLs. Hancock *et al.* (2019) showed increased mortality rates in Pale grass blue butterfly and Sproull *et al.* (2021) detected effects at a subcellular level on Japanese field mice. It should be noted that these studies only provided cumulative doses and thus excluded them from comparison with DCRLs. The dose assessment period was shortly after the accident through 2019, but we did not identify whether exposures were acute or chronic. The present review is limited to field studies, but there are some studies on dose estimation and impact assessment under controlled environments replicating the FDNPP accident (*e.g.*, Fujiwara *et al.*, 2015). Studies on radiation effects without dose estimation were excluded from review; as these studies often have information on air dose rates, it may be possible to reconstruct doses in the future studies.

5 Conclusion

This review provides a summary of current findings on doses to non-human species and the related effects after the FDNPP accident by categorizing RAPs and comparing them with DCRL under the ICRP's environmental protection system. Most data were collected soon after the accident and close to FDNPP, which was largely affected by the accident. Two main methods for dose estimation were equilibrium or dynamic models based on direct measurements of environmental media. A majority of estimated dose rates were within or below DCRL bands, but several values largely exceeded the DCRLs. Half of the articles estimated dose only, while the other half also contained radiation effects assessments. Eight of these concluded there were some impacts. The observed effects were at the subcellular level, such as chromosomal aberrations, and at the individual or higher level, in the form of morphological abnormalities and declining populations. The observed effects corresponding to estimated dose rates were in agreement with DCRLs. This review will contribute to robust knowledge of the effects on non-human species and improve the environmental radiological protection system.

Conflict of interest

The authors declare that they have no conflicts of interest in relation to this article.

Funding

This work was supported by Environment Research and Technology Development Fund (JPMEERF22S20900) of the Environmental Restoration and Conservation Agency Provided by the Ministry of Environment of Japan.

Ethical approval

No ethical approval was required.

Informed consent

No informed consent was required.

Authors' contributions

M. Takada: Conceptualization, methodology, investigation, writing original draft. T. Schneider: Conceptualization, supervision, writing, reviewing, editing.

Acknowledgements

We thank Speedtensaku.com (https://www.speedtensaku.com/) for editing a draft of this manuscript.

References

Anderson D, Beresford NA, Ishiniwa H, Onuma M, Nanba K, Hinton TG. 2021. Radiocesium concentration ratios and radiation dose to wild rodents in Fukushima Prefecture. *J. Environ. Radioactiv.* 226.

Anderson D, Kaneko S, Harshman A, Okuda K, Takagi T, Chinn S, Beasley JC, Nanba K, Ishiniwa H, Hinton TG. 2022. Radiocesium accumulation and germ line mutations in chronically exposed wild boar from Fukushima, with radiation doses to human consumers of contaminated meat. *Environ. Pollut.* 306.

Beresford NA, Copplestone D. 2011. Effects of ionizing radiation on wildlife: What knowledge have we gained between the Chernobyl and Fukushima accidents? *Integr. Environ. Asses.* 7: 371–3.

de With G, Bezhenar R, Maderich V, Yevdin Y, Iosjpe M, Jung KT, Qiao F, Perianez R. 2021. Development of a dynamic food chain model for assessment of the radiological impact from radioactive releases to the aquatic environment. *J. Environ. Radioactiv.* 233.

Fujiwara K, Takahashi T, Nguyen P, Kubota Y, Gamou S, Sakurai S, Takahashi S. 2015. Uptake and retention of radio-caesium in earthworms cultured in soil contaminated by the Fukushima Nuclear Power Plant accident. *J. Environ. Radioactiv.* 139: 135–9.

Fuller N, Smith JT, Takase T, Ford AT, Wada T. 2022. Radiocaesium accumulation and fluctuating asymmetry in the Japanese mitten crab, *Eriocheir japonica*, along a gradient of radionuclide contamination at Fukushima. *Environ. Pollut.* 292.

Fuma S, Ihara S, Kawaguchi I, Ishikawa T, Watanabe Y, Kubota Y, Sato Y, Takahashi H, Aono T, Ishii N, Soeda H, Matsui K, Une Y, Minamiya Y, Yoshida S. 2015. Dose rate estimation of the Tohoku hynobiid salamander, *Hynobius lichenatus*, in Fukushima. *J. Environ. Radioactiv.* 143: 123–34.

Fuma S, Ihara S, Takahashi H, Inaba O, Sato Y, Kubota Y, Watanabe Y, Kawaguchi I, Aono T, Soeda H, Yoshida S. 2017. Radiocaesium contamination and dose rate estimation of terrestrial and freshwater wildlife in the exclusion zone of the Fukushima Dai-ichi Nuclear Power Plant accident. *J. Environ. Radioactiv.* 171: 176–88.

Fuma S, Soeda H, Watanabe Y, Kubota Y, Aono T. 2019. Dose rate estimation of freshwater wildlife inhabiting irrigation ponds in the exclusion zone of the Fukushima Dai-ichi Nuclear Power Plant accident. *J. Environ. Radioactiv.* 203: 172–8.

Garnier-Laplace J, Beaugelin-Seiller K, Della-Vedova C, Métivier J-M, Ritz C, Mousseau TA, Møller AP. 2015. Radiological dose reconstruction for birds reconciles outcomes of Fukushima with knowledge of dose-effect relationships. *Sci. Rep.* 5.

Garnier-Laplace J, Beaugelin-Seiller K, Hinton TG. 2011. Fukushima wildlife dose reconstruction signals ecological consequences. *Environ. Sci. Technol.* 45: 5077–8.

Giraudeau M, Bonzom JM, Ducatez S, Beaugelin-Seiller K, Deviche P, Lengagne T, Cavalie I, Camilleri V, Adam-Guillermin C, McGraw KJ. 2018. Carotenoid distribution in wild Japanese tree frogs (*Hyla japonica*) exposed to ionizing radiation in Fukushima. *Sci. Rep.* 8: 7438.

Gombeau K, Bonzom J-M, Cavalie I, Camilleri V, Orjollet D, Dubourg N, Beaugelin-Seiller K, Bourdineaud J-P, Lengagne T, Armant O, Ravanat J-L, Adam-Guillermin C. 2020. Dose-dependent genomic DNA hypermethylation and mitochondrial DNA damage in Japanese tree frogs sampled in the Fukushima Daiichi area. *J. Environ. Radioactiv.* 225.

Hancock S, Vo NTK, Omar-Nazir L, Batlle JVI, Otaki JM, Hiyama A, Byun SH, Seymour CB, Mothersill C. 2019. Transgenerational effects of historic radiation dose in pale grass blue butterflies around Fukushima following the Fukushima Dai-ichi Nuclear Power Plant meltdown accident. *Environ Res.* 168: 230–40.

Hinton TG, Alexakhin R, Balonov M, Gentner N, Hendry J, Prister B, Strand P, Woodhead D. 2007. Radiation-induced effects on plants and animals: Findings of the United Nations Chernobyl Forum. *Health Phys.* 93: 427–40.

Hiyama A, Nohara C, Kinjo S, Taira W, Gima S, Tanahara A, Otaki JM. 2012. The biological impacts of the Fukushima nuclear accident on the pale grass blue butterfly. *Sci. Rep.* 2.

Horemans N, Nauts R, Batlle JVI, Van Hees M, Jacobs G, Voorspoels S, Gaschak S, Nanba K, Saenen E. 2018. Genome-wide DNA methylation changes in two Brassicaceae species sampled alongside a radiation gradient in Chernobyl and Fukushima. *J. Environ. Radioactiv.* 192: 405–16.

IAEA. 2006. *Environmental consequences of the Chernobyl accident and their remediation: Twenty years of experience. Report of the Chernobyl Forum Expert Group "Environment"*. International Atomic Energy Agency.

IAEA. 2014. *IAEA Safety standards for protecting people and the environment. General safety requirements part 3. Radiation protection and safety of radiation sources: International Basic Safety Standards*. International Atomic Energy Agency.

ICRP Publication 103. 2007. The 2007 recommendations of the International Commission on Radiological Protection. *Ann. ICRP* 37.

ICRP Publication 108. 2008. Environmental protection: The concept and use of reference animals and plants. *Ann. ICRP* 38.

ICRP Publication 124. 2014. Protection of the environment under different exposure situations. *Ann. ICRP* 43.

Ishiniwa H, Okano T, Yoshioka A, Tamaoki M, Yokohata Y, Shindo J, Azuma N, Nakajima N, Onuma M. 2019. Concentration of radioactive materials in small mammals collected from a restricted area in Fukushima, Japan since 2012. *Ecol. Res.* 34: 7.

Johansen MP, Ruedig E, Tagami K, Uchida S, Higley K, Beresford NA. 2015. Radiological dose rates to marine fish from the Fukushima Daiichi accident: The first three years across the North Pacific. *Environ. Sci. Technol.* 49: 1277–85.

Kawagoshi T, Shiomi N, Takahashi H, Watanabe Y, Fuma S, Doi K, Kawaguchi I, Aoki M, Kubota M, Furuhata Y, Shigemura Y, Mizoguchi M, Yamada F, Tomozawa M, Sakamoto SH, Yoshida S, Kubota Y. 2017. Chromosomal aberrations in large Japanese field mice (*Apodemus speciosus*) captured near Fukushima Dai-ichi Nuclear Power Plant. *Environ. Sci. Technol.* 51: 4632–41.

Keum D-K, Kim B-H, Lim K-M, Choi Y-H. 2014. Radiation exposure to marine biota around the Fukushima Daiichi NPP. *Environ. Monit. Assess.* 186: 2949–56.

Keum D-K, Jun I, Kim B-H, Lim K-M, Choi Y-H. 2015. A dynamic model to estimate the activity concentration and whole body dose rate of marine biota as consequences of a nuclear accident. *J. Environ. Radioactiv.* 140: 84–94.

Kryshev II, Kryshev AI, Sazykina TG. 2012. Dynamics of radiation exposure to marine biota in the area of the Fukushima NPP in March–May 2011. *J. Environ. Radioactiv.* 114: 157–61.

Kubota Y, Takahashi H, Watanabe Y, Fuma S, Kawaguchi I, Aoki M, Kubota M, Furuhata Y, Shigemura Y, Yamada F, Ishikawa T, Obara S, Yoshida S. 2015a. Estimation of absorbed radiation dose rates in wild rodents inhabiting a site severely contaminated by the Fukushima Dai-ichi nuclear power plant accident. *J. Environ. Radioactiv.* 142: 124–31.

Kubota Y, Tsuji H, Kawagoshi T, Shiomi N, Takahashi H, Watanabe Y, Fuma S, Doi K, Kawaguchi I, Aoki M, Kubota M, Furuhata Y, Shigemura Y, Mizoguchi M, Yamada F, Tomozawa M, Sakamoto SH, Yoshida S. 2015b. Chromosomal aberrations in wild mice captured in areas differentially contaminated by the Fukushima Dai-Ichi Nuclear Power Plant accident. *Environ. Sci. Technol.* 49: 10074–83.

Møller AP, Nishiumi I, Mousseau TA. 2015. Cumulative effects of radioactivity from Fukushima on the abundance and biodiversity of birds. *J. Ornithol.* 156: S297– S305.

Pederson SL, Li Puma MC, Hayes JM, Okuda K, Reilly CM, Beasley JC, Li Puma LC, Hinton TG, Johnson TE, Freeman KS. 2020. Effects of chronic low-dose radiation on cataract prevalence and characterization in wild boar (*Sus scrofa*) from Fukushima, Japan. *Sci. Rep-UK* 10.

Real A, Garnier-Laplace J. 2020. The importance of deriving adequate wildlife benchmark values to optimize radiological protection in various environmental exposure situations. *J. Environ. Radioactiv.* 211: 105902.

Sproull M, Hayes J, Ishiniwa H, Nanba K, Shankavaram U, Camphausen K, Johnson TE. 2021. Proteomic biomarker analysis of serum from Japanese field mice (*Apodemus speciosus*) collected within the Fukushima difficult-to-return zone. *Health Phys.* 121: 564–73.

Strand P, Aono T, Brown J, Garnier-Laplace J, Hosseini A, Sazykina T, Steenhuisen F, Vives i Batlle J. 2014. Assessment of Fukushima-derived radiation doses and effects on wildlife in Japan. *Environ. Sci. Technol. Lett.* 1: 198–203.

Tagami K, Uchida S, Wood MD, Beresford NA. 2018. Radiocaesium transfer and radiation exposure of frogs in Fukushima Prefecture. *Sci. Rep.* 8.

Toyoda S, Murahashi M, Natsuhori M, Ito S, Ivannikov A, Todaka A. 2019. Retrospective ESR reconstruction of cattle tooth enamel doses from the radioactive nuclei released by the accident of Fukushima Dai-Ichi atomic power plants. *Radiat. Prot. Dosim.* 186: 48–53.

UNSCEAR. 2013. Annex A. Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami. New York: United Nations.

UNSCEAR. 2014. Annex A: Levels and effects of radiation exposure to the nuclear accident after the 2011 Great East-Japan earthquake and tsunami. New York: United Nations.

UNSCEAR. 2021. Annex B. Levels and effects of radiation exposure due to the accident at the Fukushima Daiichi Nuclear Power Station: Implications of information published since the UNSCEAR 2013 Report. New York: United Nations.

Urushihara Y, Kawasumi K, Endo S, Tanaka K, Hirakawa Y, Hayashi G, Sekine T, Kino Y, Kuwahara Y, Suzuki M, Fukumoto M, Yamashiro H, Abe Y, Fukuda T, Shinoda H, Isogai E, Arai T, Fukumoto M. 2016. Analysis of plasma protein concentrations and enzyme activities in cattle within the ex-evacuation zone of the Fukushima Daiichi Nuclear Plant accident. *PloS One* 11.

Vives i Batlle J, Aono T, Brown JE, Hosseini A, Gamier-Laplace J, Sazykina T, Steenhuisen F, Strand P. 2014. The impact of the Fukushima nuclear accident on marine biota: Retrospective assessment of the first year and perspectives. *Sci. Total. Evviron.* 487: 143–53.

Watanabe Y, Ichikawa S, Kubota M, Hoshino J, Kubota Y, Maruyama K, Fuma S, Kawaguchi I, Yoschenko VI, Yoshida S. 2015. Morphological defects in native Japanese fir trees around the Fukushima Daiichi Nuclear Power Plant. *Sci. Rep.* 5: 13232.

Yoschenko V, Nanba K, Yoshida S, Watanabe Y, Takase T, Sato N, Keitoku K. 2016. Morphological abnormalities in Japanese red pine (*Pinus densiflora*) at the territories contaminated as a result of the accident at Fukushima Dai-Ichi Nuclear Power Plant. *J. Environ. Radioactiv.* 165: 60–7.

Yoshioka A, Mishima Y, Fukasawa K. 2015. Pollinators and other flying insects inside and outside the Fukushima evacuation zone. *PloS One* 10: e0140957.

Cite this article as: Takada M, Schneider T. 2023. Radiation doses to non-human species after the Fukushima accident and comparison with ICRP's DCRLs: A systematic qualitative review. *Radioprotection* 58(3): 181–195

Appendix A. Study characteristics and main findings of the 27 eligible articles.

Reference	Animals and plants	Focus	Study site	Period for data collection	Targeted radionuclides	Method for dosimetry	Estimated dose	Effect	Memo
Anderson *et al.* (2021)	Wild rodents (Apodemus argenteus, Apodemus speciosus)	Absorbed dose	Namie town	2012, 2014, 2016	^{134}Cs, ^{137}Cs	Used actual measured values with the ERICA tool. Evaluated exposure at the time of the survey.	1.3–33 µGy/h	N/A	Rodent radiocesium data was from Ishiniwa *et al.* (2019)
Anderson *et al.* (2022)	Wild boar (Sus scrofa)	Absorbed dose and germ line mutations	Evacuation zone and in nearby areas	2016, 2017, 2018, 2019	^{134}Cs, ^{137}Cs	Internal exposure from actual measured values with the ERICA tool and external exposure from air dose rates. Evaluated exposure at the time of the survey.	0.02–36 µGy/h Lifetime doses: < 0.1–700 mGy	Did not cause elevated mutation rates in loci.	
de With *et al.* (2021)	Non-piscivorous fish, piscivorous fish, invertebrates, demersal fish, bottom predators, coastal predators	Absorbed dose	Coastal area located at the discharge area of the Fukushima Dai-ichi NPP and the surrounding regional area	2011, 2012, 2013	^{3}H, ^{90}Sr, ^{131}I, ^{134}Cs, ^{137}Cs	Dynamic model to estimate exposure at the accident retrospectively.	Non-piscivorous fish: 0.7–6066.3 µGy/d Piscivorous fish: 3.1–410.1 µGy/d Invertebrates: 2.7–277 µGy/d Demersal fish: 2.9–132 µGy/d Bottom predators: 3.9–207 µGy/d Coastal predators: 2.7–212 µGy/d	N/A	
Fuller *et al.* (2022)	Japanese mitten crab (Eriocheir japonica)	Absorbed dose and fluctuating asymmetry	4–44 km in distance from the FDNPS	2017	^{134}Cs, ^{137}Cs	Used actual measured values with the ERICA tool. Evaluated exposure at the time of the survey.	0.016–37.7 µGy/h	No significant relationship between radiocaesium accumulation and fluctuating asymmetry	
Fuma *et al.* (2015)	Tohoku hynobiid salamander	Absorbed dose	Namie town, Minami-soma	2011, 2012, 2013	^{134}Cs, ^{137}Cs	Used actual measured values	Adults: 0.2–47 µGy/h	N/A	

Appendix A. (continued).

Reference	Animals and plants	Focus	Study site	Period for data collection	Targeted radionuclides	Method for dosimetry	Estimated dose	Effect	Memo
	(Hynobius lichenatus)		city, Otama village, Shimogo town, Showa village			with the ERICA tool. Evaluated exposure at the time of the survey.	Overwintering larvae: 0.2–11 µGy/h Embryos: 6.3–24 µGy/h		
Fuma *et al.* (2017)	Mosses, fungi, herbaceous plants, ferns, amphibians, reptiles, bivalves, insects, earthworms	Absorbed dose	Minami-soma city, Date city, Iitate village, Namie town, Katsurao village, Nihonmatsu city	2011, 2012	^{134}Cs, ^{137}Cs	Used actual measured values with the ERICA tool. Evaluated exposure at the time of the survey.	Mosses: 9.5–160 µGy/h Fungi: 4.4–39 µGy/h Herbaceous plants: 2.4–13 µGy/h Ferns: 2.6–44 µGy/h Amphibians: 3.4–76 µGy/h Bivalves: 4.6–8.5 µGy/h Insects: 1.9–23 µGy/h Earthworms: 26–40 µGy/h	N/A	
Fuma *et al.* (2019)	Amphibians, birds, pelagic fish, phytoplankton, zooplankton, benthic fish, crustaceans, insect larvae, mollusks-bivalves, mollusks-gastropods, reptiles, vascular plants	Absorbed dose	Exclusion zone	2013, 2014, 2015, 2016, 2017	^{134}Cs, ^{137}Cs	Used actual measured values with the ERICA tool. Evaluated exposure at the time of the survey.	Amphibians: 0.5–2.9 µGy/h Birds: 0.9–5.0 µGy/h Pelagic fish: 1.3–7.1 µGy/h Phytoplankton: 0.02–0.10 µGy/h Zooplankton: 0.01–0.08 µGy/h Benthic fish: 1.4–55 µGy/h Crustaceans: 0.3–66 µGy/h Insect larvae: 0.4–132 µGy/h Mollusks-bivalves: 0.06–57 µGy/h Mollusks-	N/A	

Appendix A. (continued).

Reference	Animals and plants	Focus	Study site	Period for data collection	Targeted radionuclides	Method for dosimetry	Estimated dose	Effect	Memo
							gastropods: 0.06–60 µGy/h Reptiles: 1.6–56 µGy/h Vascular plants: 0.09–66 µGy/h		
Garnier-Laplace *et al.* (2011)	Plants, birds, soil invertebrates, forest rodents, marine birds, macroalgae, benthic biota (fish, mollusks, crustaceans)	Absorbed dose	Iitate village, coastal area located at the Fukushima Dai-ichi NPP	2011	^{134}Cs, ^{137}Cs, ^{131}I	ERICA tool.	Plants: 1 mGy/d Birds: 1.5 mGy/d Soil invertebrates: 2.3 mGy/d Forest rodents: 3.9 mGy/d Marine birds: 210 mGy/d Macroalgae: 4600 mGy/d Benthic biota (fish, mollusks, crustaceans): 2600 mGy/d	N/A	
Garnier-Laplace *et al.* (2015)	Birds	Absorbed dose, abundance and species diversity	50 km northwest area	2011–2014	^{134}Cs, ^{137}Cs, ^{131}I	Estimated exposure at the time of the survey based on actual measured data of soil radioactivity and air dose rate.	0.3–97 µGy/h	Abundance and species diversity decreased with increasing total doses.	Re-analysed a data subset described in Møller *et al.* (2015)
Giraudeau *et al.* (2018)	Japanese tree frogs (Hyla japonica)	Absorbed dose and carotenoid distribution	Kawamata town, Iitate village, Namie town, Nihonmatsu city	2012	^{134}Cs, ^{137}Cs, ^{110m}Ag	Evaluated exposure at the time of the survey from actual measured samples.	0.18–34.20 µGy/h	No effects on tissue carotenoid levels	
Gombeau *et al.* (2020)	Japanese tree frogs (Dryophytes japonicus)	Absorbed dose, global genomic DNA methylation level and mitochondrial DNA damages	50 km area around the FDNPP	2013	^{134}Cs, ^{137}Cs	Evaluated exposure at the time of the survey from actual measured samples.	0.3–7.7 µGy/h	Increase of DNA methylation and mitochondrial DNA damage	

Appendix A. (continued).

Reference	Animals and plants	Focus	Study site	Period for data collection	Targeted radionuclides	Method for dosimetry	Estimated dose	Effect	Memo
Hancock *et al.* (2019)	Pale grass blue butterflies (Zizeeria maha)	Absorbed dose, mortality/ abnormality	Within a 596-km radius of the Fukushima Dai-ichi NPP	2011	^{134}Cs, ^{137}Cs	Dynamic model to estimate exposure at the accident retrospectively. Only external exposure is considered.	0.0037–0.10 Gy	Genomic instability, morphological abnormality, and mortality rates	Data from Hiyama *et al.* (2012) on the morphological abnormality frequencies. Only external exposure considered.
Horemans *et al.* (2018)	Shepherd's purse (Capsella bursa-pastoris)	Absorbed dose, genome-wide DNA methylation changes	Aizu, Nakadori, Hamadori	2016	^{134}Cs, ^{137}Cs	Actual measured values with the ERICA tool. Evaluated exposure at the time of the survey.	0.027–38 µGy/h	No change in genome-wide methylation levels	
Johansen *et al.* (2015)	Marine fish, greenlings (Hexagrammos otakii)	Absorbed dose	FDNPP Port, 3 km east of FDNPP	2011, 2012, 2013, 2014	^{134}Cs, ^{137}Cs, ^{3}H, ^{90}Sr, ^{110m}Ag, ^{99}Tc, ^{235}U, ^{239}Pu, ^{240}Pu, ^{241}Am, ^{40}K, ^{210}Po, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{238}U	Used actual measured values with the ERICA tool. Evaluated exposure at the time of the survey.	Marine Fish: 2.0E-02–4.3E+00 mGy/d Greenlings (Hexagrammos otakii): 2.1E-03–4.4E-02 mGy/d	N/A	
Kawagoshi *et al.* (2017)	Wild rodents (Apodemus argenteus)	Absorbed dose and chromosomal aberrations	Iwaki city, Namie town, Okuma town	2012, 2013	^{134}Cs, ^{137}Cs	Internal exposure from actual measured values with the ERICA tool. External exposure from air dose rate. Evaluated exposure at the time of the survey.	0.008–3.67 mGy/d Cumulative dose: 1.3–1387 mGy	Chromosomal aberrations in the splenic lymphocytes increase with the estimated dose rates and accumulated doses	
Keum *et al.* (2014)	Pelagic fish, benthic fish (flat fish), mollusks, crustaceans (crabs), macroalgae (brown seaweed), polychaete worms (benthic worms)	Absorbed dose	30 m north, 330 m south, 15 km offshore	2011	^{134}Cs, ^{137}Cs, ^{131}I	Equilibrium model with the measured seawater activity concentrations.	Maximum value Pelagic fish: 4.8E+04 µGy/d Crustaceans (crabs): 3.6E+06 µGy/d Benthic fish (flat fish): 3.8E+06 µGy/d Macroalgae (brown	N/A	

Appendix A. (continued).

Reference	Animals and plants	Focus	Study site	Period for data collection	Targeted radionuclides	Method for dosimetry	Estimated dose	Effect	Memo
							seaweed): 5.2E+06 µGy/d Mollusks: 6.6E+06 µGy/d Polychaete worms (benthic worms): 8.0E+06 µGy/d		
Keum *et al.* (2015)	Benthic fish, mollusks, crustaceans, macroalgae	Absorbed dose	In the port of the Fukushima Daiichi Nuclear Power Station	About 2.5 years from the accident	^{134}Cs, ^{137}Cs, ^{131}I	Dynamic model to estimate exposure at the accident retrospectively.	10−1.0E+06 µGy/d (Read from graph) Accumulated dose for the initial 3 months Benthic fish: ca 4.2 Gy Crustaceans: ca 4.0 Gy Mollusks: ca 4.4 Gy Macroalgae: ca 4.5 Gy	N/A	
Kryshev *et al.* (2012)	Fish, mollusks, algae	Absorbed dose	30 km from the NPP and coastal zone near the NPP	2011	^{134}Cs, ^{137}Cs, ^{131}I	Dynamic model to estimate exposure at the accident retrospectively.	Fish: 11.2–52.3 µGy/h Mollusks: 12.2–57.6 µGy/h Algae: 14.2–714.9 µGy/h	N/A	
Kubota *et al.* (2015a)	Wild rodents (Apodemus argenteus, Apodemus speciosus, Microtus montebelli)	Absorbed dose	Okuma town	2013	^{134}Cs, ^{137}Cs	Internal exposure; actual measured values with the ERICA tool. External exposure; from air dose rate. Evaluated exposure at the time of the survey.	41.3–88.8 µGy/h	N/A	
Kubota *et al.* (2015b)	Wild rodents (Apodemus argenteus, Mus musculus)	Absorbed dose and chromosomal aberrations	Iwaki city, Namie town, Okuma town	2012	^{134}Cs, ^{137}Cs	Used actual measured values with the ERICA tool. Evaluated	0.02–3.5 mGy/d Cumulative dose: 2.1–1050 mGy	Chromosomal aberrations increase with dose rate	

Appendix A. (continued).

Reference	Animals and plants	Focus	Study site	Period for data collection	Targeted radionuclides	Method for dosimetry	Estimated dose	Effect	Memo
						exposure at the time of the survey and cumulative dose with age in days.			
Pederson *et al.* (2020)	Wild boars (Sus scrofa)	Absorbed dose and cataract prevalence	Exclusion zone, Minami-soma city, Fukushima city	2017	^{134}Cs, ^{137}Cs	Internal exposure; actual measured values with the ERICA tool. External exposure from air dose rate. Evaluated exposure at the time of the survey and lifetime exposure retrospectively.	Upper-bound, lifetime radiation dose: 1–1596 mGy	No effect on cataract prevalence	
Sproull *et al.* (2021)	Japanese field mice (Apodemus speciosus)	Absorbed dose and changes in proteomic biomarker expression	Namie town	2018	^{134}Cs, ^{137}Cs	Internal exposure from the radioactivity concentration and external exposure from the air dose rate. Evaluated exposure at the time of the survey.	Lifetime dose: 0.01–0.64 Gy	Changes in expression of proteomic biomarkers in the serum	
Tagami *et al.* (2018)	Montane Brown (Rana ornativentris), Wrinkled (Glandirana rugosa)	Absorbed dose	Inawashiro town/Kita-shiobara village, Soma city	2012, 2013, 2015, 2016	^{134}Cs, ^{137}Cs	Actual measured values with the ERICA tool. Evaluated exposure at the time of the survey.	Frogspawn: 8.3E-08–2.9E-03 µGy/h Tadpoles: 1.0E-01–5.0E-01 µGy/h Adults: 1.1E-01–9.7E-01 µGy/h	N/A	
Toyoda *et al.* (2019)	Cattle	Absorbed dose	Okuma town, Namie town	2016, 2017	–	Electron spin resonance (ESR) tooth enamel dosimetry	Cumulative dose: 80–1210 mGy	N/A	
Urushihara *et al.* (2016)	Cattle	Absorbed dose, plasma protein	Within a 20-km radius of FNPP	2011, 2012	^{134}Cs, ^{137}Cs	Internal exposure from the radioactivity	9.1–155.1 µGy/d Cumulative dose: 3.5–85.5 mGy	Modified plasma protein and enzyme levels	

Appendix A. (continued).

Reference	Animals and plants	Focus	Study site	Period for data collection	Targeted radionuclides	Method for dosimetry	Estimated dose	Effect	Memo
		concentrations, and enzyme activities				concentration and external exposure from the air dose rate. Evaluated exposure at the time of the survey.			
Vives i Batlle *et al.* (2014)	Fish, crustaceans, macroalgae, mollusks	Absorbed dose	–	2011, 2012	^{134}Cs, ^{137}Cs, ^{131}I	Dynamic model to estimate exposure at the accident retrospectively.	No values available in the text. Only graphs.	N/A	As part of an overall assessment for the terrestrial and aquatic ecosystems of Fukushima (Strand *et al.*, 2014: UNSCEAR, 2014)