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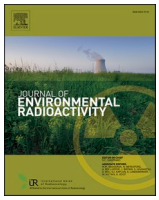

Review

Fundamentals of wildlife dosimetry and lessons learned from a decade of measuring external dose rates in the field

Thomas G. Hinton [a,b,*], Donovan Anderson [c], Edda Bæk [d], Vikas C. Baranwal [e], James C. Beasley [f], Helen L. Bontrager [f], David Broggio [g], Justin Brown [d], Michael E. Byrne [h], Hannah C. Gerke [f], Hiroko Ishiniwa [a], Stacey L. Lance [f], Ole C. Lind [b], Cara N. Love [f], Hiroko Nagata [a], Kenji Nanba [a], Kei Okuda [i], Brit Salbu [b], Dmitry Shamovich [j], Lavrans Skuterud [k], François Trompier [g], Sarah C. Webster [f], Viachaslau Zabrotski [l]

[a] *Institute of Environmental Radioactivity, Fukushima University, Fukushima, Japan*
[b] *CERAD CoE, Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway*
[c] *Institute of Radiation Emergency Medicine, Hirosaki University, Aomori, Japan*
[d] *Norwegian Radiation and Nuclear Safety Authority, Østerås, Norway*
[e] *Geological Survey of Norway, Trondheim, Norway*
[f] *Savannah River Ecology Laboratory, University of Georgia, Aiken, SC, USA*
[g] *Institute for Radiation Protection and Nuclear Safety, Fontenay-aux-Roses, France*
[h] *School of Natural Resources, University of Missouri, Columbia, MO, USA*
[i] *Faculty of Human Environmental Sciences, Hiroshima Shudo University, Hiroshima, Japan*
[j] *Sosnovy Bor, Vitebsk Region, Belarus*
[k] *Orkland kommune, P.O. Box 83, NO-7301, Orkanger, Norway*
[l] *Republican Center for Hydrometeorology, Control of Radioactive Contamination and Environmental Monitoring (Belhydromet), Minsk, Belarus*

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ABSTRACT

Methods for determining the radiation dose received by exposed biota require major improvements to reduce uncertainties and increase precision. We share our experiences in attempting to quantify external dose rates to free-ranging wildlife using GPS-coupled dosimetry methods. The manuscript is a primer on fundamental concepts in wildlife dosimetry in which the complexities of quantifying dose rates are highlighted, and lessons learned are presented based on research with wild boar and snakes at Fukushima, wolves at Chornobyl, and reindeer in Norway. GPS-coupled dosimeters produced empirical data to which numerical simulations of external dose using computer software were compared. Our data did not support a standing paradigm in risk analyses: Using averaged soil contaminant levels to model external dose rates conservatively overestimate the dose to individuals within a population. Following this paradigm will likely lead to misguided recommendations for risk management. The GPS-dosimetry data also demonstrated the critical importance of how modeled external dose rates are impacted by the scale at which contaminants are mapped. When contaminant mapping scales are coarse even detailed knowledge about each animal's home range was inadequate to accurately predict external dose rates. Importantly, modeled external dose rates based on a single measurement at a trap site did not correlate to actual dose rates measured on free ranging animals. These findings provide empirical data to support published concerns about inadequate dosimetry in much of the published Chernobyl and Fukushima dose-effects research. Our data indicate that a huge portion of that literature should be challenged, and that improper dosimetry remains a significant source of controversy in radiation dose-effect research.

* Corresponding author. Institute of Environmental Radioactivity, Fukushima University, Fukushima, Japan.
E-mail addresses: tghinton@gmail.com (T.G. Hinton), ande4163@hirosaki-u.ac.jp (D. Anderson), edda.baek@gmail.com (E. Bæk), vikas.baranwal@ngu.no (V.C. Baranwal), beasley@srel.uga.edu (J.C. Beasley), hlbontrager@gmail.com (H.L. Bontrager), david.broggio@irsn.fr (D. Broggio), Justin.Brown@dsa.no (J. Brown), byrneme@missouri.edu (M.E. Byrne), hgerke.23@gmail.com (H.C. Gerke), ishiniwa@ier.fukushima-u.ac.jp (H. Ishiniwa), lance@srel.uga.edu (S.L. Lance), ole-christian.lind@nmbu.no (O.C. Lind), caranlove@gmail.com (C.N. Love), ce-nhiroko@adb.fukushima-u.ac.jp (H. Nagata), nanba@sss.fukushima-u.ac.jp (K. Nanba), kokuda@alpha.shudo-u.ac.jp (K. Okuda), brit.salbu@nmbu.no (B. Salbu), dshamovich@tut.by (D. Shamovich), Lavrans.skuterud@gmail.com (L. Skuterud), francois.trompier@irsn.fr (F. Trompier), swebster@usgs.gov (S.C. Webster), zvn@hmc.by (V. Zabrotski).

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1. Introduction

Determining the radiation dose received by biota after a release of radionuclides to the environment is critical to radioecological studies and risk assessments. Dose rates can be compared to benchmark values thought to be protective of the environment and help risk managers make informed decisions on potential intervention strategies. Additionally, precise and accurate radiation dosimetry is essential to researchers linking dose rates to observed effects. However, determining the radiation dose received by organisms, especially free ranging animals, is one of the most challenging aspects of exposure science, and substantive improvements are needed to reduce uncertainties and increase the reliability of environmental dosimetry (Stark et al., 2017). Herein, we share our experiences over the last decade of attempting to quantify external dose rates to free ranging wildlife using new, GPS-coupled dosimetry methods attached to a diversity of vertebrates inhabiting multiple radiologically contaminated landscapes. The complexities of quantifying dose rates are highlighted, and lessons learned are presented based on research with wild boar (*Sus scrofa*) and snakes (*Elaphe* spp) at Fukushima, Japan (Gerke et al., 2020; Bontrager et al., 2024), wolves (*Canis lupus*) at Chornobyl (Hinton et al., 2019), and Norwegian reindeer (*Rangifer tarandus*) grazing pastures contaminated by Chornobyl fallout (Bæk et al., 2023). The manuscript is a primer on fundamental concepts in wildlife dosimetry, with an emphasis on external dose rates to free-ranging animals in terrestrial environments. Data generated from these studies indicate that a fundamental paradigm commonly applied in ecological risk assessments for numerous types of contaminants is often wrong, and that the authors of many published manuscripts on the environmental effects of radiation, including some of our own, likely miscalculated the dose received by animals and thus biased their interpretation of the dose rate at which effects were observed.

2. Review: dosimetry fundamentals

2.1. Review: units of radiation dose

Radiation dose is defined as the energy absorbed per mass of tissue (Joules/kg) following exposure to ionizing radiation (USEPA, 2023). An absorbed dose equal to one J of energy per kilogram mass equals one Gy (Gy). The mass can be anything (e.g., air, rock, soft tissue, bone). Most environmental dosimetrists use dose rate (e.g., Gy/h) to relate absorbed dose to radiation effects. A Gy, however, is a very large dose seldom observed in the environment except in extreme accident conditions. Doses one million times lower are more typical and units of dose rate (μGy/h) are commonly reported in environmental dose manuscripts, including recent reports from major nuclear accidents at Fukushima, Japan and Chornobyl, Ukraine (e.g., Beresford et al., 2020a; Anderson et al., 2022). Additionally, accepted dosimetry benchmarks below which populations of wildlife are thought to be protected are given as dose rates (e.g. the generic predicted no-effect dose rate of 10 μGy/h; Andersson et al., 2009).

In human dosimetry, the effective dose rate (μSv/h) is often used. The effective dose, in units of sieverts (Sv), is the absorbed dose (Gy) to the whole body adjusted for its propensity to cause effects to humans based on radiation type (e.g. alpha, beta, gamma) and the relative sensitivity of individual organs (USEPA, 2023). An effective dose is an indicator of the potential long-term health effects (e.g., cancer occurrence) in humans, and therefore not appropriate for wildlife dosimetry. Dose to wildlife should be reported as absorbed dose or absorbed dose rate in units, or subunits, of Gy.

2.2. Review: components of dose and dose conversion coefficients

Quantifying radiation dose to wildlife is challenging because the dose is composed of two components: internal and external. An animal's internal dose occurs from the intake of radioactively contaminated food, water, and air. External dose occurs from radiation emitted by radionuclides associated with components of the environment (soil, plants, detritus, etc.). Animals are irradiated externally as they move within various segments of their home range, each contaminated to a different level, and are therefore exposed to frequently changing external dose rates. Internal and external dose rates should be estimated independently and then combined to obtain a total dose rate for use in risk analysis or in developing dose-response relationships (Beaugelin-Seiller et al., 2020). Despite the importance of both internal and external dose, there are many examples in the literature where researchers examined radiation effects but failed to account for both components (e.g., Møller and Mousseau, 2011; Hiyama et al., 2012; Møller et al., 2012; Boratyński et al., 2014; Murase et al., 2015; Lehmann et al., 2016).

It would be convenient if correlations between internal and external doses were strong, or even predictable, such that determining one would provide data for the other. Typically, this is not the case; for example, no significant correlation was found between whole body radioactivity levels and external dose in Chornobyl mice ($r = 0.12$, $p > 0.2$; Chesser et al., 2000) or in Fukushima snakes ($R^2 = 0.17$, $p = 0.13$; Gerke et al., 2020). Further complicating this relationship, internal dose can be the dominant contributor to the total dose (e.g., Gaschak et al., 2011; Sotiropoulou and Florou, 2020), and in other situations external dose contributes the most (e.g., Oskolkov et al., 2011; Kubota et al., 2015; Beresford et al., 2020a). Indeed, the relative contributions of internal vs external pathways to the total dose can vary among individuals of the same species living within the same contaminated environment (e.g., Chornobyl wolves; Hinton et al., 2019).

The underlying physics of energy from radioactive decay interacting with biological tissues and causing an absorbed dose is well established (reviewed in Baeyens et al., 2023). However, determining dose to organisms within their natural environments is complicated (Stark et al., 2017), in part because: "*Doses are the result of complex and non-linear interactions of: (a) contamination levels in the environment, (b) radionuclide-specific decay properties, including type, energy and yield of the emitted radiations, (c) geometrical relationships between the source of the radiation and the target organisms, (d) composition and shielding properties of the materials/media in the environment, and (e) habitat and size of the organism*" (Ulanovsky and Pröhl, 2008). The sensitivity of external dose to changes in many of the components listed above have been modeled within international programs (EMRAS and MODARIA) to assist regulatory bodies and risk assessors in protecting the environment from ionizing radiation (IAEA, 2021).

To facilitate dosimetry, Dose Conversion Coefficients (DCCs) have been derived and tabulated to translate nuclide-specific radioactivity concentrations in terrestrial animals (Bq/kg wet wt.) and soil (Bq/kg dry wt.) to biota dose rates (μGy/h) from internal and external exposures (Amiro, 1997; Ulanovsky and Pröhl, 2008; ICRP, 2008). DCCs are a key component of wildlife dosimetry models that simulate dose rates to animals based on radioactivity levels in the environment (e.g., ERICA Tool: Brown et al., 2016; RESRAD-BIOTA: USDOE, 2004).

2.3. Review: uncertainties in dose-effect relationships

Dose-effect relationships are fundamental to our understanding the risks from radiation exposures. Effects observed in animals exposed to radiation vary tremendously and include numerous biological endpoints, such as: DNA damage; changes in immune responses; increased secretion of stress hormones; changes in the intestinal microbiome community; decreased fertility; and decreased longevity (reviewed in Lourenço et al., 2023). Each effect endpoint responds differently to radiation exposure, and each has a different dose-response relationship. Some endpoints are far more sensitive to radiation than others.

Ideally, the science of dosimetry would be sufficiently robust to be able to predict effects for all endpoints as a function of radiation dose rate. However, our knowledge of radiation dose-responses has not yet

reached that level of sophistication for dose rates typically encountered in the environment. Given a specific dose rate, it is rather difficult to precisely predict what the effect will be. For example, what is the minimum dose rate required to significantly increase DNA damage or cause cataract formation in wild boar chronically exposed to environmental levels of radiation? Unfortunately, our ability to predict specific effects as a function of dose remains shrouded with uncertainties and is one of the greatest research needs for understanding radiation effects to the environment.

Much of the uncertainty in dose-response relationships for wildlife stems from uncertainty in the dose component (Barnthouse, 1995; Hinton et al., 2013; Stark et al., 2017; Strand et al., 2017; Beresford et al., 2019). Our research over the last decade indicates that external dose is particularly difficult to quantify accurately. Determining external dose is challenging because radioactive contamination typically varies by orders of magnitude within relatively short distances, particularly if the contamination is dispersed by atmospheric fallout. The variation is due to atmospheric conditions during the initial deposition and landscape variations such as slope, vegetation structure, and soil type (Morino et al., 2013; Kubota et al., 2015; Kato et al., 2019). Variations in those same parameters influence post-depositional radionuclide migration across the landscape to create a patchwork of variable contaminant densities (Ishida, 2016; Onda et al., 2020). Thus, all animals are exposed to widely different external dose rates within their home ranges. Additionally, it is difficult to know how much time an animal spends in the various habitats available to it. Habitat quality is the primary factor that influences the amount of time wildlife spend in various portions of a landscape (Johnson et al., 2007), and when high quality habitat and high contamination levels co-occur, increased doses are likely. External dose rate is therefore a spatial-temporal phenomenon driven by animals using numerous habitats, each differing in contamination levels (Hope, 2005, Fig. 1).

Additional uncertainties in dose-effect studies occur in the decision of whether to correlate effects to current dose rates (μGy/h) or accumulated life-time doses (mGy). Logically, some effect endpoints, such as stress responses due to radiation exposure (indicated, for example, by cortisol levels in blood or hair samples), are most likely influenced by an animal's radiation exposure over the near-term (weeks to months). Other effect endpoints, such as cataract formation or telomere lengths, are likely impacted by long term exposures and may correlate better to life-time dose.

Added uncertainty is present in life-time dose calculations because the age of the animal must also be accurately determined and incorporated into the dose estimate. Current dose rates multiplied by the age of the animal produce an estimate of life-time dose. This assumes constant exposure throughout an animal's life, which for most species may not be realistic. For long-lived biota inhabiting areas contaminated from nuclear accidents, dose rates may have been substantially higher when the animal was younger and exposed to short-lived radioisotopes that have since decreased significantly due to radioactive decay and contaminant dispersion. Back-calculation of prior radionuclide abundance can help make life-time dose estimates more realistic. While models of radiation dose rates to free-ranging animals have considerable uncertainties, the uncertainties increase when estimates of life-time dose are attempted. In two of our wild boar studies, we attempted to manage the uncertainties of life-time dose estimates by using an approach adapted from multi-tiered risk analyses. We chose model parameters that inflated the life-time dose calculation to a "plausible upper-bound level" by selecting values that maximize each animal's internal and external life-time dose (see Pederson et al., 2020; Cunningham et al., 2021 for details).

2.4. Review: dosimetry needs for ecological risks vs dose-effect research

When considering wildlife dosimetry, it is important to recognize the two primary reasons for determining radiation dose to wildlife: 1) within an ecological risk framework, and 2) for dose-effect studies. The approaches used and precision required to estimate dose rates differ considerably between the two.

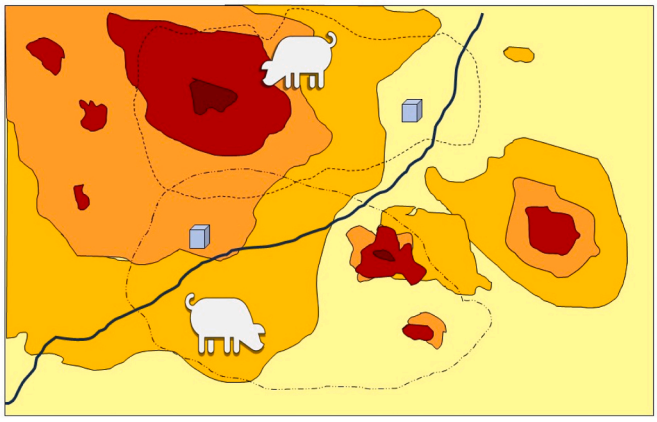

Fig. 1. The challenge of predicting external dose to free ranging wildlife is shown in this cartoon depicting a landscape with a heterogeneous distribution of contaminants. A gradient of five contamination levels is suggested with darker colors indicating greater soil radioactivity concentrations. The home ranges of two wild boars are indicated by dashed lines. Blue boxes indicate the locations where each boar was captured along a road (broad black line) that bisects the contaminated area. Ambient dose rates were taken at each trap site. The boars are exposed to widely different external dose rates due to the range in contaminant levels within their respective home ranges. The upper home range contains a higher percentage of areas having greater contamination levels, and that boar would likely receive a higher external dose. However, ambient dose readings at the trap locations would predict the opposite; external dose would be higher in the boar occupying the lower home range because the trap, and corresponding ambient dose reading, happened to be in a more contaminated area. The point of the cartoon is to show that to accurately predict external dose knowledge is needed on the amount of time each boar spends in its various sub-habitats, each differing in contaminant concentration, and that single measurements made at trap sites can be misleading.

Ecological risk calculations are typically a series of computer simulations that become more rigorous with each successive step (i.e., Tier) as more site-specific input data are called for (Suter II et al., 2000; Stark et al., 2017; Beresford et al., 2022). The need for more detailed data is driven by the simulated estimate of dose relative to a dose benchmark value thought to be protective of wildlife. Within a first-tier risk analysis assessors attempt to minimize expensive, detailed assessments by purposely choosing highly conservative input parameters for the model simulation that result in a larger dose than the animals are likely to receive. For example, in a first-tier scoping (or initial screening) assessment the maximum soil radioactivity concentration within a contaminated area is often used as input within a model simulation to intentionally maximize dose to wildlife (Prlić et al., 2017). The maximum concentration is chosen regardless of its feasibility from an ecological perspective. An example is choosing the maximum soil contamination level (e.g., the darkest spots in the home ranges of boar in Fig. 1) even if the maximum occurs in such a small area that the wildlife species of interest could not realistically live within its boundaries because a larger living area is required to meet the animal's needs. If the simulated dose based on maximized exposures are below the benchmark value, risk assessors can be confident that harmful effects are not occurring in animals exposed to lesser, real, but unknown exposures. Such conservative approaches are used to quickly eliminate specific contaminants-of-concern, or species-of-concern, from further, more costly risk analyses. However, if benchmark limits are exceeded in a scoping (or initial Tier-1 screening) assessment, then a further screening risk assessment (Tier-2) is normally conducted, with simple, generalized input assumptions (Suter II et al., 2000) using best estimates of biota and media activity concentrations, rather than maximum values (Prlić et al., 2017). If benchmark limits are still exceeded, then more detailed

calculations are conducted in a third tier by adding site- or species-specific input to model exposures more realistically (USDOE, 2019). Third tier analyses are typically more expensive because of the required site-and species-specific data needed. Thus, dose estimates for early tier ecological risk analyses are often purposely conservative and known to lack realism, with the hopes of pragmatically demonstrating that wildlife is not being exposed to dangerous levels of contaminants.

In contrast to the conservative approach to dosimetry used in early-tiers of an ecological risk analysis, researchers attempting to establish dose-effect relationships try to quantify dose rates as precisely as possible, given limited budgets and other constraints, so that the uncertainties of derived dose-effect relationships are reduced and a greater confidence in results can be achieved (Bouville et al., 2014). Our experiences in quantifying external dose relative to the contrasting needs of the risk assessor and the dose-effect researcher are highlighted herein.

2.5. Review: two common assumptions made with external dose

Because the spatial-temporal aspects of external dosimetry are not easy to quantify, researchers typically assume simple methods are adequate for estimating radiation dose rates to wildlife. Two common assumptions often associated with simple methods for estimating external dose rate are.

(1) for screening risk assessment purposes (i.e. Tier-2), best estimates of contaminant concentrations are typically used instead of maximum values. Averaged values of contaminants are often recommended as the best estimates, and averaged values are assumed to be conservative for purposes of complying with dose rate benchmarks. For example, guidance on screening risk analyses based on contaminated soils (USEPA, 1996) states that "*an average concentration is used in most assessments when the focus is on estimating long-term, chronic exposures*". Likewise, ecological risk assessment guidance (USDOE, 2019) states that average values of contaminant concentrations should be conservative for purpose of complying with dose rate criteria; that "*In protecting populations, as opposed to protecting individuals, considerable averaging over space and time could be allowed and still ensure adequate protection*"; and that "*mean concentrations are assumed in this technical standard to approximate those concentrations to which a representative individual within a population would be exposed*". Additionally, a summary report of the IAEA's EMRAS and MODARIA programs (with goals of improving capabilities in the field of environmental radiation dose assessment) stated that the "'*conventional approach' of averaging soil activity concentrations over an appropriate area is suitable for screening-level assessments*" (IAEA, 2021). The justification for using averaged values as best estimates is the assumption that animals move randomly across areas of varying exposure, spending equivalent amounts of time in each and thus exposure over time is best represented by the averaged contaminant concentration in the exposure area (USEPA, 2003). For illustrative purposes, if the entire rectangular area of Fig. 1 represented the area in which a population of boars was contaminated, the mean contaminant level within that area would, according to this paradigm, result in a conservative (i.e., over) estimate of external dose rate.

(2) for dose-effect research, an assumption often made is that a single measurement of exposure at the trap location of an animal (represented by blue boxes in Fig. 1) adequately represent the external dose rate to that individual (e.g., Møller and Mousseau, 2013; Boratyński et al., 2014; Fuma et al., 2017; Lehmann et al., 2016; Beaugelin-Seiller et al., 2020). However, the use of this simple approach represents a potentially fallible assumption in exposure science (including ecological risk analyses) – that an estimate made using minimal data can adequately capture the dose rates of wildlife moving through and interacting with a complex contaminated landscape (Bontrager et al., 2024).

Historically, there has been a lack of empirical field data on external dose rates to test if either of the assumptions stated above are valid (NRC, 2012). Using averaged contaminant concentrations across a landscape and using a single measurement at a trap site does not consider the spatial-temporal aspects of animal-contaminant interactions. The results of modeled external dose rates derived from averaged contaminant levels, and single measurements at trap sites (even though commonly found in the literature), can thus be challenged because data to validate the models (based on directly measured external dose rates on individual animals) are rare. Much of our research over the last decade, based on a new wildlife dosimetry tool (i.e., GPS-coupled dosimetry; Hinton et al., 2015), has allowed us to test these paradigms and thereby suggest ways to improve the accuracy of external dose rate measurements on free-ranging wildlife.

3. Methods review: how to estimate external dose

3.1. Methods review: numerical simulations

There are exceptions, but typically external dose rate is not determined from direct measurements on animals in the field. Instead, most published data on radiation dose rates to terrestrial wildlife are based on numerical simulations using computer software where the radioactivity concentration in soil is extrapolated to an estimate of external dose rate to wildlife. Dose models are used because of their pragmatic ease and as an alternative to the difficult and expensive tasks of capturing wild animals.

Dosimetry models for wildlife, such as the ERICA Tool (Brown et al., 2016) and RESRAD-BIOTA (Yu et al., 2003), rely heavily on various empirical ratios (ERs) to estimate radioactivity concentrations (Bq/kg) in animals. Aggregated Transfer Factors (T_{ag}; m^2/kg) and Concentration Ratios (*CR*; unitless) are ERs often used to estimate radionuclide activity concentrations in terrestrial wildlife (Bq/kg) from radioactivity levels in soil (Bq/m^2 soil for T_{ag} values; Bq/kg soil for *CR*s). After the ERs are applied, Dose Conversion Coefficients (*DCC*s) are used to convert radioactivity concentrations in animal tissues (Bq/kg) to dose rates (μGy/h) from internal pathways, and to convert soil radioactivity levels to external dose rate. ERs are radionuclide- and animal species-specific. Unfortunately, variations in ERs always range over several orders of magnitude for the same animal species-radionuclide combination (IAEA, 2010; Tagami et al., 2016; IAEA, 2021). Thus, their use greatly increases the uncertainties associated with dose rate estimates. Additionally, ERs are constants and assume an equilibrium in radioactivity concentrations exists among components of the environment, whereas equilibrium seldom occurs (Salbu, 2016). Although work to improve the predictive power of ERs is progressing (e.g. Beresford and Willey, 2019; Whicker et al., 2023), the large variations in ERs severely limit their utility in accurately predicting radiation dose rates to biota (Whicker et al., 1999; Anderson et al., 2019). Importantly, ERs neither capture the large spatial heterogeneity in levels of contamination nor the temporal variability of wildlife space use within their home ranges. Thus, doses derived from ERs should be limited to those situations for which ERs were originally intended – for carrying out screening-level calculations within risk assessments (IAEA, 2010). Empirical ratios should not be used to estimate dose quantitatively in research where dose-effect relationships are developed for exposed wildlife.

3.2. Methods review: ambient dose rate

Rather than computer simulations, a common field method of estimating external dose to wildlife is to measure the ambient dose rate at the animal trap site with a handheld dose rate meter used in area radiation monitoring for human dosimetry (e.g. Onuma et al., 2020;

Anderson et al., 2022). The instrument is calibrated to report ambient gamma dose equivalent rates to humans at a depth of 10 mm under the skin surface (H*(10)). Ambient dose rates are typically taken at a standard height of 1 m above ground to mimic exposure to critical adult human organs. The ambient equivalent dose (ICRU, 1985) quantifies the risk to human health from radiation exposure, including natural background radiation. The difference between H*(10) ambient dose (μSv) for humans and absorbed dose (μGy) for wildlife, via energy specific air kerma rates (ICRP, 1996), is typically small (~7 %, Kubota et al., 2015; Pederson et al., 2020) relative to instrument reading uncertainties (10 % as reported by manufacturer) and the much larger overall uncertainties in estimating external doses to free ranging animals. Thus, numerical conversions are not usually performed and instead the dosimetry units from the ambient dose rate instrument (μSv/h) are changed directly to those appropriate for non-human biota (μGy/h).

A source of error much larger than the unit conversion discussed above is that researchers using ambient dose rates assume the single ambient dose measurement at the trap site is representative of the external dose rate experienced by that animal across its entire home range. Considering the wide range of contaminant levels inherent within a landscape (Fig. 1), the probability is low that a dose rate reading from one single location will match the spatial-temporal aspects of external exposure experienced by an animal, especially for wide-ranging species. Nonetheless, such estimates of external dose rates from single measurements are often correlated to effect endpoints in dose-effect studies (e.g., Mousseau and Møller, 2013; Boratyński et al., 2014; Lehmann et al., 2016; Kesäniemi et al., 2019).

3.3. Methods review: passive dosimeters

A major improvement over measuring ambient dose rate at a single location is to place dosimeters in several habitats within an animal's home range. Passive devices, such as Thermoluminescent Dosimeters (TLD) or Optically Stimulated Luminescence (OSL) dosimeters, have been used to measure environmental doses at a finer scale than single location measurements (reviewed by Aramrun et al., 2018). Passive dosimeters integrate dose over the period they are deployed, and division by the time deployed converts the integrated dose to a single dose rate. By placing numerous dosimeters in the field, a researcher can quantify different dose rates as a function of habitat type. The different dose rates can then be inserted into wildlife dose models and proportioned timewise to the researchers' expectation of how the species uses habitats within its home range. The use of multiple passive dosimeters results in a better estimate of an animal's external dose rate based on the species' ecology (Gaines et al., 2005). Researchers have also used passive dosimeters within animal carcasses, or inside phantoms that mimic animals, to measure dose rates to internal organs of animals or as a more realistic whole-body measure of dose rate compared to a bare passive dosimeter placed on the ground (Rodgers and Holmes, 2008; Stark and Pettersson, 2008; Kubota et al., 2015; Fuma et al., 2015).

The most realistic use of passive dosimeters is when they are placed directly on live animals. Woodhead (1973) pioneered this method when he attached TLDs to 3580 flat fish (*Pleuronectes platessa*) in the Irish Sea. He was able to recapture ~1/3 of the tagged fish, enough to clearly show a pronounced logarithmic distribution in dose rates among the exposed fish population. At Chornobyl, TLDs were placed on 68 rodents, of which 13 were recaptured to reveal that external dose was 30 times greater than internal dose (Chesser et al., 2000). Using shielded (from ^{90}Sr beta radiation) and unshielded TLDs, Beresford et al. (2008) found that gamma emissions from ^{137}Cs comprised ≥99 % of the external dose to the 85 Chornobyl rodents they were able to recapture from the initial 230 outfitted with dosimeters. Aramrun et al. (2019) compared the response of four different types of passive dosimeters on 12 reindeer grazing Chornobyl contaminated pastures in Norway. Differences in external dose measured among the different dosimeters over an 11-month period were not significant, with a maximum difference between dosimeter types being a factor of 1.3 (Aramrun et al., 2019). Gerke et al. (2020) used passive dosimeters on Fukushima snakes (Elaphe climacophora, n = 8; E. quadrivirgata, n = 1) and found that incorporating animal behavior in models improved dose rate estimations.

In the studies highlighted above, passive dosimeters added significant precision and reduced uncertainties of external dose measurements. There are some disadvantages, however, of passive dosimeters: (1) the animal must be recaptured to recover the dosimeter, (2) passive dosimeters must be analyzed in the laboratory with specialized equipment, and (3) passive dosimeters produce a single reading of the integrated dose over the entire time the dosimeter is attached to the animal. Passive dosimetry provides no information on the variation in external dose rates during the integration period, or the amount of dose received in specific habitats that may vary tremendously in contaminant density. Thus, passive dosimeters are not suitable for addressing questions about spatial-temporal variation in external dose rates.

3.4. Methods review: retrospective dosimetry

Retrospective dosimetry determines the absorbed radiation dose to environmental materials in situations where conventional dosimeters were not in place at the time of the exposure (Fattibene et al., 2023). Retrospective dosimetry integrates dose over the time the material was exposed and has been used on humans to estimate doses received during accidents, and for chronic exposures. For example, absorbed doses to residents of contaminated areas following the Chernobyl accident were determined by X-band Electron Paramagnetic Resonance (EPR) spectroscopy of their tooth enamel (Simon et al., 2007). Good correlations were found between EPR methods and calculated doses (Ivannikov et al., 2004). Tooth enamel is one of the most sensitive materials for EPR dosimetry, enabling doses as low as 30 mGy to be detected (Hoshi et al., 2007). The technique has been applied to animal teeth, for example bovine teeth in Fukushima, and compared with estimated doses extrapolated from environmental dose rate maps (Todaka et al., 2020). Most EPR retrospective studies are still feasibility studies using the teeth of different species of animals and comparing sensitivities between different types of biological samples within the same animal (Harshman and Johnson, 2018). The sensitivity of tooth enamel in most animals is comparable to that of humans. However, many parameters still need to be studied, such as the impact of sample preparation, signal processing, recording parameters, etc. (Romanyukha et al., 2005; Toyoda et al., 2006). Molars are the most suitable teeth for this type of dosimetry because of the large amount of enamel. Also, molar location in the back of the jaw reduces contributions to the EPR signal from UV radiation, which is known to be a confounding factor. Additionally, contributions of dose from internal contamination of animals remain a real challenge when estimating external dose to teeth (Klevezal et al., 1999; Romanyukha et al., 2005). Ultimately, the interpretation of the estimated dose is always very delicate because it requires precise knowledge of the age of the tooth and the impact of the physiology of the tooth on the EPR signal. Other types of biological samples have also been studied using EPR (e.g., insect wings, Kazakis et al., 2016). *In vivo* EPR techniques have also been tried to monitor dose to animals on a regular basis, particularly with low-frequency (L-band) EPR (Yamaguchi et al., 2021). Alternatively, the use of high-frequency EPR, which only requires sample masses of a few mg, may allow very limited sampling from living animals with invasive, but minimum detriment (Romanyukha et al., 2014). These techniques certainly merit further development so that they can be considered in future radioecology studies.

4. Novel tool for external dose rate

4.1. Tool development: GPS-coupled dosimeters on animals

To eliminate some of the disadvantages of passive dosimeters, we

developed a new tool that tracks the physical location of animals and simultaneously measures their external dose rates from gamma emissions of radioactivity (Hinton et al., 2015). The new tool does not require recapturing the animal, nor laboratory analysis to obtain the dose rate data, and importantly, researchers obtain external dose rate data in near real time while the animal roams freely within its environment. The tool contains an electronic dosimeter wired to communicate with the GPS technology inside the protective housing of a wildlife GPS transmitter. Electronic dosimeters are classified as active because, unlike passive dosimeters, the dose rate can be read any time during use. GPS-dosimeter combinations have been used previously within vehicles or in backpacks worn by humans where size of the units, battery life and environmental conditions were of no concern (Okuyama et al., 2005; Whicker et al., 2008; Kawano et al., 2012). Our contribution was to miniaturize the components so that they could be attached to an animal via a collar, have sufficient battery life, and withstand harsh environmental conditions. The weight of our GPS-dosimeters was ~985 g, which limits their use to animals ≥30 kg. Future technological advancements will facilitate further miniaturization of these units for use on a broader size range of animals.

The GPS-coupled dosimeters continuously integrate external dose and send data to the researcher via email at user defined intervals, via the same satellites that send the GPS locations of the animal (Fig. 2). Subtraction of the dose between two-time intervals produces a mean dose rate to which the animal was exposed while in the geographical area delineated by the GPS coordinates during the same period. For example, we used 35-min intervals for eight Chornobyl wolves, tracked from 165 to 180 days, resulting in ~6600 individual locations and external dose rate readings per animal (Hinton et al., 2019). We also tracked 16 wild boar within the exclusion zone of Fukushima at hourly intervals, for an average of 68 ± 50 days, yielding over 22,800 GPS fixes and dose rate readings (Bontrager et al., 2024). GPS-coupled dosimeters were also used on three Norwegian reindeer, in a lower dose environment, and tracked for 155 days (Bæk et al., 2023). Because the pasture contamination grazed by the reindeer was relatively low, resulting in hourly external dose rates that approached the detection limits of the dosimeters, hourly dose rates were summed to achieve a daily dose rate (μGy/day), thereby enhancing the strength of statistical analyses (Bæk et al., 2023).

Dosimeters, both passive and electronic, placed on non-human biota require unit conversions and calibrations to understand what the reported dose rates actually represent. The electronic dosimeters (Mirion's SOR/R dosimeter; www.mirion.com) incorporated into the GPS-dosimeters were calibrated by the manufacturer to report dose equivalent rates from external exposure to humans at a depth of 10 mm under the skin surface (H*(10)), in units of μSv/h. The Supplemental Section of Hinton et al. (2019) details steps to convert dose equivalent rates in humans to a dose rate for wildlife with appropriate units. The steps resulted in a conversion factor of 1 μSv/h = 0.97 μGy/h. The conversion factor was smaller than the inherent variability of the dosimeter when making multiple measurements from an identical radioactive source (~10 %, as stated by Mirion), thus, we opted to merely change dosimetric units and not invoke the correction factor.

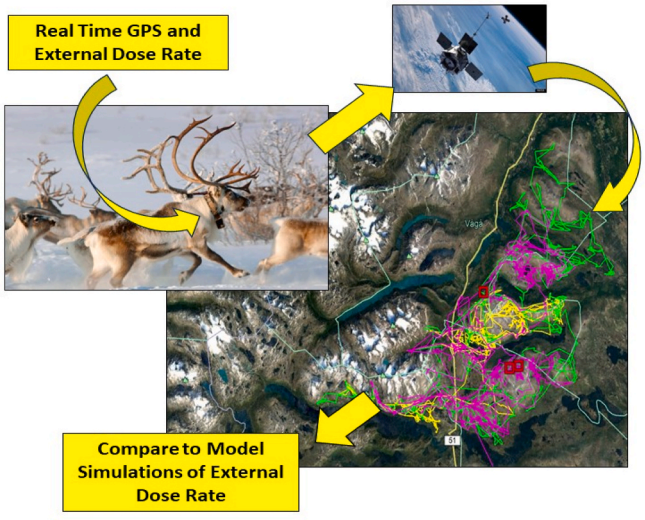

Fig. 2. Depiction of GPS-coupled dosimeter on a collared reindeer (Bæk et al., 2023). The animal's physical location and external dose are sent to researchers, via satellites, at a user-defined interval. External dose rates can then be compared to model simulations.

More complicated procedures are required to remove the unwanted contribution of radiation internal to the animal increasing the dosimeter measurement of external dose. Internal pathways of contamination result in radioactive materials existing within the body of animals. Radiation emitted from within the body interacts with the dosimeter worn on the neck of the animal and contributes to the external dose reading attributed to environmental radiation. It is necessary to subtract the internal contribution to have an accurate measurement of external dose. Because each animal's internal radiation burden differs, the internal bias adjustment requires determining radiation levels within each animal. We developed a method to whole-body assay each animal in the field for internal ^{134}Cs and ^{137}Cs radioactivity concentrations (Bq/kg). We used a 1-cm^3 Cadmium–Zinc-Telluride (CZT) radiation detector coupled to a field computer and assayed the animal while it was anesthetized for fitting with a GPS-dosimeter collar (Supplement to Hinton et al., 2019).

We derived a method to account for the internal contamination's contribution to the dosimeter's external dose measurement based on Monte Carlo calculations using a voxel phantom of a wolf (details in Supplement to Hinton et al., 2019). The Monte Carlo corrected external dose factor agreed well with a correction factor derived for passive dosimeters on reindeer using a calibrated ^{137}Cs phantom to represent large mammals (Aramrun et al., 2018). Both methods produced a correction factor of 0.023 nGy/h contributing to the external dose read by the dosimeter for each Bq/kg ^{137}Cs inside the animal. This correction factor should be appropriate for similar sized mammals (i.e., deer, wild boar, wolf) in future studies. The dose rate from internal radiation should be subtracted from the dose measured on the GPS-collar to obtain a more precise measure of external dose rate.

Internal contaminant contributions to the readings of external dose rates measured with passive dosimeters, placed on smaller animals such as rodents, are likely needed as well. The need was highlighted by the research of Beresford et al. (2008), in which they stated that their measurements of external dose to Chornobyl rodents using TLDs likely included uncorrected contributions from the animal itself, because whole-body measurements of ^{137}Cs in rodents exceeded the ^{137}Cs activity concentrations in soil by as much as 20-fold. In the published studies in which passive dosimeters have been placed on small animals, none that we are aware of corrected the external dose measurements for contributions from internal contamination.

Because our GPS-dosimeters were too large for animals less than 30-kg in size, we developed a method for smaller animals using a combination of passive dosimeters, VHF transmitters, and GPS units, all attached to the same individual animal (Gerke et al., 2020). The units were used on Fukushima snakes (Fig. 3). Because a passive dosimeter integrates dose for the entire time it is deployed, capturing variation in external dose rates for single individuals is not possible. With some species, multiple recaptures of the same individual may be possible and provide dose rates using passive dosimeters. In the Fukushima snake study, four snakes were captured multiple times, and the passive dosimeters were replaced at each recapture (Gerke et al., 2020). Recovery of passive dosimeters from the same individual indicated that dose rates varied over time and location, although the maximum difference (0.7 μGy/h) was relatively small (about 30% of the average dose rate; Gerke et al., 2020).

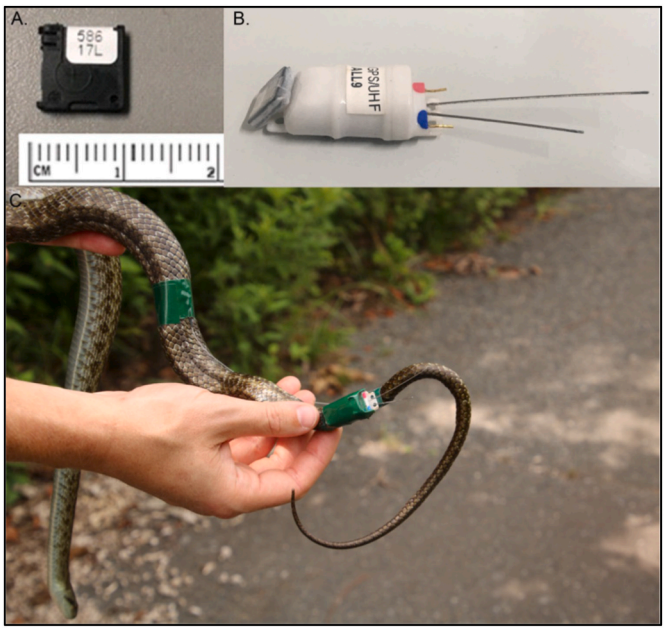

Fig. 3. Photo of: A) optically stimulated luminescence (OSL) dosimeter, B) OSL dosimeter attached to GPS/UHF transmitter, and C) VHF transmitter and GPS/UHF transmitter with OSL dosimeter on the tail of a Fukushima snake (Gerke et al., 2020).

Because of the lower limits of detection inherent in all dosimeters, confidence in GPS-dosimeter data increases with increasing environmental radioactivity levels. Confidence in measuring external dose is greatest when working in highly contaminated environments where the lower limit of detection is well below measured dose rates and contributions from other natural sources of radiation are miniscule compared to the contamination of interest. For example, mean ^{137}Cs activity density in the soil at Chornobyl was large (~1040 kBq/m^2) and dominated external dose to wolves (~2 μGy/h) such that the contribution that cosmic radiation made to the GPS-dosimeter could be dismissed. Whereas the Chornobyl contaminated pastures in Norway had declined in radioactivity from levels determined soon after the accident, and the soil ^{137}Cs density (~20 kBq/m^2) resulted in a much smaller external dose to the reindeer (~1.5 μGy/day), requiring corrections from cosmic (~1 μGy/day) and natural background radiation (~0.1 μGy/day). Details for correcting the electronic and passive dosimeters are presented within Bæk et al. (2023) and Aramrun et al. (2019), respectively.

4.2. Tool develoment: linked contaminant mapping data

GPS-dosimeters are powerful tools for quantifying external dose to free-ranging wildlife. The tool's power is enhanced considerably if the collared animal is traversing landscapes that have been mapped for radioactive contaminants. When contaminant maps and empirical measurements of external dose are combined, the accuracy of modeled external dose rates can be tested, along with the two dosimetry assumptions presented in **Section 2.5**.

All our GPS-dosimetry studies occurred in landscapes where radioactive contaminant maps existed. The contaminant maps were produced to evaluate risks to humans and assist in long-term management of the impacted areas. External doses to wolves were explored within the Belarus portion of Chornobyl's Exclusion Zone where radioactive contamination densities were mapped from extensive soil sampling (Izrael and Bogdevich, 2009). External doses to Norwegian reindeer were studied in pastures contaminated by Chornobyl fallout where soil radioactivity levels of ^{137}Cs, as well as naturally occurring radioisotopes of U, Th and K, were mapped based on airborne gamma-ray spectrometry (Baranwal et al., 2020).

Our studies of wild boar occurred within Fukushima's Difficult to Return Zone where humans were evacuated, and contamination has been mapped using various methods that differ greatly in how finely contamination is surveyed spatially. This variability in scale of contamination mapping allowed Bontrager et al. (2024) to compare GPS-dosimetry data to modeled estimates of dose rates using contaminant maps at three different scales: (1) a coarse soil survey in which the contaminated area was divided into squares of five km^2, with one survey location per square (Saito and Onda, 2015) resulting in the average nearest distance between soil samples being 3719 ± 854 m (from which an interpolated map of 550 m resolution was constructed using Inverse Distance Weighting because the samples were too sparse to use kriging); (2) a finer scale soil survey from 2011 (Saito et al., 2015) in which the average nearest distance between soil samples was 1277 ± 554 m, from which an interpolated map with a 550 m resolution could be developed using regression kriging; and (3) annual aerial surveys (Sanada and Torii, 2015) from which contamination levels were mapped to a resolution of 275 m.

4.3. Tool development: how interactions of mapping scale and animal use influence external dose estimates

To test how increased knowledge of animal movement impacts external dose predictions, we combined contaminant maps of different scales (**Section 4.2**) with model simulations of dose derived from increasing levels of knowledge about animal use of the area. The animal use levels were: 1) external dose based on a single measurement at the trap site; 2) external dose derived from a single soil survey point located nearest to the animal trap site; 3) external dose based on the maximum soil activity concentration within a circle of the trap site chosen to be larger than the typical home range for the species (i.e. 5-km radius for Fukushima wild boar); 4) external dose based on average soil activity concentration within a home range typical for the species (derived from the literature) and centered at the trap site (1.1 km^2); and lastly, 5) external dose based on the averaged soil activity concentrations within home range and core areas of individual animals wearing GPS units (Bontrager et al., 2024).

The animal knowledge scenarios listed above made an ideal data set for testing how the scale of knowledge about wildlife use of the landscape, along with scale in which contaminant heterogeneity is mapped, combine to impact the realism (relative to accurate dose-effect research) and conservativeness (relative to ecological risk analyses) of modeled dose estimates (Bontrager et al., 2024). All model simulations of external dose were compared to actual external dose rates measured on Fukushima wild boar wearing GPS-dosimeters. The lessons learned from this work are presented below.

5. Lessons learned from GPS-coupled dosimeters

5.1. Lesson learned: variation in external dose rate

GPS-dosimeters can quantify the variation in external dose rates among individuals within the same population. This is an important statistic that can also be obtained with passive dosimeters (e.g., Woodhead, 1973). Variation in dose rates among Chornobyl rodents, for example, derived from passive dosimeters, led Chesser et al. (2000) to suggest that the variation in dose rates may be more important than mean values when considering the overall impact on mammalian populations.

Equally important, but unobtainable with passive dosimeters, is the variation in external dose rates over time for single individuals. GPS-dosimeters revealed the maximum external dose rates for one of the Chornobyl wolves was 30 times its mean dose rate, and external dose rates of another wolf varied 30-fold over a 12-day period (Hinton et al., 2019). Variations in dose rates to reindeer over 24-h periods were about

5-fold (Bæk et al., 2023). Short term variations in external dose rates were also apparent with boar at Fukushima. External dose rates for one female boar were similar for many days, and then started to oscillate with large periodic spikes (Fig. 4). Examination of the GPS location data showed that the boar was living within 4-km of the damaged nuclear reactor when the spikes in dose rates occurred. Analyses of the data showed that the boar was feeding in abandoned rice paddies (where dose rates were relatively low) and then seeking refuge at a single location in a nearby, highly contaminated forest. Each time the boar moved to the rice paddies its external dose rate decreased sharply, and when the boar returned to the forest refuge the dose rate dramatically increased (Fig. 4). Collectively, these results highlight both the inherent limitations in studies lacking detailed dosimetry data, as well as the possibilities for improving dose-effects studies in free ranging wildlife in the future.

5.2. Lesson learned: averaged contaminant densities do not produce conservative estimates of dose

As highlighted in **Section 2.5**, a common paradigm in screening risk analyses is that soil activity concentrations averaged over an extended contaminated area (typically that used by a population) will produce a conservative estimate of external dose rate that is greater than the dose rate experienced by animals in that environment. Having now tested this paradigm using three mammalian species that differed widely in their respective niches [predator (wolf); omnivore (boar); herbivore (reindeer)], mean home range size (reindeer = 833; wolf = 226; boar = 4 km^2), and mean soil ^{137}Cs contaminant density (wolf = 1195; boar = 365; reindeer = 20 kBq/m^2), the preponderance of empirical data show that the modeled estimate of external dose based on a grand mean of contaminant density is typically less than the actual dose measured with GPS-dosimeters. Modeled dose estimates based on mean soil radioactivity under-predicted external dose rates by 15–70% for 14 of the 16 boar, five of the eight wolves, and all three reindeer. The reindeer results are supported by those of Aramrun et al. (2019), where simulated exposures based on average soil contamination levels under-predicted the average external dose measured with passive dosimeters placed on 12 reindeer. The large heterogeneity of contaminant densities within an animal's environment and the animal's allocation of time to preferred habitats cause averaged values to underpredict the real external dose experienced by at least some members of the population. The fundamental principle behind a conservative risk assessment is that the dose simulated by a model is assured to be greater than what an animal is likely to experience in the field. The under-predictions of model simulated dose documented herein are not in agreement with the conservatism sought in screening-level risk assessments. Therefore, following this paradigm within a screening level risk analysis will likely result in a biased interpretation of results and lead to misguided recommendations for risk management.

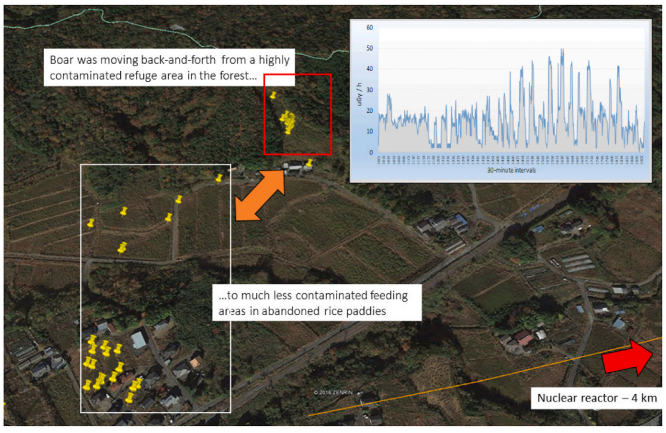

Fig. 4. Variation in external dose rate observed for a wild boar living within 4-km of the damaged nuclear reactor at Fukushima. Yellow pins are the physical locations of the boar as determined by GPS data. Dose rates over time (insert) decreased when the boar went into the abandoned rice paddies, and peaked when it sought refuge in the highly contaminated forest.

Of the methods tested [i.e., sample at trap site; sample at nearest survey location; mean soil contaminant within a presumptive home range; and maximum contaminant concentration within a circle chosen to be larger than the typical home range (5-km radius for Fukushima boar)], only the maximum dose within a 5-km radius of the trap site resulted in modeled external dose rates consistently conservative (i.e. greater) than the empirically measured dose rates (Bontrager et al., 2024).

5.3. Lesson learned: home range and core areas improve external dose rate estimates

Because of the GPS component, valuable data on animal movement, home range and core areas (areas of intensive use within the home range) can be obtained with the dosimetry data when wildlife are fitted with GPS-dosimetry collars (Getz et al., 2007). These attributes differ considerably among wildlife species, likely influencing their external dose. For example, the eight wolves monitored with GPS-dosimeters at Chornobyl had an average home range size of 226 ± 104 km^2, while their core areas were comparatively small (8 ± 7 km^2), covering only 3% of their home range (Hinton et al., 2019). In contrast, the three reindeer that were collared had average home ranges that were almost four times larger than the wolves (833 ± 146 km^2), reflecting their migratory behavior, with large core areas (160 ± 71 km^2) that were 20 % of their home ranges (Bæk et al., 2023). The Fukushima wild boar (n = 16) had small home ranges of only 4.1 ± 9.0 km^2 with core areas of 0.55 ± 1.25 km^2, illustrating the wide disparity in both home range size, as well as patterns of space use within home ranges among species (and even individuals within species).

Our GPS-dosimetry data show that external dose rates based on soil contamination improves considerably if the area of contamination corresponds to the home range of the animal (99% Utilization Distribution) rather than based on a grand average of the entire contaminated area (Fig. 1). External dose rate based on soil contamination improves even more if it corresponds to the animal's core area of high use (50 % Utilization Distribution). Area-weighted mean soil contamination levels in an animal's home range accounts for the spatial use of contaminated habitats, but not the amount of time spent in those habitats. The latter is approximated in the delineation of core areas. This was evident with data from the Chornobyl wolves where the weighted mean ^{137}Cs distribution in soil (kBq/m^2) was determined in both the home range and core area of each individual and correlated to external dose rates measured with GPS-dosimeters. This method was robust and the resulting external dose rates were not significantly different from the mean readings obtained from the GPS-dosimeters worn by the eight animals. While strong correlations occurred between empirical dose rates measured with GPS-dosimeters and soil activity densities in the wolf's home range (R^2 = 0.89), correlations improved when correlated to radioactivity in core areas (R^2 = 0.99; Fig. 5). More recent data with Norwegian reindeer supported the relationships observed for wolves. Using mean contaminant levels within defined home ranges improved predictions of external dose rates by 17 % and by 24 % when core areas were used, although the R^2 values were not as robust as with the wolf data (Bæk et al., 2023). Likewise, external dose rates calculated in ERICA using soil samples within snake home ranges were generally in agreement with doses from OSL dosimeters on snakes (i.e., within a factor of two; Gerke et al., 2020). Collectively, the GPS-dosimeter data reinforce the importance of accounting for temporal and spatial variability of contaminant densities and animal habitat preferences when simulating exposure to biota.

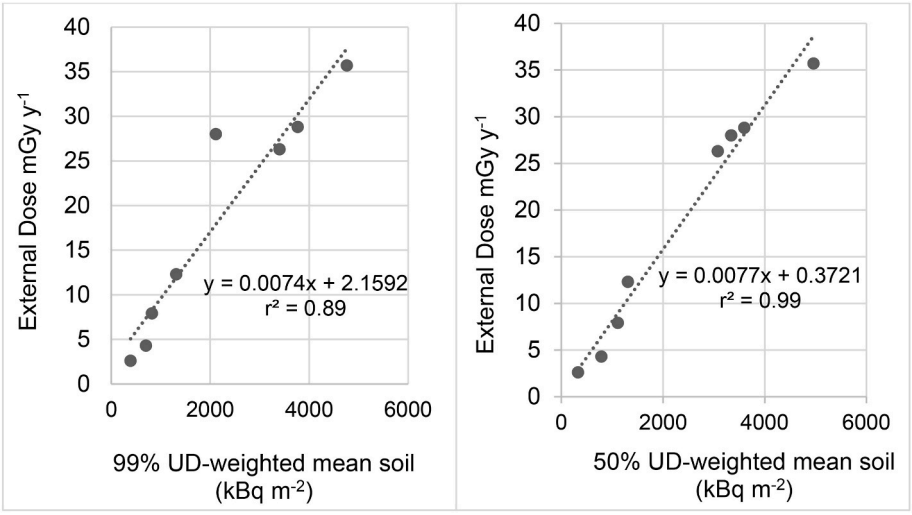

Fig. 5. Correlations between weighted mean soil ^{137}Cs densities in wolf home ranges (99 % Utilization Distribution; left panel) and core areas (50 % Utilization Distribution; right panel) at Chornobyl with external dose rates from GPS-dosimeters worn on individual animals (Hinton et al., 2019).

5.4. Lesson learned: scale of contaminant mapping and knowledge of animal use combine to impact external dose rate estimates

The most robust tests to date of how the density at which contaminants are mapped and knowledge of animal movement combine to affect model estimates of external dose rates were conducted on Fukushima wild boar (Bontrager et al., 2024). With only a sparse knowledge of contaminant heterogeneity across the landscape (mean distance between contaminant sampling points = 3719 m; Table 1) it was not possible to accurately model external dose rate, regardless of how much animal movement data exist. Surprisingly, with such sparse knowledge of contaminant distribution, modeled external dose rates did not correlate to doses empirically measured using GPS-dosimeters even if the animal's home range and core areas of intensive use were known (R^2 = 0.06; Table 1).

As information about contaminant heterogeneity increased (middle and far right columns of Table 1), the R^2 values increased. Moderate contaminant mapping resolution (1277 m between points) saw an increase in R^2, but it remained weak (<0.5) unless detailed animal use information was available. Fine-scale mapping of contamination (53 m between points) permitted external dose to be predicted with moderate strength (R^2 > 0.5) even if knowledge of animal use was limited. As knowledge of animal use of the area increased (right column of Table 1), the R^2 values increased dramatically.

5.5. Lesson learned: single dose measurement at trap site is not predictive of external dose rates

Among the many lessons learned from our use of GPS-dosimeters, perhaps the one with the greatest implication to published data has been that estimates of external dose rates based on a single measurement at a trap site do not correlate with actual dose rates measured on animals. We found no correlation between external dose rates measured at boar trap sites and dose rates measured on free-ranging boar using GPS-dosimeters (R^2 = 0.02; Bontrager et al., 2024). Likewise, no correlation was found between external dose rates measured with passive dosimeters on snakes with ambient dose rates taken at their capture locations (R^2 = 0.07, p = 0.31). The lack of correlation is noteworthy because a single measurement at the trap site is the most common field method used to estimate external dose to wildlife (e.g., Ryabokon et al., 2005; Møller et al., 2012; Møller et al. 2014; Møller et al. 2015; Fuma et al., 2017; Urushihara et al., 2018; Onuma et al., 2020; as well as some of our own research: Cunningham et al., 2021; Anderson et al., 2022). The lack of a correlation makes a vast number of published dose-effect conclusions based on single measurements at trap locations questionable.

Table 1
Comparisons of how the quality (i.e., scale of resolution) for various data input schemes impact model simulations of external dose rate. Model simulations were compared based on the strength of regressing model output to actual external dose rates measured by GPS-dosimeters on individual boar. Mapping resolution of contamination across the landscape increases from left to right in the table columns (3719 m, 1277 m, and 53 m between sample points). Knowledge about animal use of the area increases from top row of the table, where a single datum from the nearest survey location to the trap is assumed to be representative of an animal's external dose, to the bottom row where contaminant concentrations are averaged within the GPS-delineated core area of intensive use for each animal. Coefficients of determination from the regressions are shown. We considered R^2 ≥ 0.75 to be strongly correlated (bold font), 0.50 to 0.74 to be moderate (underlined font), and <0.49 to be weakly correlated (Bontrager et al., 2024).

Method by Which External Dose Rate was Simulated with a Dose Model	Mean Distance Between Sampling Points Used to Produce Contaminant Map		
	3719 ± 854 m (Soil sampling; Inverse Distance Weighted to 550 m)	1277 ± 554 m (Soil sampling; Kriged to 550 m)	53 ± 79 m (Aerial survey; Resampled to 275m)
Nearest Survey Location from Trap	R^2 = 0.01	R^2 = 0.03	$\underline{R^2 = 0.58}$
Mean Contaminant Density Within Presumptive Home Range Around Trap Site	R^2 = 0.0	R^2 = 0.46	$\underline{R^2 = 0.62}$
Mean Contaminant Density Within GPS-Derived Home Range	R^2 = 0.04	R^2 = 0.44	**R^2 = 0.78**
Mean Contaminant Density Within GPS-Derived Core Area	R^2 = 0.06	$\underline{R^2 = 0.56}$	**R^2 = 0.91**

A single measurement of any parameter is deemed inadequate in most disciplines of science; however, it has often been espoused as acceptable for external dose to wildlife (IAEA, 2018; Beaugelin-Seiller et al., 2020). The historic acceptability of the method stems largely from not having empirical field data to test if a single measurement of external dose adequately captures the inherent variability in dose rates, and from research on rodents with relatively small home ranges, although those results are mixed. For example, external dose rates to

rodents based on soil samples using the ERICA Tool compared well to ambient dose rates taken at 1-m height ($r^2 = 0.86$; separate analyses of data presented in Table 6 of Anderson et al., 2021). Chesser et al. (2000) placed TLDs on 68 meadow voles trapped in the Red Forest of Chornobyl and recovered 13 animals. Voles captured within several meters of one another differed by an order of magnitude in their Cs concentrations and dose rate estimates. The mean external dose estimated from TLDs (0.74 mGy/d) agreed with mean estimates obtained from a hand-held dose rate meter at ground level (3 mrem/h = 0.72 mGy/d). The researchers did not report analyses of correlation. In contrast, the research on dose rates to Fukushima snakes using attached OSL dosimeters (mean 2.2 ± 0.6 μGy/h) also appeared at first to agree remarkably well with mean ambient dose rate readings using a hand-held instrument at snake capture locations (mean 2.6 ± 1.0 μSv/h); however, OSL dosimeters on snakes did not correlate to ambient dose rates ($R^2 = 0.07$, $p = 0.31$; Gerke et al., 2020). Similarly, Beresford et al. (2008), working with TLDs on rodents at Chornobyl, found mean predictions of dose rates based on soil samples were in reasonable agreement with mean TLD measurements on mice, whereas individual dose rates were not well predicted.

Collectively, these data confirm the observation of Steenland and Savitz (1997): "*The void in fine-scale exposure data on an individual or a species means that considerable error may be introduced in assessing dose–response relationships.*" The error can also be propagated by modeling attempts to improve dosimetry if the models rely on the same sparse knowledge of contaminant heterogeneity. An excellent example of potential biased interpretation of data due to poor dosimetry is the dose-effect research on Fukushima birds (Møller et al., 2015), where the authors relied on a single measurement of ambient dose rate at each bird survey location. Garnier-Laplace et al. (2015) recognized the problem of a single ambient dose measurement and sought to improve the published bird dosimetry results. They conducted an extensive dose reconstruction of the Møller et al. (2015) data using state-of-the-art dosimetry models. Rather than ambient dose rate at each bird census location, Garnier-Laplace et al. (2015) modeled external dose using the nearest soil activity concentration data to each bird census point. The distances between bird census points and soil sampling points varied from 12 m to 1.6 km (Garnier-Laplace et al., 2015). Indeed, the soil survey data used by Garnier-Laplace et al. (2015) was the same data (i.e., Saito et al., 2015) used by Bontrager et al. (2024), and from which Table 1 was derived. Bontrager et al. (2024) found that modeled dose rates using the nearest soil sampling point (as was done by Garnier-Laplace et al., 2015) did not correlate with external dose rates measured from GPS-dosimeters ($R^2 = 0.03$). Although our studies were conducted on wild boar, one would not expect drastic improvements in correlations, if any, when working with highly mobile avian species. Thus, using inadequate input data in a sophisticated dosimetry model will still result in poor dosimetry if the contaminant density is not sufficiently characterized. Therefore, the reported dose-effect relationships do not warrant the certainty of conclusions stated in the original paper (Møller et al., 2015) or in the follow-up paper in which dose rates were reconstructed (Garnier-Laplace et al., 2015).

6. Conclusions

The development of animal-applicable GPS-dosimeters addresses the lack of appropriate dosimetry technology for free-ranging wildlife, which has been one of the greatest limitations in exposure science and ecological risk assessments (Sanchez et al., 2010; NRC, 2012; Hinton et al., 2013; Stark et al., 2017). The application of this new technology across various contaminated sites revealed that individual animals experience significant variations in external dose rates. Variations in dose rates are driven by the complex, mosaic heterogeneity of contaminant distribution among environments and by the nonrandom, selective use of those mosaic micro-habitats by animals over time. Thus, sampling scale, in terms of how finely contaminant heterogeneity is mapped spatially and how detailed an individual's spatial usage of the landscape is tracked, significantly impacts the accuracy of external dose simulations by models.

Importantly, GPS dosimeters produce empirical data on dose rates to which computer simulations of external dose can be compared and validated, providing the most rigorous tests to date of several paradigms used in wildlife dosimetry. From an ecological risk assessment perspective, sufficient data has now accumulated to reject the paradigm that averaged soil contaminant levels can be used to conservatively estimate dose rates. Using averaged soil contaminant levels failed to overestimate external dose rates (i.e., be conservative) for many individuals within a population and will likely lead to misguided recommendations for risk management. Instead, conservative predictions can be achieved by using the maximum contaminant level within an area known to be larger than the typical home range size of the species. This method was found to be conservative even when the scale of contaminant mapping was coarse (Bontrager et al., 2024).

In contrast to the conservative goals within the early tiers of ecological risk analyses, dose-effect research requires utmost accuracy in dose rate estimates. The critical importance of how modeled external dose rates are impacted by the scale at which contaminants are mapped has now been demonstrated with empirical data. Indeed, if mapping scale is coarse (column 1, Table 1) even detailed knowledge about contamination within each animal's home range and core area of high use was inadequate to accurately predict external dose rates. Correlations improve significantly if fine-scale contaminants maps are used, even if little is known about animal use of the area. The take home lesson for improving estimates of external dose rates is that it is not necessary to capture an animal and put an expensive GPS-dosimeter on it, but it is necessary to quantify fine-scale contaminant variation within the animal's home range, whether that home range size is presumptive, based on literature values for the species, or actual home ranges measured with animal tracking devices.

The conclusion from our GPS-dosimetry studies with perhaps the largest impact to the field of radioecology is that modeled external dose rates based on a single measurement at a trap site did not correlate to actual dose rates measured on free ranging animals. This finding provides empirical data to support previous stated concerns by Smith (2008), Hinton et al. (2013), Strand et al. (2017), Beaugelin-Seiller et al. (2020), Beresford et al. (2020b, 2020c) and Jackson et al. (2022) about inadequate dosimetry in much of the published Chernobyl and Fukushima dose-effects research. The finding indicates that a huge portion of that literature should be challenged, and that improper dosimetry remains a significant source of controversy in dose-effect research.

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CRediT authorship contribution statement

Thomas G. Hinton: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation. **Donovan Anderson:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Edda Bæk:** Writing – review & editing,

Visualization, Investigation, Formal analysis. **Vikas C. Baranwal:** Writing – review & editing, Resources, Investigation. **James C. Beasley:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Helen L. Bontrager:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **David Broggio:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation. **Justin Brown:** Writing – review & editing, Project administration, Funding acquisition. **Michael E. Byrne:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Hannah C. Gerke:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hiroko Ishiniwa:** Writing – review & editing, Investigation. **Stacey L. Lance:** Writing – review & editing, Investigation, Funding acquisition. **Ole C. Lind:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Cara N. Love:** Writing – review & editing, Investigation, Formal analysis. **Hiroko Nagata:** Writing – review & editing, Project administration, Investigation. **Kenji Nanba:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Kei Okuda:** Writing – review & editing, Resources, Project administration, Methodology, Investigation. **Brit Salbu:** Writing – review & editing, Project administration, Investigation, Funding acquisition, Conceptualization. **Dmitry Shamovich:** Investigation, Methodology, Resources, Writing – review & editing. **Lavrans Skuterud:** Writing – review & editing, Investigation. **François Trompier:** Writing – review & editing, Methodology, Investigation, Data curation. **Sarah C. Webster:** Writing – review & editing, Investigation, Formal analysis. **Viachaslau Zabrotski:** Writing – review & editing, Resources, Project administration, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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