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INTERNATIONAL VIEWPOINTS ON ENVIRONMENTAL PROTECTION: GOALS AND METHODS

Paul A. Johnston, Simon Carroll, Angela D. Stephenson
Ruth L. Stringer & David Santillo
Greenpeace Research Laboratories, University of Exeter, EX4 4QE, UK.

Abstract

Environmental protection of natural ecosystems against the effects of radiation has been largely predicated upon human radiological protection regimes. It has been explicitly assumed that if human populations are adequately protected then this will also confer protection to other species at the population level and hence to the "environment".

Accordingly, non-human organisms have principally been incorporated into regulatory and assessment frameworks in recognition of their role as part of diverse critical pathways of radionuclide transfer to human populations. Hence, the utility of these non-human organisms in assessing hazards to ecosystems is strictly limited since their selection for monitoring purposes relates more to human perspectives than to their role and importance in natural ecosystems.

By contrast, a multispecies ecosystem level approach should work on the basis of selecting "keystone" species and evaluating the effects of radiation upon natural ecosystem dynamics. This would accommodate the full range of sub-lethal effects, differential life-stage sensitivity, reproductive sensitivity and interspecific interactions.

While such an approach would undoubtedly improve the current situation, experience from chemical ecotoxicology suggests that the selection and verification of suitable endpoints will prove difficult beyond an organismal level. Thus, a regulatory regime based upon this approach is almost certain to be less than effective at protecting the environment.

The precautionary approach to environmental protection has largely grown from an awareness of the limitations of ecotoxicological studies and protocols. This paper, therefore, considers the need for application of such an approach in relation to environmental protection requirements of the nuclear industry.

Introduction

The discovery of natural radioactivity by Henri Becquerel in 1896 was followed by the generation of artificial radionuclides in 1934 by Frederic Joliot. Boron and aluminium were bombarded with alpha-particles to produce ^{13}N and ^{30}P. Subsequently, researchers began to investigate the products of bombarding a range of elements of the periodic table with accelerated protons, deuterons and alpha-particles. Some 2600 nuclides are now known, comprising 260 stable nuclides, 25 very long-lived naturally occurring radionuclides and more than 2300 man-made radionuclides. The artificial radionuclides have half lives ranging from micro-seconds and less to tens of thousands of years. Indeed, the vast majority of artificial nuclides are extremely short-lived [1].

There is little doubt that the greatest input of artificial radionuclides into the natural environment has taken place through the atmospheric testing of nuclear weapons. Much of this activity has been distributed relatively evenly throughout the global environment. The second most important contributor has been the nuclear fuel cycle, including fabrication of fuel elements, the generation of nuclear power and, in particular, the reprocessing of spent fuel elements [2].

From the outset, considerable efforts were made to harness the perceived benefits of ionising radiation in clinical applications [3] while at the same time, as a result of these endeavours, the harmful characteristics also became apparent [4]. The focus upon clinical applications seems to have led to a uniquely anthropocentric view of radiation hazards as compared to the hazards posed by what may be termed "conventional" chemical toxins. Indeed, the rationale that addressing human health concerns will, of itself, confer protection upon the wider environment has long been discredited as a premise in ecotoxicology where the discipline evolved separately from occupational hygiene. Indeed the only area where this philosophy overtly persists is in the regulation of radionuclides [5].

In other fields of environmental research it has been recognised that numerous factors need to be taken into account which may not be immediately obvious from considering the human health aspects alone. These include the greater sensitivity of organisms other than humans to a given exposure, the lack of ecosystem analogues of many human responses and the converse, potentially more intense exposures within natural ecosystems. and the greater degree to which non-human organisms are coupled to their environment [6].

Recently it seems that the limitations and dangers of this approach to radioprotection on the one hand, and radioecology on the other, have become more widely recognised. This has led to calls for more specific radiological protection criteria for natural populations of organisms [7,8,9]. The underlying assumptions on which current practice is predicated have been exposed as being based upon limited information or, indeed, to be unjustified in terms of the degree of environmental coupling experienced by natural populations in impacted areas. Nonetheless, implicit in these discussions is the notion that, while the philosophy itself needs to evolve, no actual instances in which it has failed to protect natural communities have to date been observed or identified.

The asserted lack of damage to natural populations is highly questionable given existing, though rare, comparative assessments of radiosensitivity [10]. Be this as it may, there is no doubt that a more sophisticated approach is required as focus inevitably shifts from the impacts of the diffuse exposures caused by weapons testing. The various phases of the nuclear power industry result in much more localised impacts from defined point sources and this has far reaching implications for the way in which environmental radio-protection is achieved. In addition, a new paradigm of radio-protection needs to be formulated to accommodate changing moral and ethical views of general environmental protection.

Despite being one of the earliest disciplines to engage in the elucidation of dose/response relationships, radioecology has fallen far behind other fields of science in its approach to environmental protection. This paper, therefore, outlines those areas where radioecology could profitably draw examples from the developments forged and limitations experienced in the field of chemical ecotoxicology. It discusses how some of these could be used in the development of a more robust strategy for radioprotection of natural communities and ecosystems.

Some Failures of the Anthropocentric Paradigm

Current approaches to the regulation of artificial radionuclides in the environment are exemplified by one of the series of reports produced by the UK Ministry of Agriculture Fisheries and Food. In this, the results of monitoring environmental samples are interpreted in terms of radiation exposures to the public. The procedure involves the identification of critical groups. These may be consumers of fish and shellfish, or those who spend time in contact with contaminated sediments including house-boat dwellers, fishermen handling contaminated gear, anglers and wildfowlers. The likely cumulative exposures are then expressed as a committed dose equivalent. This effective dose is compared to a maximum dose limit to the public of 1mSv per year in the UK.

The MAFF reports simply do not explore the significance of the non-human components of the ecosystem. Moreover, a majority of the studies reported in the peer reviewed literature address mechanistic aspects of impacts upon human food chains, transfer of radionuclides between environmental compartments or simple reporting of radionuclide contamination levels [13-19]. This situation is not helped by definitions which seek to exclude effects of radiation on ecological systems from the discipline of radioecology. Such definitions [20] constrain these aspects within a field of research named radiation ecology. This seems a somewhat artificial divide and one which has done little to advance understanding of impacts of radiation upon natural systems.

The failure of this paradigm in wider environmental terms becomes apparent when actual doses of radiation, evaluated in a conventional manner, are estimated for wildlife populations. For instance, black-headed gulls at Ravenglass near Sellafield were estimated to be exposed to an effective whole-body dose of 2.8mSv over the 120 day period that they are resident in the estuary. To put such figures in the context of human body burdens, median whole body levels of ^{137}Cs of 300 members of the public were found to be around 90Bq which approximates to around 3 Bq/kg of muscle using a conversion factor for muscle mass [21]. The highest reported whole body burden reported [22] was 4350 Bq which approximates to 124 Bq/kg assuming a 70kg total body weight of which 50% is muscle. Levels of around 200-600Bq/kg of ^{137}Cs were found in skeletal muscle of birds from Ravenglass [23].

Significantly, measurements in other species of birds in Ravenglass have shown that some species such as shelduck, curlew, oystercatcher, bar-tailed godwit and mallard are contaminated with ^{137}Cs at levels between 10-60 fold higher than in black-headed gulls. This may reflect differences in feeding habits, given that gulls will feed offshore whereas the other species feed in close contact with contaminated, shallow water sediments. Indeed, elevated levels of radionuclides have been reported for a number of key invertebrates food species in the Ravenglass Estuary [23]. Alternatively, these species of birds may simply spend longer periods at Ravenglass than black-headed gulls thereby increasing their exposure. Although its has been claimed that the population as a whole is not deleteriously affected, it is difficult to see how this conclusion has been reached in the absence of baseline data.

Marine mammals could also face extreme high exposures to radiation because their diet consists entirely of fish. There has been little or no monitoring of radiation in marine mammals close to Sellafield. However, it has been calculated that the potential dose to grey seals (*Halichoerus grypus*) could be as high as 36 mSv per year [24]. Monitoring grey seals alone would not be adequate to assess the risks to marine mammals due to interspecific differences. Common seals (*Phoca vitulina*), for example, are likely to be at greater risk because their more restricted feeding patterns than those of grey seals, which may travel considerable distances to feed. A further complication arises from the assumption that radioactive contaminants and their effects will be evenly distributed in the body mass of contaminated animals. That this is a highly unlikely assumption is illustrated by the well known specific human radiosensitivity of particular organs in humans and the organ specific absorbed doses after administration of radiopharmaceuticals [1].

Monitoring of fish and shellfish as a component of programmes investigating potential human exposure have clearly shown wide interspecific differences in accumulated radionuclides. For example, levels of ^{137}Cs in shellfish in Sellafield coastal waters in 1990 were in the range 8-25 Bq/kg while in fish the mean was 37 Bq/kg. In the case of $^{239/240}Pu$ the difference is reversed and more dramatic. Shellfish, such as winkles, mussels and limpets, carry a burden around 200-300 times greater than plaice and cod. $^{239/240}Pu$ levels were 19 Bq/kg in limpets compared to 0.049 Bq/kg in cod caught in the Sellafield coastal area during 1990 [25]. These elements when ingested are capable of inflicting greater damage due to their alpha and beta emissions. A concentration factor of over 2000 has been determined for isotopes of technetium, discharged from both Cap-la-Hague and Sellafield, in the lobster *(Homarus gammarus)*. The whole body concentration factor of plutonium in lobster was found to be about 250, but the assessment is complicated by the periodic moult which these animals undergo and the fact that they eat discarded exoskeletons [26]. Most of the plutonium is retained in the digestive organs of the animal, leading to an uneven dose distribution and serious underestimation of organ-specific exposure through use of the whole body concentration factor.

Twelve species of marine invertebrates have also been comparatively examined in the Ravenglass estuary [23]. Unsurprisingly, elevated levels of nuclides were found in all invertebrates sampled, with particularly high levels in the annelid worm *Nereis diversicolor*, gastropod molluscs *Hydrobia ulvae* and, *Littorina littorea* and the bivalve

Scrobicularia plana. These are all important avian food resources. "Hot particles" have been found in winkles analysed for alpha particle activity suggesting that effects of radioactivity could be concentrated in specific organ systems of these animals [12] rather than over the whole body.

In addition, many species of invertebrate regulate both essential and non- essential metallic elements. This regulation takes a number of forms, ranging from metal binding by proteins to the immobilisation of the metals into phosphate rich granules within the cell. In some cases these metal rich granules may be excreted, in others they may simply be stored and hence, can be ingested by predators when the invertebrate is taken as food [27, 28]. Radiotracers used in the experimental work to investigate such phenomena show that radionuclides can behave in exactly the same way [29]. The effects of these granules as localised point sources in either the invertebrates themselves or their consumers has not been investigated.

Work carried out in the Baltic has shown that natural radionuclides may also be significantly bioconcentrated. Concentration factors range from 0.5 for fish muscle to 60 for the soft tissues of molluscs in the case of uranium. Concentration factors for thorium ranged from 10 in fish muscle to 1200 in crustacea [30]. ^{210}Po is found to be accumulated particularly strongly by fish [31] with accumulation factors in cod, herring and flounder of 36,000, 13,000 and 7,000 respectively. ^{210}Po is accumulated by marine zooplankton with a concentration factor between 5,000 and 42,000 relative to concentrations in seawater [32] and also variably accumulated in benthic invertebrates [33].

Industries other than nuclear power generation may also have a significant localised impact on radionuclide levels in the environment. For example, the potential effect of bulk processing of phosphate rock is indicated by a sample of edible winkles taken in the vicinity of a discharge in Cumbria. This was found to contain 251.3 Bq/kg of polonium-210 as compared to around 7Bq/kg in samples taken from the UK east coast [24]. Incidentally, on the basis of estimated consumption rates, a dose rate to human consumers of 0.28mSv/year could result from the consumption of crab and molluscs collected from the vicinity of the plant. This is almost one third of the recommended annual dose rate of 1mSv/year. In these cases the actual form in which these elements are accumulated remains unknown.

It is quite clear, moreover, that the radioactive half life of these elements needs to be considered in association with their biological half lives and general ecological half-lives. In general the physical half life is greater than the other parameters. Biological halflife and ecological halflife may vary considerably according to the species and ecosystems involved. For example, research in the US has determined that Cs-137 with a physical half life of 30 years may have a biological half life ranging from 5.6 days in ducks to 902 days in snakes. Ecosystem half life was found to vary between 1.9 years to greater than 20 years in two species of bird [34]. It is not possible to extrapolate from observations on the behaviour of isotopes in one species to estimate behaviour in unrelated species nor to similar species in different habitats. Finally, many of the assumptions made in radioecology have been overturned or at least undermined by research conducted in the aftermath of the Chernobyl explosion [35], particularly in relation to biogeochemical cycling of radionuclides and their radiological effects upon natural ecosytems.

These limited examples illustrate the fact that the anthropocentric paradigm cannot be readily applied to the protection of populations of non-human organisms in the natural environment. It is clear that radiation exposures and their relative impacts in natural systems may be largely unpredictable. Notwithstanding this, as recently as 1992 the IAEA felt confident in reasserting the principle of radioprotection of natural ecosystems on exactly this basis [36]. By accommodating some of the points outlined above, the Agency might well have recognised that assessment of effects within real biological systems is subject to the same limitations as have been encountered in chemical toxicology.

Detection of Effects

Recently, the limits of human epidemiology have been the focus of much debate [37]. The point has been made that the sensitivity of such analyses in detecting deleterious impacts is contingent upon the methodology used to gather data and subsequently to analyse it. In the field of radioprotection, similar uncertainties are attached to risk estimates derived from epidemiological studies carried out on survivors of the Japanese atomic bombs [38]. The situation has a parallel in our uncertainties concerning natural ecosystems where most published reports (up to 90%) address only acute exposures to radiation [39]. Coupled with a focus on reproduction as the most sensitive radiological endpoint, predictions of population impacts on this restrictive basis [40] are not likely to be robust particularly when dealing with long term low level exposures.

In the field of ecological risk assessment, the selection of appropriate assessment endpoints is considered to be a critical limitation in the power of such procedures. The search for suitable endpoints in the toxicity test procedures applied in hazard assessment and subject to iterative verification has provoked much discussion in the literature [41]. Unsurprisingly, this discussion has extended into ecological risk assessment. An excellent overview of the subject of ecotoxicological endpoints has recently been published [42]. This distinguishes the substantial difference between endpoints derived from toxicity tests (such as LC50 values) and assessment endpoints. Assessment endpoints nearly always refer to effects upon higher levels of ecosystemic organisation and over larger spatial and time frames in comparison to the most sophisticated simulated systems used in tests.

The point is made that ecosystem interactions are both subtle and complex. Extrapolation from test endpoints to predict ecosystem effects may be valid under certain limited circumstances. Generally, however, constraints exist which limit the predictive power of test endpoints. These constraints, or the way in which they operate may differ markedly in a simulated ecosystem with respect to real-world systems.

The endpoints themselves fall into four broad categories. Sub-organismal endpoints involve biochemical, physiological or histological parameters, referred to as biomarkers. Although important, they are not usually of interest to environmental managers in themselves and, moreover, there are few predictive models capable of using such data as input. Organismal assessment endpoints which measure death, lifespan, reproductive vigour or behavioural responses are most often inferred from standard toxicity test data and cannot predict ecosystem effects. Population responses are favoured by environmental managers but toxicity tests are rarely designed to generate population level data. These parameters are relatively non-specific with regard to chemical agents. Nonetheless population level responses are frequently used to assess responses at the next level of organisation: whole ecosystems.

Assessment of ecosystems is fraught with difficulties since both assessment and test endpoints are extremely difficult to define. For example, impacts upon widely dispersed species, with low species number and a low reproductive rate are likely to be of greater significance, but are also the most difficult to detect. Hence, a general strategy is to select ecosystem endpoints on the basis of management goals. These are largely a matter of, at best, perception. Inevitably, the historical use of such endpoints in assessment of ecosystems has been simplistic. There is no realistic way of assigning causality by using what can be described as ecological epidemiology. With each layer of ecosystem organisation, therefore, there is a progressive move away from endpoints which have utility in the assignment of causality. The difficulties of establishing causality in both populations of humans and other organisms mean that there is a high degree of uncertainty in any predictions made and hence in determination and management of risks. These are common considerations in both ecotoxicology and radioecology.

In situations where an assessment endpoint is designated for managerial purposes, the conclusions reached concerning impact may vary according to the statistical techniques used to analyse the data. A recent highly illustrative example has emerged from the study of population studies of marine impacts of offshore oil installations. The use of more sensitive multivariate analytical techniques employed were able to detect an impact zone of 27 km^2 around each rig. This compares to the 3 km^2 impact zone resolved in previous studies. Interestingly, each North sea oil rig is reputed to discharge around 12 GBq y^{-1} of natural radionuclides with production waters [44]. Certainly, radionuclide redeposition in pipe scale has been known as a potential radiation hazard in the North Sea since 1981 [45]. Radiation measurements on production piping ranged between 0.01 microSv/h to 0.01 milliSv/h. The impact of these radionuclides in benthic environments is largely unknown and therefore their contribution to the observed impact cannot be evaluated.

Regulatory Response to Uncertainty and Failure

Subsequent to the 1987 North Sea Ministerial Declaration (1984), recognising some of the uncertainties of chemical ecology, an increasing number of Treaties and Conventions have adopted a precautionary approach to environmental protection from chemical and radioactive emissions. Examples include the Paris Convention (1992), the Helsinki Convention (1992) and the Barcelona Convention (1976). The London Convention (1972) regulates, and has banned, the dumping of radioactive wastes at sea. A significant exception has been the Convention on Nuclear Safety (1994) which in any case does not cover the disposal of radioactive wastes. A recent useful analysis of the precautionary approach in relation to the nuclear industry [46] considers that lack of certainty should not prevent regulation. Another discussion, also published by the IAEA couches the idea of precautionary strategy in terms of "acceptable" harm but highlights the problems of developing indices of actual impact [47].

In both cases above, the key uncertainty is associated with the question of whether radioecological impacts are already occurring at the population level in non-human species. Regional to global distribution of artificial radionuclides results from discharges of radioelements. Accordingly, application of the precautionary approach in a radioecological sense implies the wholesale reduction of discharges of radioactivity, an approach adopted in chemical regulation. Such an approach should be made explicit in the provisions of both the Convention on Nuclear Safety and the emerging Convention on the Safety of Radioactive Waste Management. A key element in reduction strategy must be the restriction and cessation of reprocessing activities as a priority since these are by far the most significant point sources and therefore the emissions to which the greatest magnitude of uncertainty is attached.

The acknowledgement that there is a need to bring about the wholesale reduction and elimination of radioactive emissions can also be found in the principles for the safe management of radioactive waste approved by the IAEA Board of Governors in early 1995 [48]. The IAEA, following the precedents set by many of the international and regional fora noted above, recognizes now that it is necessary to keep the releases from the various waste management steps to the minimum practicable and that the preferred approach to radioactive waste management is concentration and containment rather than dilution and dispersion. The only question remaining now is whether and to what extent the industry and its regulators will respond.

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