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Uncertainty analysis in post-accidental risk assessment models: An application to the Fukushima accident

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ABSTRACT

Environmental contamination subsequent to the atmospheric releases during the Fukushima accident resulted in high radioactive concentrations in feed and foodstuffs. Producing a realistic health risk assessment after severe nuclear accidents, and developing a sufficient understanding of environmental transfer and exposure processes, appears to be a research priority. Specifically, the characterization of uncertainties in the human ingestion pathway, as outlined by the radioecological community, is of great interest. The present work aims to (i) characterize spatial variability and parametric uncertainties raised by the processes involved in the transfer of radionuclides (^{134}Cs and ^{137}Cs) after atmospheric releases during the Fukushima accident into the terrestrial ecosystems, and (ii) study the impact of these variability and uncertainties on radioactive contamination of leafy vegetables. The implemented approach quantified uncertainties under a probabilistic modelling framework. This resulted in probability distributions derived mainly from Bayesian inference and by performing transfer calculations in the modelling platform SYMBIOSE.

1. Introduction

The atmospheric releases following severe nuclear disasters, such as those at Chernobyl and Fukushima, may potentially generate huge environmental contamination that could subsequently contaminate feed and foodstuffs at high concentrations. Providing reliable risk assessments in accidental situations is of great importance. However, it is a complex issue for crisis managers since the transfer of radionuclides from the atmosphere to terrestrial ecosystems is governed by several miscellaneous processes which involve complex physical, chemical and biological mechanisms. Indeed, while released in the atmosphere either in a gaseous form or as particles, the radionuclides are deposited onto plant canopies as a result of gravitation, meteorological, and aerodynamic conditions. Subsequently, the fraction of radionuclides initially retained at the surface of foliage (agricultural crops and forest canopies) and the fraction of radionuclides on the ground represent a source of food chain contamination and a potential risk for human populations. Developing a sufficient understanding of the environmental transfer and the processes leading to exposure of human populations in a (post-) accidental context appears a priority for decision-makers during crisis management (Hinton et al., 2013). Specifically, the characterization of the uncertainties associated with these processes is one of the key research areas underlined by the radioecology community in order to enhance risk assessment models when studying accidental atmospheric emissions of radioactive elements and their impact on the human food chain. *Uncertainty* is defined in this article as the lack of perfect knowledge about the adequacy of a defined model to reflect the situation of concern for a given impact assessment (Cullen and Frey, 1999). *Uncertainty* is reducible if additional knowledge becomes available and it includes *model uncertainty* and *input uncertainty*. The latter, also called *parametric uncertainty* describes the lack of perfect knowledge about the values of parameters and variables of one model equations (Cullen and Frey, 1999). *Variability* is defined herein as the true heterogeneity inherent to the physical, chemical or biological processes of interest or the diversity within the scenario of concern (Simon-Cornu et al., 2015). *Variability* is not reducible with the supply of additional information.

International organizations such as the World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO) have recommended quantifying uncertainty to obtain more realistic food risk assessments for many kinds of hazards (Sy et al., 2015). Within the context of environmental

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transfer of radionuclides, the International Atomic Energy Agency (IAEA, 1989) provided similar recommendations and a great number of developments were devoted to providing reliable knowledge and a good representation of the *parametric uncertainty* of processes such as radionuclides (foliar) interception, "field loss" to ground or resuspension from ground (IAEA, 2010).

To characterize *parametric uncertainty*, probabilistic modelling is one of the broadly used approaches. The probabilistic framework offers theoretical bases with convenient and flexible tools for characterizing *parametric uncertainty*. However, even though some applications of the probabilistic modelling exist in the field of radioecology the use of probability distributions in dosimetric impact assessments is relatively new. As far as we know, in the few probabilistic food risk assessments that were published after the Fukushima accident (Evangeliou et al., 2014; Koizumi et al., 2012; UNSCEAR, 2013; Yamaguchi, 2012), uncertainties in the radioecological transfers was not the main focus.

The present study aimed to characterize uncertainties when modelling the human exposure to radiocesium isotopes (^{134}Cs and ^{137}Cs) through ingestion of leafy vegetables during an accidental context. As the leaves of leafy vegetables directly intercept the radioactive deposits we focused on the activity concentration of radiocesium isotopes (^{134}Cs and ^{137}Cs) in such vegetables/plants. This work mainly consisted of (i) implementing quantitative approaches to characterize the different parametric uncertainties raised by the physical, chemical and biological processes underlying the transfer of radionuclides into the terrestrial ecosystems after severe accidents and (ii) to apply those approaches in a real severe accident scenario: the environmental contamination subsequent to the Fukushima accident. To address the first aim (i), a probabilistic modelling framework was adopted by using Bayesian inference and this resulted in the derivation of probability distributions. Uncertainty and sensitivity analyses were applied to the environmental impact calculations by using Monte Carlo simulations in SYMBIOSE (which is a modelling platform developed by the French Institute of Radiation Protection and Nuclear Safety, IRSN) in response to the second objective (ii).

2. Material and methods

In this section, the modelling platform SYMBIOSE is presented and a description of the models which are used to predict the fate of radioactive cesium in agricultural lands and specifically to calculate the concentrations of radiocesium in leafy vegetables is provided.

2.1. SYMBIOSE modelling platform

SYMBIOSE is a simulation platform for assessing the fate and transport of radioactive pollutants in ecosystems, and their impact on humans (Gonze et al., 2011; Simon-Cornu et al., 2015). Environmental models implemented in SYMBIOSE address media, such as atmospheric, terrestrial, freshwater and marine systems, as well as the major transfer processes at their interfaces. Hundreds of components and interactions are accounted for in the system, most of which are modelled using a dynamical approach. Modelled exposure pathways include: external exposure (cloud shine and ground shine); internal exposure by inhalation (plume and resuspension from the ground), and by ingestion (agricultural products, freshwater fishes, seafood). This platform is flexible enough to deal with a wide range of situations, including post-accidental crisis predictions. Calculations can be performed for various spatial situations, from simple and generic to complex and site-specific landscape-level situations. SYMBIOSE also enables accounting for uncertainty in radioecological models in a probabilistic modelling framework by using either Monte Carlo simulations or runs driven by Latin Hypercube sampling. Parametric uncertainty is defined via probability density functions (PDFs).

2.2. Modelling cesium transfer in leafy vegetables using SYMBIOSE: application to the Fukushima accident

Within the SYMBIOSE modelling platform, different modules are devoted to the transfer of radionuclides to plant canopies specific to different types of vegetation (annual crops, pasture grass and vegetable products). Specifically, the transfer of radionuclides to vegetable products such as leafy vegetables is governed by the combination of several processes that mainly include: the atmospheric deposition of radionuclides onto plant and ground surfaces; the interception of the deposited radionuclides by the leaves of plants; the field losses induced by the effect of wind, rain and the growth of plants; and the migration from ground to plant leaves. The different processes mentioned are further detailed in the sections that follow. Fig. 1 gives a conceptual illustration of the transfer of radioelements to agricultural lands, with emphasis on leafy vegetables.

2.2.1. Atmospheric deposition scenario

The spatial dispersion of ^{134}Cs and ^{137}Cs deposition and the estimation of dry deposit proportions within 80 km around the Fukushima Daiichi nuclear power plant (FDNPP) were deduced from the methodology proposed by Gonze et al. (2014). This method is based on the analysis of two kinds of field-based measurements of radiocesium deposits performed by the Japanese authorities:

- In situ spectrometry measures of bare soils in inhabited areas.
- Airborne gamma-ray spectrometry measures, which integrate radiation from the underlying land surfaces.

The methodology, its assumptions, and the conclusions drawn are further discussed by Gonze et al. (2014, 2015). These inputs, D^{Cs} (in Bq.m^{-2}.day^{-1}) the flux of radiocesium deposited on agricultural lands (soil + canopy), and K^{Cs}, the proportion of radiocesium deposited in dry conditions, i.e., the ratio between dry and wet deposits, are illustrated in Fig. 2.

2.2.2. Transfer models

Let $[\mathrm{Cs}]_{LV}^{Fol}(t_H)$ and $[\mathrm{Cs}]_{LV}^{Root}(t_H)$ denote the concentrations (expressed in kilobecquerels per kilogram of plant fresh weight, kBq.kg^{-1} fw) of radiocesium in the foliar and the root compartments of leafy vegetables at harvest (t_H). The contamination of leafy vegetables by radiocesium at harvest $[\mathrm{Cs}]_{LV}$ (t_H) was modelled, accounting for both direct contamination through the foliar pathway and indirect contamination via root uptake as expressed below (Eq. (1)).

$$[\mathrm{Cs}]_{LV}(t_H) = [\mathrm{Cs}]_{LV}^{Fol}(t_H) + [\mathrm{Cs}]_{LV}^{Root}(t_H) \quad (1)$$

2.2.2.1. Foliar pathway. The concentration of radiocesium in leafy vegetables induced by foliar uptake is given by the mass conservation equation taking into account the amount of cesium deposited and initially retained on the plant surface, the radioactive decay and the potential "field losses" due to the combined action of wind, rain and the growth of plants. This mass balance is given by the first-order differential equation below (2).

$$\frac{d}{dt}[\mathrm{Cs}]_{LV}^{Fol} = D^{Cs} \times \left(K^{Cs} \times IF_d + \left(1 - K^{Cs}\right) \times IF_w\left(H^{rain}\right)\right) - \left(\lambda^{FL} + \lambda^{Cs}\right) \times [Cs]_{LV}^{Fol} \quad (2)$$