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Cesium accumulation by aquatic organisms at different trophic levels following an experimental release into a small reservoir

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ABSTRACT

The rates of accumulation and subsequent loss of stable cesium (^{133}Cs) by organisms at different trophic levels within plankton-based and periphyton-based food chains were measured following the addition of ^{133}Cs into a small reservoir near Aiken, South Carolina, USA. An uptake parameter u (L kg^{-1} d^{-1} dry mass) and a loss rate parameter k (d^{-1}) were estimated for each organism using time–series measurements of ^{133}Cs concentrations in water and biota, and these parameters were used to estimate maximum concentrations, times to maximum concentrations, and concentration ratios (C_r). The maximum ^{133}Cs concentrations for plankton, periphyton, the insect larva *Chaoborus punctipennis*, which feeds on plankton, and the snail *Helisoma trivolvis*, which feeds on periphyton, occurred within the first 14 days following the addition, whereas the maximum concentrations for the fish species *Lepomis macrochirus* and *Micropterus salmoides* occurred after 170 days. The C_r based on dry mass for plankton and *C. punctipennis* were 1220 L kg^{-1} and 5570 L kg^{-1}, respectively, and were less than the C_r of 8630 L kg^{-1} for periphyton and 47,700 L kg^{-1} for *H. trivolvis*. Although the C_r differed between plankton-based and periphyton-based food chains, they displayed similar levels of biomagnification. Biomagnification was also indicated for fish where the C_r for the mostly nonpiscivorous *L. macrochirus* of 22,600 L kg^{-1} was three times less than that for mostly piscivorous *M. salmoides* of 71,500 L kg^{-1}. Although the C_r for *M. salmoides* was greater than those for periphyton and *H. trivolvis*, the maximum ^{133}Cs concentrations for periphyton and *H. trivolvis* were greater than that for *M. salmoides*.

1. Introduction

Much of the understanding of Cs behavior in lentic systems has been derived from studies of weapons fallout (e.g., Kolehmainen et al., 1966, 1967a; Whicker et al., 1972), local releases from nuclear facilities (e.g., Alberts et al., 1979; Evans et al., 1983; Voshell et al., 1985; Whicker et al., 1990; Milintawisamai and Panyatipsakul, 1991) and the Chernobyl accident (e.g., Hakanson et al., 1992; Vakulovsky et al., 1994; Kryshev, 1995; Smith et al., 1997, 1999, 2002). A major emphasis of these studies has been Cs accumulation by fish (e.g., Hakanson et al., 1992; Smith et al., 2002; Sundbom et al., 2003; Saxen, 2007) because of their importance in the human diet and their convenient use as indicator organisms. Less emphasis has been placed on the biota comprising the food chains that lead to fish.

There have also been relatively few experimental studies where controlled amounts of Cs isotopes have been released into lakes and reservoirs and the fate of this release followed by intensive sampling of biota (Pendleton and Hanson, 1958; Kolehmainen et al., 1967b; Hakonson and Whicker, 1975; Hesslein, 1987; Bird et al., 1998a, 1998b). Because of the diversity and complexity of even small lakes, such experimental studies have been unable to consider all members of the biota or all the linkages in the food webs. Instead, the studies have sampled representative biotic elements from different trophic levels. These experimental studies have more often involved deeper lakes where pelagic food webs dominate (Kolehmainen et al., 1967b; Hesslein, 1987; Bird et al., 1998a, 1998b) rather than shallower lakes where littoral food webs are more important (Pendleton and Hanson, 1958; Kolehmainen et al., 1967b).

The primary purposes of this paper are to document the uptake and loss rates of cesium in biota at different trophic levels following

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an experimental release of stable ^{133}Cs into the surface water of Pond 4, a small, shallow reservoir in the southeastern United States. Previous reports describing the results of releasing the ^{133}Cs into the water column of Pond 4 have 1) contrasted the behavior of ^{133}Cs additions in the pond to those in mesocosms and limnocorrals (Hinton et al., 2002), 2) examined the effect of the ^{133}Cs addition on the remobilization of ^{137}Cs from the sediments (Pinder et al., 2005), 3) demonstrated the importance of foliar uptake of Cs from the water column by macrophytes (Pinder et al., 2006), 4) compared the Cs accumulation in fish in Pond 4 to that for other experimental and Chernobyl-contaminated systems (Pinder et al., 2009), and 5) contrasted the effect of summer anoxia on Cs concentrations in the water column between Pond 4 and the neighboring and deeper Par Pond and Pond B (Pinder et al., 2010). The results presented in this paper 1) compare the responses of plankton-based and periphyton-based food chains within Pond 4 and 2) contrast the Pond 4 results with those in other lentic systems. To summarize results and facilitate comparisons among components, the uptake and loss rate parameters have been estimated for a simple model of Cs accumulation by biota. These model parameters have also been used to 1) estimate dry-mass concentration ratios (C_r) and 2) to compare these C_r among trophic levels to test for possible biomagnification of Cs.

2. Modeling approach

2.1. Model structure

To model the transient behavior of the concentrations of Cs isotopes in biota, several researchers and modelers have employed the simple uptake and loss model

$$\frac{B(t)}{d\,t} = u{*}W(t) - k{*}B(t) \qquad (1)$$

where u is an uptake constant with units L kg^{-1} d^{-1} and k is a first-order loss rate constant with units d^{-1}, W(t) is the dissolved Cs concentration in water (mg or Bq Cs per L), and B(t) is the Cs concentration in biota (mg or Bq Cs per kg dry mass). Thomann (1981) used a similar approach for modelling ^{239}Pu and ^{137}Cs in aquatic food chains. Smith et al. (2002) used Eq. (1) to examine the temporal dynamics of ^{137}Cs in fish from Chernobyl-contaminated lakes, and Smith et al. (2006) and Smith (2006) have contrasted the approach of Eq. (1) with the use of models based on concentration ratios (C_r) for non steady-state river systems. This modelling approach has been previously used in Pond 4 to analyze the temporal dynamics of ^{133}Cs in macrophytes (Pinder et al., 2006) and fish (Pinder et al., 2009). Other, more mechanistic models (e.g., Hakanson, 2000) exist to predict Cs behavior in lake food chains, but Eq. (1) is employed in this analysis because the purpose is not so much to predict movement as it is to summarize the pattern of movement into a few simple parameters that may be used to readily compare patterns among biotic components.

The parameters u and k in Eq. (1) will be referred to as uptake and loss rather than absorption and elimination because their estimated values may measure more than just physiological processes. Two separate interpretations of u are illustrated in Fig. 1 for different trophic levels within a simple food chain. For producer components (P), such as periphyton, which absorb Cs directly from the water column (W), u is an estimate of absorption rate, and the transfer $t_{1,2}$ between the water and the producer component in Fig. 1 may be expressed as u*W(t). For the first-order consumer (FOC) and second-order (SOC) consumer compartments in Fig. 1, u is not a measure of absorption from the water column or absorption from ingestion of the precursor compartment. Rather it is a measure of the transfer through the pathways from the water to the ith component, and u increases with the magnitudes of the transfers $t_{i-1,\,i}$ and declines with the magnitudes of the transfers $t_{i-1,\,0}$. The factors affecting u become increasingly complex with increases in the number of trophic levels and increases in the number of alternative pathways from the water to the consumer. For this reason, u may decline as trophic level increases despite an increase in assimilation efficiencies of Cs absorption from ingested material at higher trophic levels. This interpretation of u for consumers assumes that Cs in consumers is primarily absorbed from ingested materials.

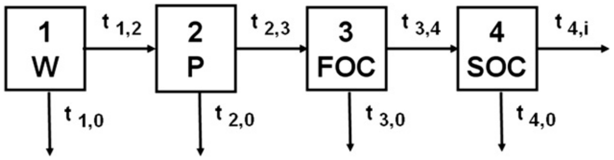

Fig. 1. Illustration of a simple food chain pathway for Cs where W = water, P = producer, FOC = first-order consumer, and SOC = second-order consumer. The $t_{i,\,j}$ indicates transfers where $t_{1,\,0}$ indicates loss of Cs from the water column, $t_{1,\,2}$ = absorption of Cs from the water column by the producers, $t_{i,\,0}$ for $i \geq 2$ indicates loss from the biota due to excretion as well as losses due to mortality, emigration and other causes, and $t_{i,i+1}$ for $i \geq 2$ indicates consumption by higher trophic levels.

The parameter k in Eq. (1) is a measure of loss that incorporates both the transfers $t_{i,\,0}$ and $t_{i,\,i+1}$ in Fig. 1. The $t_{i,\,0}$ loss involves bio-elimination (i.e., excretion and egestion from individuals) as well as losses from the population due to emigration and mortality. Because B(t) is expressed as a concentration, k may also include the effects of growth dilution (Thomann, 1981). The effects of predation, represented by the transfers $t_{i,\,i+1}$, on k for the ith component are affected by the pattern of consumption. Where concentrations are uniform among individuals in the ith component, consumption by higher trophic levels may have little impact on concentrations and k. Where individuals in the ith component with larger concentrations are preferentially consumed, k is increased. Where individuals with smaller concentrations are preferentially consumed, k is decreased.

2.2. Procedures for estimating u and k

The estimation of u and k for Cs in Pond 4 involved a two-step process. First, the declines in Cs concentrations in water following the experimental addition were approximated using a multi-component exponential equation (Whicker and Shultz, 1982) of the form:

$$W(t) = \sum_{i} a_i{*}e^{(-b_i{*}t)} \qquad (2)$$

where W(t) = the dissolved Cs concentration (μg ^{133}Cs L^{-1}) in water, a_i = the initial concentration of the ith component and b_i = the rate constant for exponential decline in the ith component, and t = time in days following the release. In the second step, estimates of u and k are obtained by fitting the following equation (Whicker and Shultz, 1982) to the time series of Cs concentrations measured in biota

$$B(t) = u{*}\sum_{i} \frac{a_i}{(k-b_i)}{*}\left(e^{(-b_i{*}t)} - e^{(-k{*}t)}\right) \qquad (3)$$

where the a_i and b_i are from Eq. (2), and B(t) is the concentration (mg ^{133}Cs kg^{-1} dry mass) in biota. In applying Eq. (3), the initial Cs concentrations in the biota (i.e., B(0)) have been treated as negligible.

In addition to the estimates of u and k, two other metrics of Eq. (3) are important. These are 1) the time to the maximum concentration observed in the biota which is a convenient measure of the rate of passage of the Cs addition through components of different trophic levels, and 2) the maximum concentration occurring in the biota at