Invariant scaling relationships and their possible application in predicting radionuclide uptake in plants

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INTRODUCTION

Bioconcentration, or transfer factors (TF) are an integral part of both human and ecologic radiological risk assessments. Typically they are used to predict uptake of a radiocontaminant from an abiotic component of the environment to a biotic component. Historically, they have been empirically obtained through field or laboratory studies, or estimated by extrapolation from the behavior of chemical analogues. Transfer factor data exist for several radionuclides in selected environments, but the emphasis is largely on plants of economic or cultural interest. Values can range over orders of magnitude for a single radionuclide (Napier, Fellows et al. 2007). The data sets for plant species tend to be restricted to those significant to the human food chain, and for which measurements can be readily obtained with reasonable cost and time constraints. If methods could be developed to estimate technically defensible TFs across a wide range of environments and species this would represent a considerable enhancement in current methods of radiological risk assessment.

BACKGROUND

Historically, Transfer Factors (TFs) have been both the product and tool used to assess radionuclide uptake in biota. There have been attempts to better understand underlying mechanisms responsible for radionuclide uptake, and therefore explain, and predict TFs, but the results have been less than satisfactory except on a limited basis (e.g., (Maraziotis 1992; Nisbet and Woodman 2000; Zhu and Smolders 2000; Ehlken and Kirchner 2002; Centofanti, Penfield et al. 2005; Willey, Tang et al. 2005). There have been attempts at alternative analysis – particularly by taxa (Willey, Tang et al. 2005) – however the data were extracted from multiple sites, with varying chemistry, potentially clouding the results. In all cases, the development of a simple, but broadly predictive tool has not emerged.

At the same time, outside the world of radioecology, there has been considerable research on application of scaling functions as a tool for understanding a broad swath of mechanisms and traits in both plants and animals. There are several allometric equations that relate animal body size to many parameters, including ingestion rate, life span, inhalation rate, home range and more (West 1987). The most common form of allometric equation is the power function: \[ Y = \alpha X^\beta \]

where Y and X are size related measures, and \( \alpha \) and \( \beta \) are constants. These functions have also been applied to plants, and are generally accepted (Niklas and Enquist 2001; Castelan-Estrada, Vivin et al. 2002; Beresford, Broadley et al. 2004; West and Brown 2005; Niklas 2006; Higley and Bytwerk 2007). Parameters that have been examined specifically for plants include annualized biomass production (which scales as mass, M, to the \( \frac{3}{4} \) power) and plant body length L, which purportedly scales as \( M^{1/4} \), although there is some controversy for metabolism, size and nitrogen content (Reich, Tjoelker et al. 2006; Enquist, Kerkhoff et al.
There have been noted distinctions between plant types in regard to the scaling exponent - for example isometric scaling, $M^1$ for non woody and $M^{3/4}$ for woody plants for selected parameters (Niklas 2006). However, there is considerable discussion on the nature and value of the exponent (Reich, Tjoelker et al. 2006). Significantly, one area that does not appear to have been investigated, is the application of allometric functions and their application to the uptake of trace, or ultratrace constituents such as radionuclides in plants.

**METHODS**

In this paper the authors tested scaling functions against tabulated radionuclide transfer factors (TFs) reported in the open literature from a variety of locales. TFs were tested against total dry mass (kg), annualized growth rates (kg/plant/yr), and plant height (m). These parameters were selected because allometric relationships have been demonstrated for each. Literature values of TFs for $^{137}$Cs, $^{90}$Sr, and $^{239}$Pu for ~40 plant species were evaluated. These nuclides were chosen because of the presumed greater abundance of data, and because they encompassed elements that ranged from essential to insignificant in their biological importance.

Plants examined included common vegetable crops, grains, fruits, trees, shrubs, and grasses. Some of the specific species included rice (presumed to be Oryza sativa L.), peanuts (presumed to be groundnut, Arachis hypogaea L.), pineapple (presumed to be Ananas comosus), cabbage (presumed to be brassica oleracea var. capitata L.), tomato (presumed to be (Lycopersicum esculentum Mill), spinach (presumed to be Indian spinach (Bassella rubra - L.), grass (presumed to be Triticale (X Triticosecale Wittmack), okra (Abelmoschus esceletus, var Clemson spineless), sweet corn (Zea mays var. silver queen), lettuce (Lactuca sativa var earl butterhead), turnips (Brassica rap var. white-globe), beans (Phaseolus vulgaris), eggplant (Solanum melongena var. Burpee hybrid), cheatgrass (Bromus tectorum L.), peas (Pisum sativum, Var. Blue Bonnet), barley (Hordum vulgare, var U. Cal. Briggs), alfalfa (Medicago sativa, var. Ranger), willow (Salix amygdaloides), sagebrush (Artemisia tridentata), Mung beans (Vigna radiata), Sorghum (presumed to be Sorghum bicolor); carrots (Daucus carota), and radishes (Raphanus sativus).

In order to adequately test the scaling concepts, and rule out the effect of site-specific chemistry on uptake, data sets were selected where information was available for multiple species grown on the same site. These include locations in the United States, Bangladesh, Australia, Taiwan and Japan (Landeen and Mitchell 1986; Seel, Whicker et al. 1995; Mollah A. S. 1998; Yoshida and Muramatsu 1998; Whicker, Hinton et al. 1999; Twining, Payne et al. 2004; Chou, Chung et al. 2005). Radionuclide-specific TFs were normalized at each site on a scale of 0-1 for all plant species tested at that locale. The purpose of normalization was to remove, as much as possible, the influence of site chemical characteristics (in their analysis, (Ehlken and Kirchner 2002) noted many of the complexities that complicate the determination of TFs).

**CONCLUSIONS AND RECOMMENDATIONS**

This work is part of an ongoing analysis, and consequently the results are preliminary. However, in the data sets examined to date, testing total dry mass (kg), annualized growth rates (kg/plant/yr), and plant height (m) against normalized TFs, scaling factors of $\sim$0.75, 0.75
and 0.1 respectively emerged— but the data are not statistically significant. In part this may be due to the small size of the data set, however there are other issues that may have contributed to the lack of statistical significance. In the course of this research it became apparent that the methodology used to calculate (and ultimately report) TFs frequently omits information useful to the testing of allometric functions. For example— total dry biomass of plants is rarely included in the literature, and therefore must be estimated from other sources (Reddy, Sanjana Reddy et al. 2003; Centofanti, Penfield et al. 2005). Also soil data collected in developing TFs does not consistently encompass the rooting zone of the plant, and therefore may provide an incomplete estimate of the available inventory. More significantly, plant species are not clearly identified in several reports, making outside determination of biomass difficult and prone to uncertainties. One other factor that makes the application of scaling in TFs problematic is that both soil and radionuclide chemical characteristics are known to impact contaminant mobility. As a result, steps must be taken to “normalize” data collected for each site, to allow extrapolation to other locales. Even with these limitations, there are tremendous potential benefits to the use of scaling functions. These include the ability to extrapolate beyond the type of data (e.g., primarily foodstuffs) previously collected, and the overall inherent transparency provided with these functions. Data collection and analysis will continue.

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REFERENCES


