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Population modelling to compare chronic external radiotoxicity between individual and population endpoints in four taxonomic groups

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ABSTRACT

In this study, we modelled population responses to chronic external gamma radiation in 12 laboratory species (including aquatic and soil invertebrates, fish and terrestrial mammals). Our aim was to compare radiosensitivity between individual and population endpoints and to examine how internationally proposed benchmarks for environmental radioprotection protected species against various risks at the population level. To do so, we used population matrix models, combining life history and chronic radiotoxicity data (derived from laboratory experiments and described in the literature and the FREDERICA database) to simulate changes in population endpoints (net reproductive rate R_0, asymptotic population growth rate λ, equilibrium population size N_{eq}) for a range of dose rates. Elasticity analyses of models showed that population responses differed depending on the affected individual endpoint (juvenile or adult survival, delay in maturity or reduction in fecundity), the considered population endpoint (R_0, λ or N_{eq}) and the life history of the studied species. Among population endpoints, net reproductive rate R_0 showed the lowest EDR_{10} (effective dose rate inducing 10% effect) in all species, with values ranging from 26 μGy h^{-1} in the mouse *Mus musculus* to 38,000 μGy h^{-1} in the fish *Oryzias latipes*. For several species, EDR_{10} for population endpoints were lower than the lowest EDR_{10} for individual endpoints. Various population level risks, differing in severity for the population, were investigated. Population extinction (predicted when radiation effects caused population growth rate λ to decrease below 1, indicating that no population growth in the long term) was predicted for dose rates ranging from 2700 μGy h^{-1} in fish to 12,000 μGy h^{-1} in soil invertebrates. A milder risk, that population growth rate λ will be reduced by 10% of the reduction causing extinction, was predicted for dose rates ranging from 24 μGy h^{-1} in mammals to 1800 μGy h^{-1} in soil invertebrates. These predictions suggested that proposed reference benchmarks from the literature for different taxonomic groups protected all simulated species against population extinction. A generic reference benchmark of 10 μGy h^{-1} protected all simulated species against 10% of the effect causing population extinction. Finally, a risk of pseudo-extinction was predicted from 2.0 μGy h^{-1} in mammals to 970 μGy h^{-1} in soil invertebrates, representing a slight but statistically significant population decline, the importance of which remains to be evaluated in natural settings.

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1. Introduction

Over the last decade, the protection of non-human biota from ionizing radiation has become a major public, regulatory and scientific concern at an international level. As a consequence, a number of national and international bodies have developed frameworks, recommendations and safety principles (IAEA , 2006; ICRP, 2007) in order to provide guidance for evaluating whether the environment is protected from the effects of ionising radiation and defining ecological protection criteria (ICRP, 2008; UNSCEAR, 2008). As part of the international effort, the suite of EC-funded projects FASSET (Williams, 2004), ERICA (Larsson, 2008) and PROTECT (Howard et al., 2010) agreed on the use of Environmental Risk Assessment (ERA) methodologies, similar to those adopted for chemical substances (e.g., EC, 2003, 2011). ERAs aim to estimate environmental risk, i.e. the probability and magnitude of adverse effects that occur in exposed biota at different levels of biological organisation (individuals, populations, communities, ecosystems) for many wildlife groups. The adopted method included a meta-analysis of chronic radiation effects from controlled laboratory toxicity tests, followed by the plot of lowest per species EDR_{10} (effective dose rate inducing 10% effect on tested endpoints, equivalent to EC_{10} for chemicals) for a range of dose rates. This accepted ERA approach was used to derive a generic Predicted No-Effect Dose Rate (*PNEDR*, equivalent to *PNEC* for chemicals) for ecosystem radiological protection of 10 μGy h^{-1} (in addition to the natural background of 10 μGy h^{-1}) (Beresford et al., 2008; Andersson et al., 2009; Garnier-Laplace et al., 2010; Hosseini et al., 2010).

There is a major discrepancy between traditional ERA methods, based on toxicity data, most often measured at the individual level in a limited number of test species, and the recommended goal for environmental radioprotection: to ensure ecosystem function by protecting the sustainability at the population level of the vast majority of all species (with special attention given to keystone, foundation, rare, protected or culturally significant species) (Andersson et al., 2009; Bradshaw et al., 2014). However, the potential effects of chemical or radioactive contaminants are poorly documented at the population level and for species in the field. Environmental risk assessors therefore rely on extrapolations of chemo- or radio-toxicity from laboratory tests to natural field conditions. In order to take account of the numerous assumptions and uncertainties underlying these extrapolations and incorporate some level of precaution in ERA, the European guidance (EC, 2011) recommends dividing the *PNEC* or *PNEDR* value derived from individual level radiotoxicity data by a safety factor. Recommended values for safety factors vary from 10,000 to 1 depending on the quality and quantity of toxicity data (acute or chronic tests, number of tested species, number of represented trophic levels etc.). Several studies have shown that extrapolating environmental risks based on safety factors is a major source of uncertainty in ERA, leading to either under- or over-estimated risks (Forbes et al., 2001). In environmental radioprotection, a comparative study of radiotoxicity data between laboratory tests and the Chernobyl exclusion zone suggested that *PNEDR* values might differ by more than one order of magnitude between controlled experimental and natural field conditions (Garnier-Laplace et al., 2013).

In order to reduce the uncertainty in ERA and its associated conservatism, an increasing number of studies have suggested applying population models of representative wildlife species to investigate population responses to toxic contaminants, including chemicals such as pesticides (Forbes and Calow, 2002; Stark et al., 2004; Hanson and Stark, 2011; Ibrahim et al., 2014) and more recently, radionuclides and ionising radiation (Alonzo et al., 2008a,b; Biron et al., 2012; Lance et al., 2012). One of the objectives of these studies was to mathematically extrapolate experimentally observed toxic effects from the individual level to the population level in order to test whether populations were more sensitive to toxicity than organisms. Approaches commonly involved: 1) a review of toxic effects induced by the assessed chemical or radiological contaminant, as measured in laboratory tests or in the field, and 2) a modelling exercise simulating population dynamics in species of interest, assuming that population responses to pollution should depend both on how key biological functions, including survival and reproduction, are affected by toxicity and how population dynamics respond to changes in these biological functions. Predictions from simple population models suggested that individual level effects might have widely different consequences for populations depending on which endpoint was affected at the individual level, which endpoint was simulated at the population level, and which species was considered (Stark et al., 2004; Raimondo et al., 2006). These predictions contradicted one of the major asumptions in ERA, that toxicity estimates at the individual level, such as EDR_{10}, might have comparable consequences at the population level, and could be directly compared among different endpoints and among different species.

As part of the research conducted during STAR (Strategy for Allied Radioecology, the EC-funded Network of Excellence in Radioecology), population modelling was carried out for aquatic invertebrates exposed to chronic gamma radiation (Lance et al., 2012), using matrix models known as Leslie matrices (Caswell, 2001). Simulations suggested the hypothesis that in some species, population level endpoints might be more radiosensitive than individual level endpoints (for example when population response resulted from simultaneous effects affecting several individual level endpoints). The present study aimed to test this hypothesis on a wider range of animal species. Selected species were those for which laboratory-based chronic external radiotoxicity data were available from FREDERICA, a database which compiles primary data on effects of ionising radiation on mortality, reproduction, mutation and morbidity in 16 wildlife groups (Copplestone et al., 2008). Following the approach applied in aquatic invertebrates (Lance et al., 2012), we simulated changes in individual and population endpoints for a range of dose rates in twelve animal species (including aquatic and soil invertebrates, fish and terrestrial mammals). The objectives were to use these exploratory models: 1) to identify the critical individual-level endpoints that had the strongest influence on population dynamics; 2) to compare radiosensitivity between individual and population endpoints; 3) to examine whether internationally proposed benchmarks for environmental radioprotection, which are based on individual-level endpoints, protect species at the population level.

2. Materials and methods

2.1. Species selection

The primary focus was given to species for which chronic radiation effect data on survival, fecundity and/or hatching were available from the FREDERICA database (Copplestone et al., 2008). Many radiation effect data found in FREDERICA were not used, such as genetic, biochemical or histological damages which are too complex to extrapolate to a population response (Lance et al., 2012). The twelve selected species (Table 1) covered four taxonomic groups including aquatic invertebrates (two marine polychaete worms, *Neanthes arenaceodentata* and *Ophryotrocha diadema*, and a freshwater gastropod, *Physa heterostropha*), soil invertebrates (two earthworm species, *Eisenia fetida* and *Lumbricus terrestris*, and the common woodlouse *Porcellio scaber*), fish (Japanese medaka *Oryzias latipes*, the guppy *Poecilia reticulata* and the