APPLICATION OF A DYNAMIC MODEL FOR EVALUATING RADIONUCLIDE CONCENTRATION IN FUNGI

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ABSTRACT

Global fallout from nuclear weapon tests in the 1960s revealed the potential of fungi as an enhanced accumulator of radioactivity. Data derived from Chernobyl fallout sampling has shown fungi to be a major accumulator of radiocesium and an important food-chain contributor to the human radiation dose. Fungi can significantly affect the radionuclide cycling in forests. According to experimental data and estimations, forest microflora, particularly fungi mycelia, could retain up to 40% of radiocesium. This paper illustrates the application of the dynamic model FORESTPATH to evaluate the contamination dynamics in fungi and the relative importance of fungal species for forest cycling. Only a few studies have been made to model fungi contaminated by radionuclides and these utilize Transfer Factors to describe soil-to-fungi uptake of radionuclides. Such an approach has serious limitations, since equilibrium conditions and specified soil sampling depths must be assumed. The FORESTPATH model uses rate of uptake and residence half-times for radionuclides to describe this process. The model was applied to describe radionuclide dynamics in fungi for the case of chronic deposition and for the accidental release of radionuclides. Experimental measurements of fallout from nuclear weapon tests and from the Chernobyl accident were used to test the FORESTPATH predictions.

INTRODUCTION

Data derived from sampling of the areas contaminated by the Chernobyl fallout have implicated the Organic Layer as being a major accumulator of radiocesium (1, 2). Fungi are the highest living biomass in the decomposing organic layer and are the primary sources of the enzymes necessary to degrade the litter and, thus, are very important for radionuclide migration in forests. Fungi mycelia and fruit bodies are mainly located in the upper part of the organic layer. Although above-ground mushrooms are a minor contributor to the total fungal biomass (according to Olsen (3), this contribution may be as low as 1%, leaving 99% in the below-ground biomass) they can contribute significantly to the human radiation dose being consumed as a food.

Very little is known about the mechanisms involved in the radionuclide uptake and retention by fungi. Fungi can play a significant role in radionuclide retention by the organic layer. Olsen et al. (4) estimated that some 32% of the total Chernobyl-derived radiocesium present in a forest soil in Norway is contained in fungi. This estimate was confirmed by experimental data (5). Their experiments with artificial washout of humus samples show that forest microflora (particularly fungi mycelia) could retain up to 40% of radiocesium. The absorption of nutrients (and thus radionuclides) by fungi from the ground occurs in aqueous solution usually from the soil solution. Fungi use enzymes to break down macromolecular complexes in solution for digestion. Once broken down, most substances are thought to move into the *hyphae,* being bound to specific carrier molecules. The rate of this uptake by both saprophytic and symbiotic fungi depends on concentration of the ion, moisture content of the soil, the growth rate of the plant and, in the case of symbiotic fungi, the transpiration rate of the host plant.

Several studies have examined the differences in the ability of saprophytic and symbiotic fungi to accumulate radiocesium. Results of several studies (5, 6) indicated that the symbiotic fungi accumulated, on average, statistically higher concentrations of radiocesium although both types of fungi collect radiocesium quite effectively. These observations can be explained by the differences in mycelium location in the soil profile as well as the migration of Chernobyl-derived radiocesium through forest soil. Other hypotheses include differential retention of radionuclides by fungi (5).

The life cycle of soil fungi may have an impact on the time of immobilization of radionuclides in mycelium. Differences exist between the life time of different species of fungi. According to Olsen et al. (4), the lifetime of mycorrhizal fruit bodies (mushrooms) is normally between 10 and 17 days. The life of fungal biomass in soil is not as well understood and is suggested to be on the order of two years. After death, the release of nutrients proceeds primarily by leaching. As water comes in contact with the cell wall of the fungi, nutrients such as K^{+} diffuse across their concentration gradient and into solution. Another less important release pathway is due to animal consumption.

Quantitative evaluation of the relative fungi contamination is a challenging task. The traditional approach is to evaluate the Transfer Factor (TF) for soil-to-fungi transfer. TF can be defined as the ratio between the activity in plant (Bq/kg dw) divided by the activity in soil (Bq/kg dw) or by the deposition per unit area (Bq/m^2). Large variability in the TF values has been reported. TF across different species varies over several orders of magnitude (7).

The TF approach has serious fundamental limitations because it is applicable only to equilibrium situations, which can only be achieved in natural ecosystems a long time after the contamination event (10-20 years for the case of forest ecosystems (1,8)). Multi-layered soil structure with variable depth of soil horizons of the natural environment and inhomogenuity of the radionuclide deposition and its soil migration requires definition of conditions for sampling depth and volume. By including an estimate of the depth to which the radiocesium has migrated (i.e., Cs-134/Cs-137), Guillitte et al. (5) were able to obtain a more accurate estimate of the ability of a particular fungi species to take up radiocesium. Thus, it is problematic in defining the soil volume where nutrient uptake occurs. The dynamics of fungal biomass growth and decay are not well understood and questions remain regarding the nutrient requirements of this plant over time.

MODELING OF ORGANIC LAYER AND MUSHROOM CONTAMINATION

The FORESTPATH model (1, 8) calculates a time series of inventories for a specific radionuclide distributed within the following six compartments: Understory, Tree, Organic Layer, Labile Soil, Fixed Soil and Deep Soil. In this paper, the model was developed further to incorporate details of radionuclide migration in the Organic Layer and fungi. The Organic Layer is represented by three horizons: Ol (litter), Of and Oh. Reported residence time for Cs in these horizons (see (1) for review) along with values for other FORESTPATH parameters for Chernobyl forests (1, 8) were used for model simulations. Figure 1 shows radionuclide accumulation by the Organic Layer as well as by the Labile and Fixed Soil compartments, in a coniferous forest in Chernobyl described in (1, 9) (an initial deposition of 5 Ci/km^2 was assumed in the calculations). Organic Layer compartments exhibit complex time dynamics. The litter compartment is significantly contaminated immediately after the deposition, but looses all its activity during the first year due to wash-off and leaching towards deeper layers. Of and Oh horizons show accumulation peaks at about two and four years respectively following the initial deposition.

Mushroom mycelia exist in different soil horizons. Given the complexity of the nutrient uptake by mushrooms and lack of theoretical description of this process, it could be assumed that mushrooms have the same contamination density as the layer in which their mycelia are located. Using this methodology, calculations have been made for contamination of two types of mushrooms in coniferous forests. The first type has mycelium developed in the Of horizon, while the second type has mycelium located in the Oh-upper layer of mineral soil. A representative edible mushroom species of the first type is *Boletus badius* (or *Xerocomus badius*) (10), while *Boletus edulis* is representative of the second type (5). Based on the FORESTPATH model, *Boletus badius* would be expected to have the same dynamic of contamination as the Of horizon (i.e., have maximum accumulation during the second year following the accident (Figure 1). *Boletus edulis* which takes nutrients from the labile soil, would be expected to increase its contamination during the first decade following the accident.

MODEL VALIDATION

Model predictions are validated based on: 1) compilation of the reported ^{137}Cs concentrations in these two mushroom species in Central Europe (generic model), and 2) concentrations reported for contaminated forests in the Exclusion Zone (site-specific model). Figure 2 shows compilation of the existing literature values for mushroom contamination (see (1) for compilation tables). It is clear that *Boletus badius* exhibits an accumulation peak around 1988, while *Boletus edulis* concentration still increases (at least until 1991). Significant variability in the reported data can be explained by different contamination levels, climatic conditions, soil structure and types, etc. In the Chernobyl forests, *Boletus badius* and *Boletus edulis* exhibit the time dynamics expected for plants with roots developed in Of and Oh-Mineral Soil compartments (Figure 3). Predicted values from the FORESTPATH are about two times larger than the values measured by the Forest Research Institute, Belarus. Due to the fact that the experimental data were obtained based on reported values for the TF, the differences of a factor of two can be explained by the large uncertainty incorporated in the TF determination.

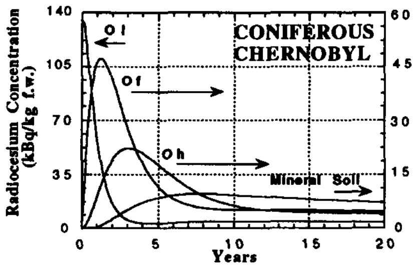

Figure 1. ^{137}Cs concentration in soil compartments of a coniferous forest in Chernobyl over 20 years from an initial acute deposition (kBg/kg f.w.). The scale of the ordinate is 140 kBq/kg for the Ol horizon and 60 kBq/kg for all other compartments.

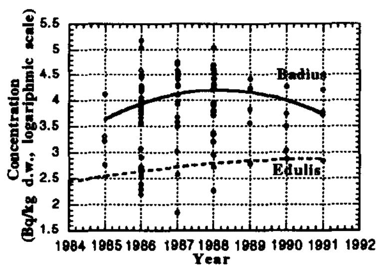

Figure 2. ^{137}Cs concentration in *Boletus badius* and *Boletus edulis* collected in European countries.

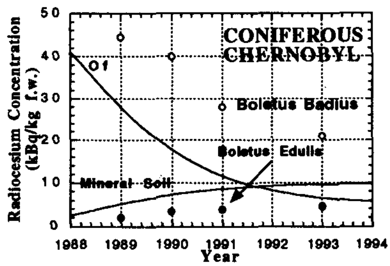

Figure 3.
Cs-137 concentration in Boletus badius and Boletus edulis collected in Chernobyl forests (circles, after Ipatyev (11)) compared to those predicted by FORESTPATH for species having mycelia in Of and Mineral Soil horizon (solid lines).

CONCLUSIONS AND RECOMMENDATIONS

FORESTPATH can be applied for detailed evaluation of the radionuclide accumulation in a specific forest compartment. The model predicted an enhanced accumulation by fungi with shallow mycelia during the first years after an acute deposition, while the accumulation peak for deep-rooted species is delayed. These predictions have been validated based on the experimental data collected in Europe (generic approach) and in the Chernobyl Exclusion Zone (site-specific application).

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