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3.10 RADIOECOLOGICAL SENSITIVITY

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ABSTRACT

After the release of radionuclides into the environment it is important to be able to readily identify major routes of radiation exposure, the most highly exposed individuals or populations and the geographical areas of most concern. Radioecological sensitivity can be broadly defined as the extent to which an ecosystem contributes to an enhanced radiation exposure to Man and biota. Radioecological sensitivity analysis integrates current knowledge on pathways, spatially attributes the underlying processes determining transfer and thereby identifies the most radioecologically sensitive areas leading to high radiation exposure. This identifies where high exposure may occur and why. A framework for the estimation of radioecological sensitivity with respect to humans is proposed and the various indicators by which it can be considered have been identified. These are (i) aggregated transfer coefficients (Tag), (ii) action (and critical) loads, (iii) fluxes and (iv) individual exposure of humans. The importance of spatial and temporal consideration of all these outputs is emphasized. Information on the extent of radionuclide transfer and exposure to humans at different spatial scales is needed to reflect the spatial differences which can occur. Single values for large areas, such as countries, can often mask large variation within the country. Similarly, the relative importance of different pathways can change with time and therefore assessments of radiological sensitivity are needed over different time periods after contamination. Radioecological sensitivity analysis can be used in radiation protection, nuclear safety and emergency preparedness when there is a need to identify areas that have the potential of being of particular concern from a risk perspective. Prior identification of radioecologically sensitive areas and exposed individuals should improve the focus of emergency preparedness and planning, and contribute to environmental impact assessment for future facilities. The concept of radioecological sensitivity should now be extended to a consideration of doses to biota.

KEY WORDS: Spatial / temporal variability, emergency, sensitivity

1. INTRODUCTION

Certain components of ecosystems can accumulate large amounts of radionuclides. The extent of variation depends upon the radionuclide and the type of ecosystem. For some radionuclides (especially Cs, Sr and I isotopes), there is now a good understanding of the underlying environmental factors leading to high exposure of humans and also improved information on variation in dietary and social habits. This enables an improvement in the identification of critical groups and quantification of the extent of their exposure. Furthermore, many factors leading to high exposure can vary both spatially and temporally, and that this can be important in determining individual doses. Many post Chernobyl studies have demonstrated that the highest exposures do not necessarily coincide with the most contaminated areas, especially in the mid-long term after an accident.

A consideration of time and space can therefore help to identify not only the key exposure routes and associated critical groups, but also the locations where high exposure will occur and where it will be sustained for longer periods of time. These analyses have been facilitated by the increasing use of Geographical Information Systems (GIS) combining dynamic models with spatially varying information. This has, in turn, prompted a reconsideration of the concept of radioecological sensitivity, which was first proposed by Aarkrog [1] who defines Radioecological Sensitivity as:

> "... the infinite time-integrated radionuclide concentration in the environmental sample considered, arising from a deposition of 1 mCi km^{-2} of the radionuclide in question".

This definition is further elaborated as follows:

> "The radioecological sensitivity of a sample is the infinite time integral of appropriate quantities of the sample from an appropriate quantity of the radionuclide deposited. The radioecological sensitivity equals the steady state concentration in the sample of the radionuclide considered from a constant annual deposition rate of the radionuclide distributed like global fallout throughout the year."

Aarkrog thus focused on radioecological sensitivity with respect to the transfer of radionuclides from deposition to the environmental sample. In this paper, we present some of the conclusions of an EC concerted action which reconsidered radioecological sensitivity with respect to the exposure to radiation of humans [2].

2. RADIOECOLOGICAL SENSITIVITY AND EXPOSURE PATHWAYS

There is often considerable variability in radiation doses, arising from both routine and accidental releases of radioactivity. Therefore, radioecological sensitivity analysis should ideally involve the application of different methods of identifying processes or factors which lead to high radiation exposure, especially with regard to spatial and temporal variation. It should identify where high exposure may occur and why. Single food products or species can be considered, or a number of key parameters to identify areas where sensitive pathways may occur together.

Thus radioecological sensitivity should be considered from a broad perspective because many different factors can influence the rate of exposure. Some factors are generically applicable to all radioactive contaminants whereas others would be relatively more important for just a few radionuclides. An ecosystem can be considered as radioecologically sensitive if it retains radionuclides for a long time in an available form to either Man or other biota. It may also act as a secondary source, disseminating radionuclides to surrounding ecosystems. Radioecological sensitivity can thus be broadly defined as the extent to which an ecosystem contributes to an enhanced radiation exposure to Man and biota.

Enhanced exposure can arise if (i) an ecosystem collects and retains more contamination (high biomass concentration, high precipitation rates, proximity to nuclear sources, ..) (ii) bioavailability is high in the affected ecosystem (iii) long retention times enhances external exposure to Man and biota. Human habits such as dietary habits, occupancy and agricultural practices may also enhance exposure.

Radioecological sensitivity is a very general term, which can be considered from a wide range of different perspectives. For most pollutants, sensitivity is assessed as the effects of pollutant input on various aspects of ecological functioning such as biochemical, physiological, morphological and behavioural responses. In radiation protection terms, the primary aim has been to provide an appropriate standard of protection to humans as the final receptor of the radioactive pollutant. Therefore, the focus of sensitivity analysis is different, but still takes into account the behaviour/transfer of the pollutant via different compartments of the ecosystem which lead finally to doses to humans.

Radioecological sensitivity in ecosystems could be considered with respect to internal and external exposure. The focus here is on radioecological sensitivity with respect to ingestion dose, but the criteria considered could also be relevant to the other exposure routes.

3. QUANTIFICATION OF RADIOECOLOGICAL SENSITIVITY

Methods of quantifying radioecological sensitivity are summarised in Figure 1. Even though the concept is applicable to all types of contamination and ecosystem, we have mainly considered atmospheric deposition onto largely terrestrial ecosystems as a contamination pathway although aquatic systems have been considered in the report [2] and are briefly mentioned here. Four quantities were identified, three of which have been commonly used in radioecology or radiation protection, namely aggregated transfer coefficients, fluxes and individual exposure of humans. In addition, a fourth quantity, the action load, was identified as a useful sensitivity measure, which defines the deposition at which the activity concentration in a food product would equal maximum permitted levels in the period following deposition. These four quantities (rectangular boxes), are each influenced or defined by different processes or factors (oval boxes). For each of these quantities, both temporal and spatial variability need to be considered. Spatial variability will depend on factors such as (i) ecosystem characteristics, (ii) variation in human utilisation of terrestrial and aquatic resources and (iii) climatic variation. Temporal variability needs to be considered from three perspectives: (i) physical half-lives of radionuclides (ii) biological half-lives in various ecosystem components and (iii) ecological half-lives in different ecosystem compartments and types of ecosystems.

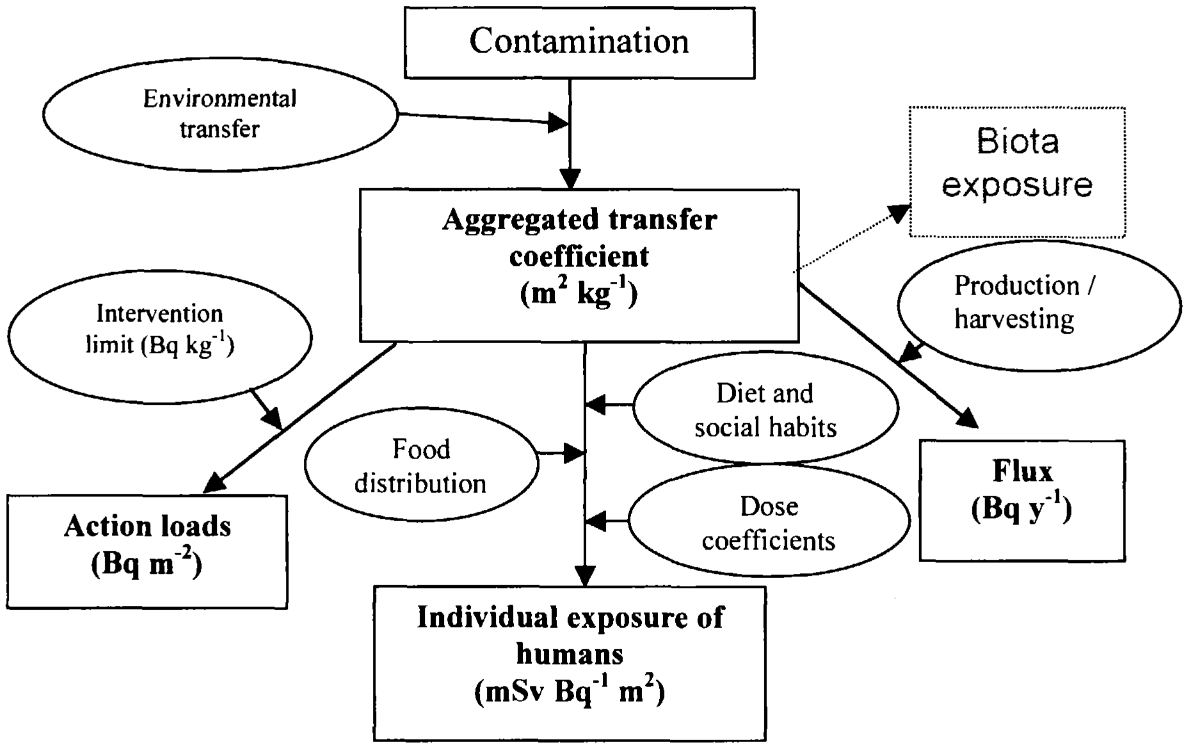

Figure 1 Scheme showing derivation and relationship between the four radioecological sensitivity indicators. All outputs are temporally and spatially variable.

Information is needed on the extent of radionuclide transfer and exposure to humans at large spatial scales, to reflect the sometimes large spatial differences which occur. Single values for large areas, such as countries, can often mask huge variation within the country. Similarly, the relative importance of different pathways can change with time and therefore it is important to make assessments of radiological sensitivity over different time periods after contamination. Thus, we recommend that radioecological sensitivity is considered for different times after deposition, (e.g. to estimate doses over 1 y, 5 y and 50 y) and also for different age groups.

3.1 Transfer To Environmental Compartments

The extent of transfer to different environmental compartments, including food products, has been quantified using a variety of different transfer functions, including concentration ratios for soil-plant and transfer coefficients for plants to animals. In Figure 1, we have based the assessment on an area basis, and therefore the most appropriate transfer function to consider is the aggregated transfer coefficient, (Tag), defined as the activity concentration in a food product (Bq kg^{-1}) divided by the corresponding radionuclide deposition (Bq m^{-2}); with units of m^2 kg^{-1}. The application of Tag values is most suitable for terrestrial ecosystems, for freshwater and marine systems they are more difficult to quantify and apply appropriately. Different environmental factors influence the extent to which deposited radionuclides are transferred to food products. The relative importance of different factors obviously varies with each radionuclide.

Initially, the source term is critical since the physical and chemical form of the radionuclide affects its initial bioavailability. For instance, radionuclides in fuel particles deposited after the Chernobyl accident were much less mobile than those on condensed particles. If environmental mobility is reduced due to the chemical form of the contaminating radionuclides, their net export from any ecosystem will also be low. The most radioecologically sensitive source will be one which emits radionuclides in a highly bioavailable form, or where bioavailability increases in the environment with time (eg Chernobyl particle dissolution releasing ^{90}Sr).

In terrestrial ecosystems there are many factors which influence the extent of uptake into food products. For most radioiodine isotopes, only factors influencing short-term exposure such as interception and weathering need to be considered whereas for radiocaesium and radiostrontium soil to plant uptake are also important. For animal, diet selection which can vary seasonally and subsequent gut absorption rates and biological half lives are all important variables.

Marine ecosystems are relatively less radioecologically sensitive compared to freshwater and terrestrial environments with respect to atmospheric radionuclide deposition. Such insensitivity is a result of the capacity of marine ecosystems to quickly dilute an input of radioactive pollutant through processes such as advective currents and waves, coupled with the large volumes involved. Thus, short term consequences are likely to be more important, in marine ecosystems as dilution will occur over the long term. Key factors which influence radioecological sensitivity in marine systems include: (i) dispersion of radionuclides in the marine environment (ii) residence times of radionuclides in the water column (iii) sedimentation rates (iv) concentration factors of marine biota(v) velocity of interchange within estuarine areas, and (vi) location and harvesting rate.

3.2 Fluxes

The flux is defined as the total amount of radioactivity produced in a specified environmental product over a given time period (e.g. Bq y^{-1}) which is transferred from one compartment to another. For collective dose estimation, agricultural production statistics need to be incorporated so that fluxes of radionuclides can be quantified. To improve the quantification of the collective doses, it is important to assess the spatial dimension of the key parameters defining radioecological sensitivity. Identification of high fluxes requires a consideration of both variation in environmental transfer pathways (discussed above) and of rates of production and harvesting of food. For agricultural products, national statistics for many countries are compiled into international sources. Such data can therefore be used relatively easily in assessments of flux. A greater problem is connected with the estimation of the extent of harvesting of wild or free food products from extensive ecosystems such as forests and upland areas, which are rarely quantified.

Key products from terrestrial ecosystems, especially in the short term after an accident and for routine releases, include milk (and dairy products), leafy green vegetables, meat and cereals. Thus, the intensity of milk production per unit area is a sensitive criteria for estimation of both individual and collective dose. For certain EC countries, the production of milk from sheep or goats is important due to both production rates (Figure 2) and the high observed transfer of radionuclides compared with cattle. However, some of the categories of food products consumed are not consistent with radiological measurements, for example, dairy products are sub-divided into different categories which would have different radionuclide activity concentrations. Thus, the extent of processing of goat milk, which varies considerably between countries, would influence the total amount of radionuclide consumed

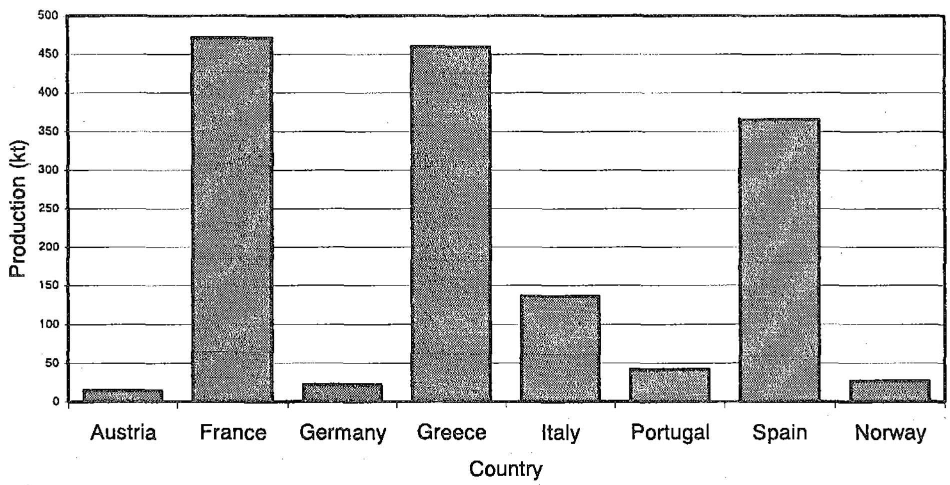

Figure 2 Annual production of goat milk in different European countries [3]

If there are areas producing food with a low level of contamination, but with a high production, these areas may contribute significantly to the collective dose. It is valuable to identify these areas because countermeasures can also be applied with the objective of reducing collective as well as individual dose. This will be dependent on the most cost effective action from scenario to scenario.

3.3 Action Loads

Radioecological sensitivity has previously been quantified in terms of critical loads, which were originally developed in response to the impacts of anthropogenic acidifying emissions. The critical loads approach has been developed to cover a wide range of both pollutants and receptors and can be defined [4] as:

> *'a quantitative estimate of an exposure to one or more pollutants below which significantly harmful effects on specified sensitive elements of the environment do not occur according to present knowledge'*

Critical loads are damage thresholds for pollutant deposition, and imply that if deposition is below the threshold then there is no effect and thus no problem whereas if it is above the threshold then harm will occur. From a radioecological perspective, the critical load for a food product has been defined as the level of radionuclide deposition (Bq m^2) which leads to activity concentrations in a food product above intervention limits at a given time after deposition. This approach was initially developed for radiocaesium using empirically derived aggregated transfer coefficients for clay, loam, sand and peat soil groups in the mid- to long-term after a radiocaesium deposition event with respect to ^{137}Cs transfer to cow milk [5]. Estimation of critical loads has also been incorporated within semi-mechanistic models, allowing the dynamic quantification of radiocaesium critical loads for many food products after deposition. If critical loads are based on soil to plant uptake, they are not relevant to the early phase after deposition, when surface contamination dominates. In such circumstances, short term "action loads" might be defined in the same way as critical loads but which would depend on the extent of interception and weathering on plant surfaces. Maps or tables of action loads for different food products can be combined with maps of deposition following any future nuclear accidents for the rapid identification of areas that are either sensitive or resilient to radiocaesium deposition, and targeting use of resources.

The relevant maximum permitted levels for foodstuffs in the European Community are given in Table 1. It should be emphasized that these values are not in force now, they will enter into force if an accident occurs after a decision by the Commission. They will be evaluated and possibly changed within 3 months.

Table 1 Maximum permitted levels for foodstuffs [6]

Radionuclides	**Maximum Permissible activity levels in foodstuffs (Bq kg^{-1})**			
	Baby Food	**Dairy Products**	**Other Products**	**Liquid Food**
Caesium	400	1000	1250	1000
Iodine	150	500	2000	500
Strontium	75	125	750	125
Plutonium	1	20	80	20

The quantification of action loads provides a useful initial spatially variable reference guide concerning the amount of a specified radionuclide that would need to be deposited to give rise to concentrations which exceed intervention levels. For terrestrial ecosystems, they are determined by interception and weathering rates. Action loads will be site and season specific and are best estimated using models which describe deposition and weathering mechanistically.

In freshwater ecosystems, action loads for drinking water (from lakes and reservoirs) depend on the initial runoff and the mean depth, for fish it is more difficult to estimate and probably not meaningful, but critical loads for later periods will be affected by transfer rates from water and nutrient levels in water. The concept is less easily applicable for marine systems where considerable dilution of a surface deposit occurs, and where concern is often more directed to point source continuous releases into marine ecosystems.

3.4 Individual Exposure Of Humans

The individual indicator with the units mSv per Bq^{-1} m^{2} is the end point which is most similar to that suggested by Aarkrog, although we recommend that this quantity should be considered for a number of different time periods rather than to infinity. The value requires an estimate of the amount of radioactivity consumed, estimated from activity concentration in food products and information on dietary habits. This is then converted to Sv using the appropriate dose coefficient.

The types and amount of food which are eaten are a critical factor influencing ingested dose. The concept of identifying critical or reference groups with respect to one or a few food products has been well developed. Well known examples are an aquatic critical group are shellfish consumers in Cumbria, UK and a terrestrial critical group are reindeer meat consumers. Other radioecologically sensitive groups due to consumption of a range of products have been identified such as hunters and gatherers in forests. In general, self-sufficiency with respect to diet and food production tends to make people more radioecologically sensitive.

4. EXAMPLES OF RADIOECOLOGICAL SENSITIVITY

The considered enhanced improvement in our understanding of radiocaesium behaviour has enabled radioecologically sensitive areas and pathways to be identified in the last decade. One example is the

Arctic. In the Arctic Monitoring and Assessment Programme (AMAP) an analysis was undertaken of the "vulnerability" (or sensitivity) of Arctic ecosystems to radionuclide contamination [7]. Compared to temperate ecosystems, the arctic was shown to be much more vulnerable to radiocaesium contamination and arctic terrestrial and freshwater ecosystems are more vulnerable to atmospheric radiocaesium contamination than marine ecosystems. The main contributing factors to the enhanced vulnerability are the high transfer rates to semi-natural products in the arctic, the long ecological half-lives and the consumption of relatively large amounts of these products by arctic inhabitants, especially indigenous groups of reindeer herders. The most vulnerable pathway was the transfer of radiocaesium to humans via lichen and reindeer, however, other products such as milk, freshwater fish and lamb could also be important. Assessment of critical loads in the Arctic has emphasized that ecological half-lives are an important aspect of critical loads, since previously deposited fallout may have a significant long term contamination effect for food products or environmental compartments with long ecological half-lives [8].

Similarly, after the Chernobyl accident, rural communities in the former Soviet Union with subsistence economies had persistently higher radiocaesium intakes than inhabitants of cities due to the use of forests to collect highly contaminated mushrooms and the ingestion of milk from privately owned cows which grazed on unimproved pasture [9].

5. APPLICATION

In principle, radioecological sensitivity is a generic concept and, in that sense, source- independent. It is applicable to practices as well as interventions as defined by ICRP[1] [10]. However, the practical application is different for these two different situations. For practices, the radioecological sensitivity of an area or ecosystem can be taken into account as part of a pre-planning and an optimisation procedure of a particular source. For interventions, knowledge about radioecological sensitivity incorporated as part of emergency preparedness can assist in prioritising after an accident has occurred (e.g. the identification of which areas should be considered first, in what way and when, for instance by using previously quantified action loads). Nevertheless, radioecological sensitivity is not a concept that will be used extensively in an acute situation such as directly after an accident. It can be used in radiation protection, nuclear safety and emergency preparedness when there is a need to identify areas that have the potential of being of particular concern from a risk perspective. If radioecologically sensitive areas are identified in advance in an emergency preparedness plan, the efforts to improve the situation can be implemented faster and be more efficiently focussed on the appropriate countermeasures in these areas. Identification of sensitive areas may also lead to that identified problems can be reduced by actions taken in advance, before an accident occurs.

It is of major importance to be able to reliably estimate the doses to individuals, as these are often the limiting parameter for regulations. In practice, however, these doses are seldom possible to measure. Dose estimates must therefore usually be based on estimates of diet, social habits, food availability and dose coefficients. A more direct, and measurable quantity is action load. This can be related to the intervention limits set by the authorities. With knowledge of the transfer of radionuclides in the ecosystem, for example expressed in terms of aggregated transfer coefficients, these relations can be established beforehand in an emergency preparedness plan. In principle, then, some of the identified problems can be reduced beforehand, before an accident occurs, if this is deemed to be economically and socially acceptable.

Further work is needed on uncertainties associated with the use of spatial data in radioecological sensitivity analysis. The concept of radioecological sensitivity should be extended to consider doses to biota.

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[1] A practice is a human activity that is undertaken by choice but which increases the overall exposure of man. Practices are controlled to restrict the additional radiation doses. Intervention, on the other hand, is an action against radiation exposures that already exist with the intention to reduce the exposures.

6. ACKNOWLEDGMENTS

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