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Beresford, N. A.; Horemans, N.; Copplestone, D.; Raines, K. E.; Orizaola, G.; Wood, M. D.; Laanen, P.; Whitehead, H. C.; Burrows, J. E.; Tinsley, M. C.; Smith, J. T.; Bonzom, J. M.; Gagnaire, B.; Adam-Guillermin, C.; Gashchak, S.; Jha, A. N.; de, Menezes A; Willey, N.; Spurgeon, D.

Published in:
Journal of Environmental Radioactivity

DOI:
10.1016/j.jenvrad.2019.106033

Publication date:
2019

Citation for published version (APA):
Beresford, N. A., Horemans, N., Copplestone, D., Raines, K. E., Orizaola, G., Wood, M. D., Laanen, P., Whitehead, H. C., Burrows, J. E., Tinsley, M. C., Smith, J. T., Bonzom, J. M., Gagnaire, B., Adam-Guillermin, C., Gashchak, S., Jha, A. N., de, M. A., Willey, N., & Spurgeon, D. (2019). Towards solving a scientific controversy – The effects of ionising radiation on the environment. *Journal of Environmental Radioactivity*, *0*(0), 106033-106033. https://doi.org/10.1016/j.jenvrad.2019.106033

Towards solving a significant scientific controversy – the effects of ionising radiation on the environment

Background

Human use of radioactivity is increasing in fields such as nuclear power generation and nuclear medicine. Nuclear power continues to be a part of many countries' energy portfolios and may increase dramatically in some Asian countries and Russia, with up to 300 new reactors currently proposed; other countries without existing nuclear power programmes are beginning to develop them (e.g. some African nations and Persian Gulf states). Worldwide there are *c*.450 operating nuclear power plants (NPPs) and 60 under construction (World Nuclear Association 2019). The continued use of nuclear power is considered, by some, as essential in the transition to low-carbon economies (e.g. Liu et al. 2013). At the same time, many nations face having to develop long-term strategies, and consequent infrastructure, to manage high-level radioactive waste (as arising from nuclear power production); other nations are challenged with legacy issues associated with past and on-going uranium mining and processing.

However, 'nuclear' is not the only source of radionuclides released to the environment. Medical applications of ionising radiation represent the greatest man-made source of ionising radiation exposure to the public (Hoeschen 2018). Whilst the focus for medical radiation protection research is understandably on protection of workers and patients, the medical uses of radioisotopes result in releases of, often poorly studied, radionuclides to the environment. To ensure the safe operation of nuclear, medical and other facilities using radiation we need excellent and robust science on which we can base dose assessments. Issues around nuclear power and radiation have a high media profile often resulting in public concerns over safety and environmental impact.

The system for the protection of humans from ionising radiation is relatively well-developed (ICRP 2007). However, since *c*.2000, the International Commission on Radiological Protection's (ICRP) radiation protection framework has required demonstration of the protection of the environment (or wildlife) from radioactive releases (ICRP 2007). Many countries are now conducting assessments of the potential impact of radioactive releases on the environment (e.g. see Brown et al. 2016). Whilst there has been rapid development of appropriate radiological environmental impact assessment tools (e.g. Beresford et al. 2008a), the supporting science is still developing. Furthermore, there is considerable scientific disagreement on the extent of the impacts of radiation on wildlife in areas of Ukraine/Belarus and Japan contaminated by the Chernobyl and Fukushima reactor accidents respectively (e.g. Beresford, (Scott) et al. 2016, 2019a; Chesser & Baker 2006; Mousseau & Møller 2009, 2011; Smith 2019). Some studies conducted into the effects of the Chernobyl and Fukushima accidents report significant impacts of radiation on wildlife at extremely low dose rates. For instance, significant reductions in invertebrate numbers over dose rates which are in the typical range for natural background exposures (Møller & Mousseau 2009), and LD_{50} values (the lethal dose required to kill 50% of exposed individuals) for butterfly larvae (Hiyama et al., 2012) below the commonly used generic 'predicted no effect dose rate' of 10 µGy h^{-1} (Andersson et al. 2009; see discussion in Copplestone & Beresford 2014). If, such studies have been correctly conducted and interpreted, then the results would have implications for the system of radiation protection for both the environment and humans (Beresford & Copplestone 2011). Conversely, many studies have reported, the lack of substantial effects of radiation on wildlife in the Chernobyl Exclusion Zone (CEZ) (e.g. Chesser & Baker 2006; Deryabina et al. 2015; Murphy et al. 2011; Bonzom et al. 2016).

Many factors may contribute to the reported observations of effects at extremely low dose rates including: lack of consideration of internal exposure; failure to account properly for important (and in many instances) known confounding factors; residual influence of historic acute/high exposure; incorrect interpretation of statistical results (e.g. a statistically significant correlation does not necessarily imply causation especially if it explains little of the observed variation) (Gaschak 2016; Beaugelin-Sellier et al. 2019; Beresford Scott et al. 2019).

The scientific disagreement on the impacts of radiation in the CEZ and Fukushima impacted areas of Japan has a relatively high profile in the media; it has also been used to challenge the recommendations of international bodies/national regulators. Reports of effects at low exposure rates also have the potential to psychologically impact on human populations living in/near areas 'contaminated' by the Chernobyl and Fukushima accidents. The disagreement amongst radiation effects studies is undoubtedly radioecology's greatest controversy, and it must be addressed through robust and openly reported scientific research, including open sharing of expertise, open exchange of data sets and independent study replication.

This statement paper focusses on research needs with respect to the effects of radiation on the environment (identified needs for human focussed radiological protection research can be found elsewhere (Février et al. 2014; Salomaa 2016; ICRP 2017)). We emphasis the potential for learning from natural laboratories (namely field sites contaminated by the Chernobyl and Fukushima accidents), taking into account advances from two recent co-ordinated research programmes TREE (https://tree.ceh.ac.uk/) and STAR-COMET[1] (https://radioecology-exchange.org/).

International and national organisations have previously made recommendations on radiological research priorities in order to improve our knowledge on the effects of radiation on wildlife and on ecosystem processes (e.g. plant production, the degradation of dead organic matter, and elemental cycling), and better define environmental radiological assessment approaches (Hinton et al. 2013; Garnier-Laplace et al. 2018; Pentreath 2009; ICRP 2017). These previous recommendations can be broadly summarised as:

1. Improve the estimate of exposure through improved transfer and dosimetry models.
2. Investigate, and subsequently understand, dose-response relationships through studies under both laboratory and contaminated natural conditions (with the recommendation to make better use of contaminated areas, such as the Chernobyl Exclusion Zone (CEZ), to test hypotheses and models).
3. Provide data on radiation effects for key organisms (e.g. those providing the basis for the Reference Animals and Plants within the ICRPs proposed framework for the environment (ICRP 2009)) for which data are deficient or totally lacking.
4. Determine if there are differences between organisms in radiosensitivity (for similar endpoints) and establish the mechanisms for these differences.
5. Understand how radiation effects combine in a broader ecological context at higher levels of biological organisation (population dynamics, trophic interactions, indirect effects at the community level, and consequences for ecosystem functioning).
6. Investigate how other stressors influence the response to radiation.

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[1] The STAR and COMET projects were both funded under the EC EURATOM programme, involving largely the same organisations with COMET taking forward activities initiated by STAR.

7. Identify the prevalence and effects on sensitivity of any potential mechanisms underlying different multi-generational responses to long-term ecologically relevant exposures.
8. Develop relevant biomarkers for monitoring and evaluating effect levels that are explicitly linked to known mechanisms through which radiation exposures affect species.
9. Ensure that new capacity is both developed and maintained recognising the skills shortage in radiation protection and radioecology.

The STAR-COMET and TREE projects were large multi-institute programmes, in part designed to address these identified priorities. Independently reviewing the COMET and TREE projects, Thorne (2018) concluded that *'…programmes, such as COMET and TREE, have helped to avert a significant decrease in available expertise over the last ten years. Continued diligence and investment is required to ensure that this expertise is maintained in the future. Let us not wait for another major accident to serve as a reminder that radioecological expertise needs to be maintained*.' An overview of contributions to answering the scientific questions is given below.

Overview of recent activities

The CEZ was proposed by the European radioecological community as a 'radioecological observatory' (or natural laboratory) (Steiner et al. 2013), in part because contamination rates in some areas are such that we may anticipate observing radiation effects in wild organisms. Radioecological observatories are contaminated field sites that could provide a co-ordinated focus for long-term joint field investigations (Muikku et al. 2018). The TREE and COMET projects collaborated, establishing wider networks to extend the scope of their individual research and using common field sites within the CEZ. This productive collaboration demonstrated that the 'radioecological observatories' concept can be successful. Together, the TREE and COMET projects represent the largest co-ordinated study of the effects of radiation on wildlife conducted in the CEZ, with research considering a range of freshwater and terrestrial species, from plants to mammals.

The COMET and TREE projects have only recently finished, and although some studies have already been published (see publications lists on https://tree.ceh.ac.uk/content/tree-publications-and-datasets, https://radioecology-exchange.org/content/star-publications and https://radioecology-exchange.org/) and are cited within this article, data analyses are still on-going. However, the time is now appropriate to review the progress made by these projects against the previously identified priorities, and to highlight remaining research needs and the new questions raised.

Exposure

A criticism of many studies reporting effects on wildlife in the CEZ is that the estimation of exposure is poor (Beaugelin-Seiller et al. 2019; Beresford, Scott et al 2019). Many studies relate observations simply to dose rate readings from handheld dosimeters, with no consideration of internal exposure (e.g. Møller & Mousseau, 2009, 2013; Lehmann et al., 2016).

The estimation of radionuclide transfer to wildlife, and hence internal dose, is acknowledged to be a major uncertainty in environmental assessment (e.g. IAEA 2014; Beresford et al.

2008a). Most assessment models use a simple concentration ratio (CR) relating the activity concentration in an organism to that in the relevant media (typically soil and water for terrestrial and aquatic organisms respectively (IAEA 2014)). Concentration ratios are highly variable, with ranges over four orders of magnitude being common for a given organism-radionuclide combination (IAEA 2014); site-specific factors (e.g. soil or water chemistry) being a major contributor to this variation. Furthermore, for many organisms and/or radionuclides data are lacking.

The TREE and COMET projects collaborated in establishing an alternative approach based on taxonomic groupings (Beresford et al. 2013). This approach (i) gives a method of prediction which takes account of the effect of site, and (ii) offers an extrapolation methodology to provide predictions of activity concentrations for organisms for which data are lacking. The validations undertaken to date have shown the resultant transfer predictions to be better than those obtained using the CR approach for Cs and freshwater fish (Beresford et al 2013, 2016), and Sr, Cs, U, Pb and Se for terrestrial species (Søvik et al. 2017; Beresford & Willey 2019). However, whilst it was possible to apply this approach to the available data for marine species for Cs, validation against blind test datasets for a range of marine species revealed poor predictions (Brown et al. 2019); further work is required to determine the applicability of this approach to marine ecosystems.

Measuring activity concentrations in organisms is preferable to having to predict them. However, in many situations, it is undesirable to euthanize animals for laboratory analyses. Live-monitoring techniques have been widely used to determine the activity concentrations of gamma-emitting radionuclides such as ^{134,137}Cs and ^{131}I in live-animals (e.g. Meredith et al. 1988; Brynildsen & Strand 1994; Moss & Horrill 1996; Beresford et al. 1997). However, in the CEZ (or other contaminated sites) radionuclides other than gamma-emitters may contribute significantly to dose. To address this, a detector capable of measuring gamma-emitters and ^{90}Sr has been developed and applied in the CEZ (Fawkes 2018); unlike previous detectors capable of simultaneous gamma and beta measurements (Bondarkov et al. 2011), this new detector is fully portable making it suitable for use in the field.

Few studies have considered the validation of external dose rates predicted by assessment models (to our knowledge before the studies discussed here only Beresford et al. (2008b) had attempted to do this). Aramrum et al. 2018 evaluated different dosimeters that could be attached to free ranging animals and discussed their field application. A subsequent field study (with reindeer (*Rangifer tarandus tarandus*)) demonstrated that using knowledge of animal behaviour (in this case determined using GPS tracking) resulted in better predictions than simply assuming that the animals utilised all of the study area equally (Aramrum et al 2019). Hinton et al. (2015) describe the development of a combined Global Positioning System – electronic dosimeter capable of sending location and integrated dose measurements via satellite whilst fitted to study animals (the unit was successfully field-tested by mounting on a collar and fitting to wild pigs at the Savannah River Site (USA)).

Effects

Key to the work plans of many of the effect studies was to combine field and laboratory studies using the same organisms (e.g. Goodman 2019; Raines 2018), which enables tests of whether effects observed in the field are likely to be due to radiation rather than other known or potentially unmeasured covariates.

Key organisms

New radiation effects data were produced for previously poorly studied organisms. For example, invertebrates comprised less than 7% of low-dose radiation effects studies in the FREDERICA radiation effects database (Hingston et al. 2007); the recent studies considered a range of invertebrates including earthworms, bees, *Daphnia pulex*, *Asellus aquaticus* and *Caenorhabditis elegans*. In some cases, the species selected for study within the COMET and TREE projects were chosen as they aligned with the definition of the Reference Animals and Plants (RAPs) that are being used within the developing ICRP framework for radiological protection of the environment (ICRP 2009). Data obtained from studies on these species will be of value to develop further the ICRP system (ICRP 2017). Organisms representative of the RAPs which were studied included, bees (Raines 2008), earthworms (Newbold et al., submitted), frogs (Giraudeau et al. 2018; Gombeau et al. submitted) and pine trees (Volkova et al., 2018). In the case of bees, there were previously no effects data available (ICRP, 2009). By studying bumblebees, the TREE project has provided the first data to inform on the placement of derived consideration reference levels (DCRLs) for the ICRP RAP Bee (DCRLs are defined as "a band of dose rate within which there is likely to be some chance of deleterious effects of ionising radiation occurring to individuals of that type of RAP" (ICRP 2009)).

Recognising the general lack of transgenerational and multigenerational studies and their potential importance in understanding the impacts of long-term exposure in radiologically contaminated environments, some studies focussed on model organisms with well-defined genomes allowing complex genetic/epigenetic analyses. Species studied included *Arabidopsis thaliana* (Horemans et al. 2018; van de Walle et al. 2016; Caplin & Willey, 2018), *Daphnia pulex* (Goodman, 2019; Parisot et al. 2015), *Danio rerio* (Gombeau et al. 2017), *Caenorhabditis elegans* (Dutilleul et al. 2015). The short lifecycle of some of the selected species made them especially suited for conducting transgenerational and multigenerational effects studies.

Some of the studied species are present in both the Fukushima Exclusion Zone (FEZ) and the CEZ, enabling some studies to be conducted on the same/similar species at the two sites (e.g. Horemans et al. 2018). Many of the species also allowed comparative field and controlled laboratory studies.

Types of biological response

Prior to COMET and TREE projects, the Radioecology Strategic Research Agenda (SRA) (Février et al. 2014) identified the need to "mechanistically understand how processes link radiation induced effects in wildlife from molecular to individual levels of biological complexity". A mechanistic understanding of how organisms respond to radiation will help us to establish why species respond differently to radiation exposure. Consequently, several studies examined epigenetic and genetic changes in response to radiation exposure in different species.

In *Arabidopsis thaliana* sampled from the CEZ, genome-wide methylation decreased in response to increasing radiation dose rates (Horemans et al. 2018). Contrastingly, in the FEZ, there was no alteration to genome-wide methylation of another member of the same taxonimic (Brassicaceae) family, *Capsella bursa-pastoris* (Horemans et al. 2018). Amplified fragment length polymorphisms (AFLPs) measured in Scots Pine exposed to contamination after the

Chernobly accident revealed hyper-methylation of the irradiated pine genomes, but this was not associated with the annual dose received (Volkova et al. 2018). However, in a study of DNA methylation in earthworms also using an AFLP approach, no link between internal dose rate and DNA methylation status was found (Newbold et al submitted).

For tree frogs sampled in Fukushima, the absorbed total dose rate was estimated together with mitochondrial DNA damage and DNA methylation (Gombeau et al., submitted). Frogs from contaminated sites exhibited a dose dependent increase of global genomic DNA methylation level and of mitochondrial DNA damages. This result suggests that DNA methylation is involved in genomic instability, possibly providing a favorable ability to organisms to adapt to stressful environmental conditions.

Several reproductive parameters were measured in a range of freshwater organisms from the CEZ. No significant alterations to reproductive fitness were detected in fish species (*Rutilus rutilus* and *Perca fluviatilis*; Lerebours et al. 2018) and crustaceans (*Asellus aquaticus,* Fuller et al. 2018, *Daphnia pulex*, Goodman et al. 2019). A small reproductive response was seen in fish which was likely, but not conclusively, linked to radiation (Lerebours et al. 2018).

The CEZ as a multi-stressor environment?

It has previously been speculated that the CEZ may contain areas with high concentrations of some non-radioactive pollutants (with the implication that these may contribute to any observed effects). This speculation resulted from knowledge of materials used by fire fighters in response to the Chernobyl accident (e.g. 2500 t of Pb were dropped onto the burning reactor (National Report of Ukraine 2011)). However, a study conducted on a terrestrial site in the Red Forest, found levels of Pb in soil typical for European soils (Beresford et al. 2019b), which agrees with Jagoe et al. (1998) who found no elevated Pb (or Hg) concentrations in freshwater ecosystems close to the Chernobyl NPP. Hence, based on current evidence, it seems unlikely that there is widespread non-radiological contamination in the CEZ because of the accident. However, it is conceivable that due to industrial activities pre-1986, some areas of the CEZ may be polluted with historical non-radiological contaminants (Sharov et al. 2016).

However, organisms within the CEZ are likely exposed to a range of other stressors that are likely to be influencing reported relationships between exposure and 'effect'. For instance, the predominant soil in much of the CEZ, including the most contaminated areas, is sandy with implications for some species (e.g. such soil conditions are not favourable or earthworms (Newbold et al. submitted)). Similarly, habitat quality is poor in the more contaminated areas (Gaschak 2016; Beresford Scott et al. 2019) and large areas of the Red Forest (Earth's most radiologically contaminated terrestrial ecosystem) are prone to spring flooding. Perhaps unexpectedly, with respect to the Red Forest, which is the most contaminated terrestrial ecosystem, human disturbance is relatively high due to proximity to the nuclear power complex and access roads.

In July 2016, the Red Forest suffered a widespread fire affecting about 80% of its area. This presented a unique opportunity for studying the interaction between radiation and an additional stressor (fire) on ecosystem recovery (see https://www.ceh.ac.uk/redfire for details).

Future research questions

The effects of radiation on the environment, or wildlife, remains an area of considerable scientific disagreement with a high public profile. Recent studies, as outlined above, have significantly advanced our understanding of species-level radiation effects for a limited range of test organisms. There has been an assumption that extending/adapting the radiological protection framework for humans will suffice for protecting the environment. However, whilst frameworks for the environment and humans will be able to contain many similar elements there are important differences.

A step change in research is required to improve understanding of the effects of radiation on wildlife. In our view, there should be a focus on answering the following questions:

- *What are the key factors determining interspecies vulnerability to radiation?* Sensitive species may require special attention for monitoring and radioprotection. We need to develop a fundamental mechanistic understanding of why organisms respond differently to radiation exposure. In this context, we need to understand how the potential susceptibility to relevant molecular initiating events that trigger adverse outcome pathways (e.g. critical DNA damage) vary between species and how protective mechanisms (e.g. DNA repair mechanisms) in those species may attenuate such effects. This will help to define robust benchmark doses that are protective of all species. This is especially required as some recent research suggests that current international protection benchmarks may not be protective of all organism groups (Raines 2018). Differences in sensitivity between species also lie behind overall effects at higher levels (community, ecosystem), since interactions between species will be altered. Understanding the mechanisms of inter-species radiation sensitivity may also help us understand mechanisms behind intra-species variation.
- *What are the combined ecological effects of changes in developmental/reproductive endpoints of different species within an ecosystem?* The aim of environmental protection is generally to protect populations/communities. However, our knowledge is founded on responses of individuals to radiation exposure. Recent studies (ALLIANCE, on-line) demonstrate shifts in developmental and reproductive endpoints (e.g. flowering time or sexual maturity) due to radiation exposure. Although these shifts may appear minor when considered in isolation, their combined ecological effects may be significant (e.g., delayed production of pollinators and earlier flowering may mean no floral resources are available for pollinators). Here there is potential to learn from work done in the area of phenology in climate research in which researcher have sought to understand how species life-cycle dynamics may become uncoupled from the resources (e.g. food supply, nest sites, pollinators) on which they rely. Addressing this question would enable an evaluation of the potential impact of radiation on ecosystem function and the provision of goods and services provided by the environment of importance to humans.
- *What is the impact of previous 'acute' radiation exposure on organisms in contaminated environments now*? There are a number of studies reporting significant impacts of radiation on wildlife in the CEZ at relatively low dose rates (e.g. Aguileta et al. 2016; Bezrukov et al. 2015; Møller & Mousseau 2009, 2013, 2018; Morelli et al. 2018). However, in these studies, the effects of radiation on CEZ wildlife are often related to current, comparatively low, exposure levels. We hypothesise that such observations may, in part, result from acute historic exposures (Beresford, Scott et al.

2019a). For example, ecological changes in community structure may results in communities entering different stable states from which return to the original condition is impaired. Further, when chemicals interact with the epigenome there is increasing evidence that this can lead to heritable changes in properties such as DNA methylation status, histones and even microRNA expression than can results in modified physiological states in direct progeny (and even later) generations (Horemans et al. 2019). For radiation, we can (probably uniquely for a pollutant) reconstruct past exposures with some confidence. Consequently, it should be possible to test our hypothesis by combining field and laboratory studies with retrospective dose assessment.

- *What are the interactions between radiation and other stressors (both natural and anthropogenic)?* Ecotoxicology has been trying to answer the question of multi-contaminant/stressors for some years (Gilbin et al., 2015, Gagnaire et al. 2017). Radioactivity rarely occurs in isolation from other contaminants as well as abiotic and biotic stressors and we have little knowledge of their combined effects. To be able to assess the suitability of current regulations in a multi-contaminant/stressor environment, we need to address this lack of knowledge. For many species, the limits of tolerance for some types of stressors (e.g. soil pH, temperature ranges) are known. Measurements of potential stressors along with radioecological measurements may identify those cases in which radionuclide exposures coincide with other stressful conditions helping to identify those cases in which multiple stressor effects may need to be taken in to account.
- *Can biomarkers provide, non-lethal characterisation of stressor impacts?* There is growing interest in the use of biomarkers for non-lethal characterisation of exposure and impact. Radiation-specific biomarkers for environmentally relevant dose rates are lacking, but the community opinion is that biomarkers of impact (from multiple stressors) could be developed (Wood et al. submitted). Establishing relationships between non-lethal biomarker response and an effect of environmental protection relevance would provide powerful tools to underpin studies of intra-species variation in exposure response and multiple-stressor impacts. One way of describing the links between molecular initiation of the response and the observed adverse effects is through the formulation of an Adverse Outcome Pathway (AOP). The formulation of a radiation specific AOP will form a framework within which data and knowledge coming from different organisms, different levels of biological complexity and even multiple stressors are synthesised in a way that is useful for risk assessment (Ankley et al 2010); the key molecular events (which may include epigenetic change) of an AOP might serve as a potential biomarker. A radiation-related AOP for different organisms together with specific biomarkers could potentially be used in a regulatory setting, to verify the results of impact assessments for operational facilities.
- *Do organisms living in a radiologically contaminated environment become adapted to radiation across multiple generations*? Populations living in ecosystems where they are chronically exposed to stressors, including pollutants, may become adapted to these conditions through phenotypic plasticity and natural selection. The mechanisms involved in organism responses to chronic radiation exposure, both within and between generations, are the subject of an active debate in the scientific literature (e.g. Boubriak et al. 2016; Carroll et al. 2007; Goodman et al. 2019; Horemans et al. 2019). Whilst adaptation of organisms to radiation within the CEZ has been suggested (Møller &

Mousseau 2016; Boubriak et al. 2008), it has not yet been the focus of any comprehensive research programme. If it does occur, adaptation of specific populations could lead to adaptation of the ecosystem over time (e.g. the plant biome is thought to help plants cope with abiotic stress such as drought or salinity [REFERENCE - ALEX]). If adaptation to chronic radiation exposure exists in the CEZ, it will have implications for the interpretation of studies comparing current effect and exposure levels.

- *What are the effects of radiation on ecosystem functioning?* Studies have investigated the effects of ionising radiation on wildlife from subcellular to community levels in the CEZ (e.g. Beresford Scott et al. 2019) and increasingly the Fukushima region. However, the consequences of increased ionising radiation levels on key ecosystem processes such as plant production, the degradation of dead organic matter, and elemental cycling have received little attention.

The Chernobyl and Fukushima Exclusion Zones, and indeed other contaminated sites such as Kyshtym (Fesenko 2019), present large natural laboratories with spatially varying contamination levels. These locations provide an opportunity to conduct studies that help address the above questions. Future research should combine studies at contaminated field sites with controlled laboratory exposures of the same/similar organisms. Fukushima currently offers a useful comparator to Chernobyl, as it is a site more recently contaminated. To date, there have been no co-ordinated international research programmes focused on environmental effects in the Fukushima contaminated areas of Japan; to best exploit the unique scientific opportunity that Fukushima presents, the international community needs to act quickly before too much time passes.

To help address the lack of scientific consensus with respect to the effects of radiation in contaminated environments future studies should also set out to address hypothesis raised in papers reporting significant effects at in many instances extremely low dose rates.

As a final point, we reiterate the recommendation in Barnett & Welch (2016) that the underpinning data from radiation effects studies should be openly and freely available. Making data available is now a requirement of many journals and funders, but is not a practice rigorously followed. Making all of the data from radioecoloical studies openly available would represent a significant step towards understanding the disagreement on the magnitude of effects due to exposure to ionising radiation observed in both the CEZ and Fukushima areas by enabling independent re-evaluation. To this end, we have begun to openly publish all of the underlying data from our studies in the CEZ (see https://tree.ceh.ac.uk/content/tree-publications-and-datasets).

Acknowledgements

This statement paper originates following discussions held in March 2019 (https://www.ceh.ac.uk/news-and-media/blogs/what-are-effects-radiation-wildlife-discussing-results-chernobyl) between the TREE project participants and members of the European Radioecology ALLIANCE working group on ‘transgenerational effects and species radiosensitivity’ (https://radioecology-exchange.org/sites/default/files/T1_WG_for%20Radioecology%20Roadmap_Effects_Jan%202015.pdf).

The TREE project (www.ceh.ac.uk/TREE) was funded by the Natural Environment Research Council, the Environment Agency and Radioactive Waste Management Ltd.. Both the STAR and COMET projects (https://radioecology-exchange.org/) were supported by the EC EURATOM programme and respective national funders.

Thanks go to Cath Barnett (CEH Lancaster) for help in preparing this paper.

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Journal of Environmental Radioactivity xxx (xxxx) xxxx