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Bioavailability in the BORIS assessment model

M. Nordén[1], R. Avila[2], M.A. Gonze[3] and C. Tamponnet[3]

[1] *Swedish Radiation Protection Authority (SSI), 171 16 Stockholm, Sweden*
[2] *Facilia AB, Gustavslundsvägen 151A, 167 51 Bromma, Sweden*
[3] *Institut de Radioprotection et de Sûreté Nucléaire (IRSN), DEI/SECRE, Bâtiment 159, C.E. Cadarache, 13108 Saint-Paul-lez-Durance, France*

Abstract. The fifth framework EU project BORIS (Bioavailability Of Radionuclides In Soils: role of biological components and resulting improvement of prediction models) had three scientific objectives. The first was to improve understanding of the mechanisms governing the transfer of radionuclides to plants. The second was to improve existing predictive models of radionuclide interaction with soils by incorporating the knowledge acquired from the experimental results. The last and third objective was to extract from the experimental results scientific basis for the development of bioremediation methods of radionuclide contaminated soils and to apprehend the role of additional non-radioactive pollutants on radionuclide bioavailability. This paper is focused on the second objective. The purpose of the BORIS assessment model is to describe the behaviour of radionuclides in the soil-plant system with the aim of making predictions of the time dynamics of the bioavailability of radionuclides in soil and the radionuclides concentrations in plants. To be useful, the assessment model should be simple and use only a few parameters, which are commonly available or possible to measure for different sites. The model shall take into account, as much as possible, the results of the experimental studies and the mechanistic models developed in the BORIS project. The adopted approach was to introduce in the assessment model a quantitative relationship between bioavailability of the radionuclides in soil and the soil properties. To do this an operational definition of bioavailability was proposed. Here, operational means experimentally measurable, directly or indirectly, and that the bioavailability can be translated into a mathematical expression. This paper describes the reasoning behind the chosen definition of bioavailability and how it was used in the assessment model.

1. INTRODUCTION

To estimate radionuclide concentration in plants the most commonly used method is to multiply the concentration in soil by a soil-to-plant concentration ratio (CR). This method is easy to use in assessments and there exist compilations of CR for many plants and radionuclides, see for example [1] and references therein. However, CR's are highly variable as they integrate a number of soil chemical, soil biological, hydrological, physical and plant physiological processes, that in addition might be influenced by external factors such as climate and human agricultural processes [2]. In this work, the aim was to develop a method to estimate radionuclide concentrations in plants, that is easy to use and has less uncertainty than the method based on CR's. To do this, the concept of bioavailability was used and a definition was given that could be transferred into an operational expression. To be able to reach a definition that is both supported by scientific results and useful in the assessment model, several sources of information were balanced. Definitions that came out of a questionnaire that was sent out to BORIS members [3], definitions and discussions from the literature and the demands from the assessment model have all been considered. To develop the assessment model, we have used the mechanistic models developed within the BORIS project [4]: BioRUR (early version described in [5]) – a model of the soil-plant interactions and CHEMFAST - a model of the radionuclides behaviour in soil. By assessment model, we mean a set of simplified generic equations applicable to a wide range of radionuclides and soil-plant conditions. The project BORIS has been focusing on the behaviour of Cs and Sr, but the final aim is to be able to model the behaviour of any radionuclide. To make the model practically useful, it should rely only on a few parameters, which are commonly available and/or relatively easy to estimate.

2. DEFINITION OF BIOAVAILABILITY

The term bioavailability has been widely used in radioecology, not only in description of the soil-to-plant interactions, phytoavailability, but also to describe transfer to animals. However, there is a lack of a widely accepted definition of bioavailability, that is both theoretically grounded and operational, although a viable definition was proposed in [6]. In this paper, we will deal with soil-plant interactions and therefore wherever we use the term bioavailability we mean availability for uptake by plants from soil, i.e. phytoavailability. Based on discussions with the BORIS participants [3], definitions and discussions from the literature and demands from the assessment model the following definition was chosen: *the bioavailability of radionuclides in soil is a measure of the potential for radionuclides in bulk soil to be taken up by plants within a given time interval (for example within one day, one vegetative period for perennial plants or within one growing season for yearly crops)*.

Further, to make the definition quantifiable, the potential for being taken up by plants is expressed as the probability that the radionuclides are taken up by plants within a given time interval, which can only take values between 0 and 1. The total bioavailability is then the unconditional probability, which equals the weighted sum of the bioavailabilities associated with the different forms of the radionuclide in soil, i.e., the conditional probabilities:

$$B_{total} = \sum_i f_i * B_i \tag{1}$$

where,

B_{total} is the total bioavailability of a radionuclide in soil [r.u.],

f_i is the fraction of the radionuclide in the pool "*i* ", for example the soil solution [r.u.],

B_i is the bioavailability of the radionuclide in the pool "*i* ".

The fraction of radionuclides in different pools (f_i) and the corresponding bioavailabilities (B_i) can be estimated from results of fractionation studies and/or using models of the soil plant-interactions. It should be noted, that as any probability, the bioavailability values will depend on the available knowledge about the system and how the system is conceptualised, for example how different radionuclide pools are defined and which processes are included in the model.

3. APPLICATION IN THE ASSESSMENT MODEL

For the case of radionuclides that are analogues of macronutrients, it can be assumed that the plant uptake of the nutrient modulates the uptake of the radionuclide. This means, that the radionuclide and the corresponding analogue nutrient are taken up by plants in an identical manner. Furthermore, assuming that only ions in the soil solution near the roots are available for transition into the roots, the transition of the radionuclide from soil to plant roots can be represented as an independent Poisson process with the following rate:

$$TR(RN) = \frac{[RN]_{ss}}{[RN]_{ss} + [A]_{ss}} * TR \tag{2}$$

where,

TR(RN) is the transition rate of the radionuclide from the soil solution into the roots [mol/y],

TR is the overall transition rate from the soil solution into the roots [mol/y]

$[RN]_{ss}$ is the radionuclide concentration in the soil solution near the roots [mol/m^3]

$[A]_{ss}$ is the analogue nutrient concentration in the soil solution near the roots [mol/m^3]

In most cases, it can be considered that the concentration of the analogue in the soil solution is much higher than the concentration of the radionuclide and that the overall transition rate from the soil solution into the roots equals the analogue uptake rate. Further a selectivity coefficient, DF, can be introduced in equation (2), which has a value between 0 and 1, with 0 indicating that the plant completely distinguishes and rejects the radionuclide, and 1 indicating the inability of the plant to distinguish between the two ions. Finally, substituting in equation (2) the analogue and radionuclide concentrations in the soil solution by the total concentrations in the bulk soil multiplied by the bioavailability, equation (3) is obtained.

$$\frac{dUptake_{RN}}{dt} = DF * \frac{B_{RN}}{B_A} * \frac{[RN]_S}{[A]_S} * \frac{dUptake_A}{dt} \tag{3}$$

where,

$dUptake_{RN}/dt$ is the uptake rate of the radionuclide by plant [mol/m^2/d],

$dUptake_A/dt$ is the uptake rate of the stable analogue by plant [mol/m^2/d],

DF is the discrimination factor (selectivity coefficient) between the radionuclide and the analogue [r.u.],

B_{RN} is the bioavailability of the radionuclide in soil [r.u.],

B_A is the bioavailability of the analogue in soil [r.u.],

$[RN]_S$ is the total concentration of the radionuclide in bulk soil [mol/kg],

$[A]_S$ is the total concentration of the stable analogue in bulk soil [mol/kg].

The above equation shows how the concept of bioavailability can be applied in assessment models for radionuclides that are analogues of plant macronutrients, for example Cs137 (analogue of K) and Sr90 (analogue of Ca). Experiments described in the literature e.g. in the fourth framework EU project PEACE [5] and also experiments performed within the BORIS project [7], support the assumption used in the assessment model that there is a linear relationship between the uptake rate of Cs and K and also between Sr and Ca (See Figure 1 and 2). The experiments cover a wide range of agricultural plant – soil combinations.

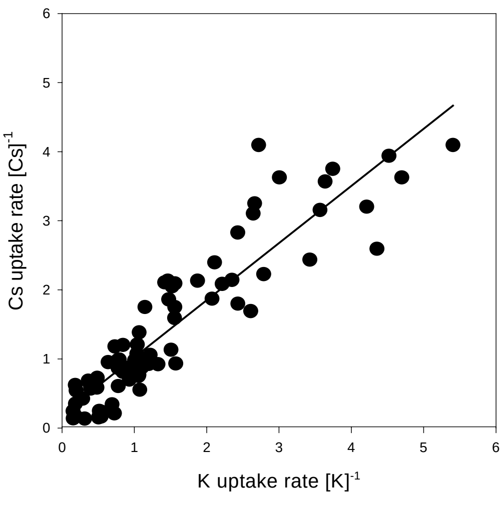

Figure 1. The relationship between Cs and K uptake rate (see [5] and [7]).

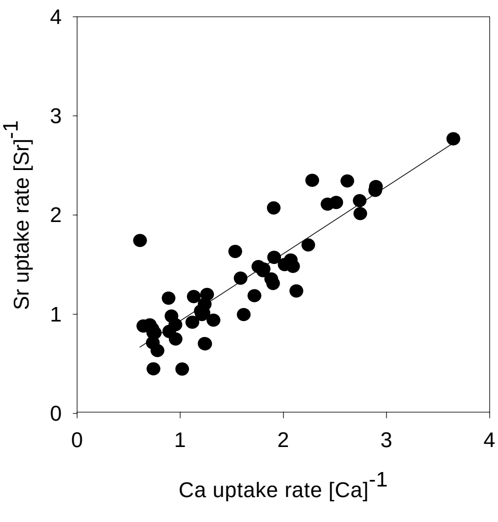

Figure 2. The relationship between Sr and Ca uptake rate (see [5] and [7]).

4. PRACTICAL APPLICATION

To make the assessment model useful in practice, it is necessary to provide a way of estimating the bioavailability. Since the bioavailability of the radionuclide and the analogue are likely to be correlated, a bioavailability factor was introduced defined as the bioavailability of the radionuclide with respect to the analogue ($B_{RN/A}$). Using the mechanistic model BioRUR the following relationship between the bioavailability factor and the plant/soil properties was derived:

$$\overline{B}_{RN/A} = \frac{1}{\overline{\gamma_A}} \; \overline{\gamma_A \left(\frac{\phi_{RN}}{\phi_A} \right)} \; \frac{\theta + \rho\, Kd_A}{\theta + \rho\, Kd_{RN}} \tag{4}$$

where,
$B_{RN/A}$ is the bioavailability factor [r.u.],
γ_A is the ratio between the actual and potential plant uptake of the analogue [r.u.],
Φ_{RN} and Φ_A are the depletion factor of the radionuclide and the analogue respectively [r.u.],
θ is the soil water content [m^3/m^3],
ρ is the soil bulk density [kg/m^3],
Kd_{RN} and Kd_A are the distribution coefficient of the radionuclide and the analogue respectively [m^3/kg].

The first and second members in equation (4) reflect the interactions between plant demand and depletion/accumulation of ions in the soil solution near the roots and are average values taken over different co-existing root-cohort segments. The last term is the bioavailability factor in situations where there is no depletion or accumulation near the roots and the analogue is taken up in the amounts demanded by the plant.

If the correlation between the plant demand and the depletion and between the depletion of the radionuclide and the analogue are neglected in equation (4), then the following simplified equation can be obtained:

$$B_{RN/A} = \frac{\left(\dfrac{\phi_{RN}}{\theta + \rho * Kd_{RN}} \right)}{\left(\dfrac{\phi_A}{\theta + \rho * Kd_A} \right)} = \frac{B_{RN}}{B_A} \tag{5}$$

The strategy adopted in the BORIS project for facilitating the practical application of the assessment model was to create tables with values of the bioavailability factors, calculated with BioRUR, for a range of common plant/soil systems.

5. CONCLUSION

In this work we have proposed an operational definition of bioavailability that can be used in assessment models of radionuclide soil to plant transfer. We have also proposed a way of expressing the bioavailability as a function of the soil plant characteristics. This approach has been used in the BORIS assessment model with the aim of reducing uncertainty in the soil to plant concentration ratios.

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