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Development and evaluation of a regression-based model to predict cesium concentration ratios for freshwater fish

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ABSTRACT

Data from published studies and World Wide Web sources were combined to produce and test a regression model to predict Cs concentration ratios for freshwater fish species. The accuracies of predicted concentration ratios, which were computed using 1) species trophic levels obtained from random resampling of known food items and 2) K concentrations in the water for 207 fish from 44 species and 43 locations, were tested against independent observations of ratios for 57 fish from 17 species from 25 locations. Accuracy was assessed as the percent of observed to predicted ratios within factors of 2 or 3. Conservatism, expressed as the lack of under prediction, was assessed as the percent of observed to predicted ratios that were less than 2 or less than 3. The model's median observed to predicted ratio was 1.26, which was not significantly different from 1, and 50% of the ratios were between 0.73 and 1.85. The percentages of ratios within factors of 2 or 3 were 67 and 82%, respectively. The percentages of ratios that were <2 or <3 were 79 and 88%, respectively. An example for Perca fluviatilis demonstrated that increased prediction accuracy could be obtained when more detailed knowledge of diet was available to estimate trophic level.

1. Introduction

An important parameter used to assess the mobility of the radionuclides ^{134}Cs and ^{137}Cs in freshwater environments and to estimate the potential risks of consuming fish from these systems is the ratio of the mean concentration of the radionuclide in the fish to its mean concentration in the water. This ratio is alternatively termed the concentration ratio or the bioaccumulation factor and has units of L kg^{-1}. Efforts to compile or predict estimates of concentration ratios (hereafter, C_r) that can be readily employed in accident assessments have led to 1) compilations of previously observed C_r (Vanderploeg et al., 1975; Blaylock, 1982; Hosseini et al., 2008; Fesenko et al., 2011; Yankovich et al., 2013) and 2) efforts to develop predictive models based on aspects of fish biology, such as diet, and water quality parameters such as K concentrations. Rowan and Rasmussen (1994) developed a predictive model (Rowan and Rasmussen, 1994; Equation (5)) applicable to both freshwater and marine systems based on whether fish were piscivorous or non-piscivorous, and measures of K and suspended sediment concentrations in the water column. The model predicts 1) greater C_r for piscivorous fish, 2) smaller C_r in waters with greater K concentrations and 3) smaller C_r in waters with greater suspended sediment concentrations. The model has been shown to predict C_r within a factor of 2 for a majority of cases (Smith et al., 2000).

Although accurate, the model contains two limiting aspects. One limitation is that in its current form it requires input data for both K concentrations and suspended sediment concentrations. The other limitation is that the model requires a judgment of whether a fish

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species is piscivorous or nonpiscivorous. Although some fish, at least as adults, are clearly piscivorous (*e.g.*, the northern pike *Esox lucius*; nomenclature for common and scientific names follows fishbase.org), others are clearly non-piscivorous (*e.g.*, the white sucker *Catostomus commersoni*). Many species show varying proportions of fish and other food items in their diet, and even among nonpiscivorous fish there are differences in trophic levels and potential concentrations of Cs in their diets. These differences occur between fish that are primarily herbivorous and those that are carnivorous but feed on invertebrates.

Recently, an extensive online database on the biology and ecology of freshwater and marine fish species (fishbase.org) has been developed and made freely available by the FishBase Global Information System (Froese and Pauly, 2011). It includes information on fish diets and food items from numerous references, and uses this information to compute estimates of mean (±Standard Error, hereafter SE) trophic levels. Fish trophic levels range from 2, indicating an herbivorous diet, through 3, indicating a primarily carnivorous diet of herbivorous species, and through 4 indicating a primarily carnivorous diet composed of other carnivorous species. For example, mean trophic levels (±SE) computed using a random resampling of reported food items for *C. commersoni* and *E. lucius* are 2.46 ± 0.16 and 4.40 ± 1.05, respectively.

The purposes of this study were 1) to combine these newly available estimates of trophic levels with the data compiled by Rowan and Rasmussen (1994) to produce an alternative predictive model for the concentration ratios of Cs isotopes in freshwater fish and 2) to test the accuracy of this model's predicted C_r using independent data from several sources.

2. Materials and methods

Three data sources were employed in this study to produce and test models to predict C_r for fish. These were: 1) the trophic level estimates from fishbase.org; 2) the data from Rowan and Rasmussen (1994) on fish C_r and the concentrations of K and suspended sediment in the water column that were used in model construction; and 3) test data of measured C_r compiled from several literature sources that were used to assess the accuracy of the predicted C_r.

2.1. Trophic level data

The trophic level estimates were obtained from fishbase.org where data on fish biology and ecology have been compiled for >30,000 species from >45,000 references and made available in various Asian and European languages. Species data may be accessed by searching either common or scientific names. Where taxonomic revisions have been made to scientific names, a search initiated using the previous name leads to the modern synonym and the appropriate data.

Several alternative methods are used in fishbase.org to estimate a mean ± SE tropic level, and the method employed depends on whether the available data from literature sources comprises 1) just lists of food items consumed or 2) more quantitative analyses of diet composition. Where both types of data are available, multiple estimates of trophic level may be made. When using lists of food items consumed, trophic level is estimated using a randomized resampling of the listed items. Where more quantitative data on diet consumption is available, the trophic level is computed from the relative proportion of the food items consumed in a process similar to that used by Vander Zander and Rasmussen (1996) to compute trophic level effects on PCB contamination in fish. These different procedures may produce different estimates of trophic level. For example, the random resampling of 31 food items for *Perca fluviatilis* (European perch) indicated a mean (±SE) trophic level of 3.66 ± 0.58, but an analysis of diet composition for adult fish indicated a mean trophic level of 4.35 ± 0.75. For all methods, the trophic level of the fish is computed as 1 plus the mean trophic level computed for its diet (*i.e.*, a fish whose diet has a mean trophic level of 2.5 would have a trophic level of 3.5). These estimation methods have been shown to agree with those computed from stable isotopic ratios (Kline and Pauly, 1988). Where data are lacking on diets, a fish's trophic level is inferred from a taxonomically related species of similar size.

Because trophic level estimates computed using the random resampling procedures were available for the majority of the species involved in this study, they have been used in the models to predict C_r. However, the potential effects of using the alternative estimates, such as those for *P. fluviatilis*, will also be discussed. These random resampling trophic levels are computed from a list of n food items, each with its own assigned trophic level, by: 1) randomly choosing one item and assigning it the largest fraction of the diet; 2) randomly selecting each of the remaining $n - 1$ items and assigning each a successively smaller fraction of the diet; 3) computing a trophic level estimate for the diet from the sum of the product of each item's trophic level and assigned proportion in the diet; 4) repeating this random selection process for a total of 100 times; and 5) computing mean and standard error from the 100 replicates.

2.2. The modeling data

The development of the predictive model was based on the data for freshwater fishes compiled by Rowan and Rasmussen (1994; Table 1) in conjunction with the newer estimates of trophic levels from the FishBase database. The Rowan and Rasmussen (1994) data included the fish's scientific name and the location of the study, the wet mass Cs concentration in the fish's whole body or muscle, the Cs concentration in the water, the K concentration in the water (μM K L^{-1}) and, for some locations, the suspended sediment load (mg L^{-1}) (Table 1). Cesium concentrations were alternatively expressed as mass for ^{133}Cs and Bq for ^{137}Cs, and no distinction was made between the C_r for ^{133}Cs and ^{137}Cs. These data contained no distinction between concentrations for whole fish and those for only muscle tissue and, as a consequence, no distinction with regard to muscle versus whole-body made in the subsequent use of the model to predict C_r in fish.

Rowan and Rasmussen's (1994) study contained data for 244 observations on more than 60 species of fish from 46 locations in freshwater systems in Europe and North America, but two sets of their data were excluded from the modeling analysis in this study. First, those species which occurred in only a single location were excluded. Second, all data from locations on the U. S. Department of Energy's Savannah River Site (hereafter, SRS) were also excluded. Studies at the SRS (Newman and Brisbin, 1990; Whicker et al., 1990; Pinder et al., 2009) have consistently reported relatively small K concentrations in the water and relatively large C_r for fish species.

Table 1
The mean, n = number, standard deviation, median, minimum and maximum for the predictor variables trophic level, concentrations of K (μM L^{-1}), and suspended samples (mg L^{-1}) in the water. Trophic levels are computed for 44 species. Concentrations of K and suspended sediments are computed for 43 and 14 locations, respectively.

Variable	n	Mean	Standard deviation	Median	Minimum	Maximum
Trophic level	44	3.47	0.48	3.53	2.40	4.42
K	43	67.9	90.6	36	8	512
Suspended sediment	14	10.4	18.6	3.4	0.21	70.7