THESIS

THE ASSIMILATION AND ELIMINATION OF CESIUM BY FRESHWATER INVERTEBRATES

Submitted by

Tracy M. Tostowaryk

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY TRACY M. TOSTOWARYK ENTITLED "THE ASSIMILATION AND ELIMINATION OF CESIUM BY FRESHWATER INVERTEBRATES" BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

Committee on Graduate Work

[redacted]

Adviser

[redacted]

Co-Adviser

[redacted]

Director

ABSTRACT OF THESIS

THE ASSIMILATION AND ELIMINATION OF CESIUM BY FRESHWATER INVERTEBRATES

Freshwater invertebrates are important vectors of radioactive cesium (^{134}Cs and ^{137}Cs) in aquatic food webs, yet little is known about their cesium uptake and loss kinetics. This study provides a detailed investigation of cesium assimilation and elimination by freshwater invertebrates. Using five common freshwater invertebrates (*Gammarus lacustris, Anisoptera* sp. nymphs, *Claassenia sabulosa and Megarcys signata* nymphs, *and Orconetes* sp.), a variety of food types (oligochaete worms, mayfly nymphs and algae) and six temperature treatments (3.5 to 30 °C), the following hypotheses were tested: 1) cesium elimination rates are a positive function of water temperature; 2) cesium elimination rates increase with decreasing body size; 3) assimilation efficiencies range between 0.6 and 0.8 for diet items low in clay.

Cesium loss exhibited first order, non-linear kinetics, best described by a two component exponential model. Cesium assimilation efficiencies were higher for invertebrates fed oligochaetes (0.77) and algae (0.80) than those fed mayfly nymphs (0.20). Cesium elimination rate constants ranged from 0.002 to 0.125 d^{-1} across taxa and temperatures. Within each taxon, linear regressions of the natural logarithm of cesium elimination rate constants on temperature yielded positive, significant relationships. As

temperature coefficients were not significantly different across taxa, the data were combined into a general model of cesium elimination by freshwater invertebrates as a function of temperature, body size and a categorical variable for thermal optima (warmwater and cool-water adapted taxa). Cesium elimination rate constants were found to increase with temperature, decrease with body size, and be much lower for warmwater adapted invertebrates than cool-water adapted invertebrates. Both the cesium assimilation efficiencies and general model of cesium elimination rate constants for freshwater invertebrates are in excellent agreement with those for fish.

Quantification of cesium assimilation efficiencies and elimination rate constants for freshwater invertebrates allows, for the first time, development of dynamic aquatic food web models for risk assessments, and it enables the *in situ* quantification of invertebrate feeding rates and other bioenergetic parameters.

Tracy M. Tostowaryk
Graduate Degree Program in Ecology
Colorado State University
Fort Collins, CO 80523
Fall 2000

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In loving memory of my grandmother (Baba)

Mae Negrych,

who taught me compassion, courage and dedication.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

Introduction

Above ground nuclear weapons tests conducted primarily between the 1950's and 1980's, as well as large scale nuclear accidents, such as Chernobyl in 1986, have released large quantities of radioactive cesium (^{134}Cs and ^{137}Cs) into the atmosphere, which via atmospheric deposition, have resulted in worldwide radiocesium contamination of the environment. Because of its relatively long half-life (30.2 years) and high mobility in food chains (Whicker and Schultz 1982), ^{137}Cs continues to be detectable globally in both aquatic and terrestrial ecosystems. In addition, radiocesium continues to be released into the environment in smaller quantities on more local scales, for example, as routine emissions from nuclear generating stations and nuclear weapons production facilities. Both ^{134}Cs and ^{137}Cs are beta and gamma radiation emitters, and thus pose a radiological hazard to both human and non-human biota. Freshwater invertebrates are important vectors of radiocesium in aquatic food webs (Hewett & Jefferies 1978; Harrison et al. 1990; Hammar et al 1991; Elliott et al. 1992), yet very little is known about the uptake and loss kinetics of this important contaminant in freshwater invertebrates.

Published data on assimilation efficiencies (fractions, unitless) of cesium for freshwater invertebrates are few, whereas, many studies have quantified cesium assimilation efficiencies for fish (Table 1). Kevern et al. (1964) reported ^{134}Cs assimilation efficiencies of 0.17 for mayfly nymphs *Ephemera varia* and 0.30 for midge larvae *Chironomus commutatus,* which were fed organic detritus contaminated with

TABLE 1. Cesium assimilation efficiencies for freshwater invertebrates and fish.

Consumer Organism	Cesium-labeled food item	Assimilation Efficiency	Reference
Mayfly nymphs	organic detritus	0.17	Kevern et al. 1964
Midge larvae	organic detritus	0.30	Kevern et al. 1964
Adult giant water bug	tadpoles	<0.42 *	Guthrie and Brust 1969
Midge larvae	sediment	<0.05 *	Gerking et al. 1976
Brown trout	zooplankton	0.82	Forseth et al. 1992
	freshwater snails	0.76	Forseth et al. 1992
	chironomid larvae	0.55	Forseth et al. 1992
	Gammarus lacustris	0.48	Forseth et al. 1992
	ephemeroptera sp.	0.23	Forseth et al. 1992
Plaice	marine ragworms	0.42	Hewett and Jefferies 1978
Brown trout	brown trout muscle	0.66	Forseth et al. 1992
Golden astro	top minnows	0.73	Aoyama et al. 1978
Pike cichlid	top minnows	0.69	Aoyama and Inoue 1973
Rainbow trout	commercial trout food	0.65	Cocchio et al. 1995
Brown trout	commercial pellets	0.67	Hewett and Jefferies 1978
Carp	algae	0.8	Kevern 1965
Bluegill	algae	0.69	Kolehmainen 1972
Carp	detritus	0.07	Kevern 1965
Bluegill	detritus	0.03	Kolehmainen 1972
Bluegill	algae fed *Chironomus* larvae	0.34 to 0.69	Kolehmainen 1972
Bluegill	sediment fed *Chironomus* larvae	0.07 to 0.16	Kolehmainen 1972

* value interpreted from published data

^{134}Cs. The data of Guthrie and Brust (1969) indicate that the ^{137}Cs assimilation efficiency for adult giant water bug *Lethocerus americanus* (hemipteran) from ^{137}Cs labeled tadpoles was less than 0.42. The data of Gerking et al. (1976) for midge larvae *Chironomus plumosus* indicate that ^{134}Cs assimilation efficiencies from sediment were less than 0.05. It appears that mineral bound cesium is largely unavailable for biological uptake (Kolehmainen 1972; Eyman and Kitchings 1975). Reported values for assimilation of cesium in easily digestible foods by terrestrial invertebrates range between 0.70 and 0.94 (Reichle 1967). Reported cesium assimilation efficiencies for fish are relatively high (0.23 to 0.82) for easily digestible foods such as invertebrates, algae and fish tissue, and are relatively low (0.03 to 0.16) for foods containing clay, such as sediment and detritus (Table 1). Radiocesium assimilation efficiencies for marine invertebrates are not provided because the studies appear to have been limited to cesium uptake from water.

Published information on radiocesium elimination rates of freshwater invertebrates is limited and problematic. Questionable interpretation of the data (Guthrie and Brust 1969; Gerking et al. 1976), lack of pertinent details such as water temperature (Kevern et al. 1964) and body size (Kevern et al. 1964; Harvey 1969; Guthrie and Brust 1969), and lack of sufficient information to determine whether the experiments were conducted for sufficiently long times (Kevern et al. 1964) are major deficiencies of these studies. In spite of these deficiencies, two generalities emerge from these studies. First, Guthrie and Brust (1969) observed an inverse relationship between ^{137}Cs elimination rate and body size of larvae and adult *L. americanus*. Second, the data of Gerking et al. (1976) showed an increase in ^{134}Cs elimination rate with temperature for *C. plumosus*.

In the few limited studies on terrestrial invertebrates, cesium elimination rates were found to be proportional to temperature (Reichle and Crossley 1965; Crossley 1966; Reichle 1967), and inversely proportional to body size (Crossley 1963a; Crossley 1963b). These relationships of cesium elimination rates with temperature and body size are consistent with the larger body of data on fish (see Rowan and Rasmussen (1995) for a review). More data exist in the literature on cesium kinetics of marine invertebrates (e.g., Suzuki et al. 1978), but for the majority of studies, additional mathematical analyses of the data are required in order to obtain the cesium elimination rates.

Most mathematical models describing the uptake of radiocesium by fish and subsequent radiation doses to humans are based on steady-state transfer parameters for water to fish, despite the fact that fish obtain most radiocesium from diet rather than water directly (e.g., Hewett and Jefferies 1978; Harrison et al. 1990). This transfer parameter approach is inappropriate for **dynamic** conditions when radiocesium levels in water and organisms are fluctuating, such as following a pulse release of ^{134}Cs or ^{137}Cs into the environment during an accident (e.g., Chernobyl in 1986) or during clean-up of contaminated sites when radiocesium is resuspended back into the water column. The incorporation of fish dietary items, such as aquatic invertebrates, into truly dynamic mathematical models requires knowledge of the rates of uptake and elimination of cesium by the invertebrates. Cesium uptake rates from food are dependent on the consumption rate, concentration and assimilation efficiency of cesium.

Food consumption rates can be readily estimated once cesium assimilation efficiencies, elimination rate constants and cesium levels in food are known. While the cesium tracer method is a convenient and powerful technique for estimating consumption

rates in the environment under natural conditions, little work has been done in this regard on invertebrates. Crossley and Howden (1961) and Crossley (1963a, 1963b, 1966) estimated food consumption rates of terrestrial insects feeding on vegetation growing in a drained lake bed previously contaminated with ^{137}Cs. The remaining published studies estimated food consumption rates of invertebrates fed either in the laboratory (Reichle (1967) studied terrestrial isopods feeding on ^{134}Cs labeled lettuce; Gerking et al. (1976) studied *C. plumosus* feeding on ^{134}Cs labeled sediment), or in cesium labeled environments (Reichle and Crossley (1965) studied eight species of terrestrial arthropods in a ^{137}Cs labeled forest). Food consumption rates of fish have been the focus of many studies: e.g., Kevern (1965) estimated consumption rates of carp feeding in a ^{137}Cs contaminated lake receiving low-level radioactive wastes; Forseth et al. (1992) estimated food consumption rates of brown trout *Salmo trutta* feeding in a Norwegian lake contaminated by ^{134}Cs and ^{137}Cs released by the Chernobyl accident in 1986. Rowan and Rasmussen (1996) took the cesium tracer method for food consumption a step further, and along with measured growth rates, estimated the bioenergetic cost of fish activity *in situ*. There is interest in food consumption and assimilation by detritus-feeding benthic invertebrates beyond radiocesium transport modeling because these animals contribute greatly to nutrient cycling, energy transfer and sediment structure in lakes, streams and oceans (Gerking et al 1976). Thus, in addition to providing data for cesium transport modeling, quantification of cesium assimilation efficiencies and elimination rates of aquatic invertebrates permits the extension of the bioenergetic techniques of Rowan and Rasmussen (1996), for estimating *in situ* metabolic costs of fish, to aquatic invertebrates in their natural environment.

In this study, I quantify ^{134}Cs assimilation efficiencies and elimination rate constants of five taxa of freshwater invertebrates commonly consumed by fish. Controlled laboratory experiments were carried out on amphipods (*Gammarus lacustris*), dragonfly nymphs (Anisoptera sp.), stonefly nymphs (*Claassenia sabulosa, Megarcys signata*) and crayfish (*Orconectes* sp.) using ^{134}Cs, a gamma emitter (0.605, 0.796 MeV) with a half-life of 2.1 years. The invertebrates were fed a single meal of food labeled with ^{134}Cs, and the ^{134}Cs activity in each individual was measured over time by gamma spectrometry. Cesium becomes distributed throughout the body, in particular soft tissue, and because it is a gamma emitter, radiocesium can be easily measured by gamma spectrometry without killing the organism. The assimilation efficiencies and elimination rate constants of ^{134}Cs were subsequently estimated using non-linear regression techniques. Six different temperatures between 3.5 and 30 °C were utilized, and different sized taxa were employed in order to address the following hypotheses: 1. Cesium elimination rate constants are a positive function of water temperature; 2. Cesium elimination rate constants increase with decreasing body size; 3. Assimilation efficiencies are similar to those for fish, e.g., between 0.60 to 0.80, for diet items low in clay.

Methods

Experimental animals

Gammarus (Crustacea: Amphipoda) typically inhabit cool or cold lentic or lotic waters (Covich and Thorp 1991). Their life-cycle may be completed within a year (Covich and Thorp 1991). Although typically considered herbivores and detritivores, *G.*

lacustris have been observed to prey on smaller invertebrates, such as zooplankton (Wilhelm and Schindler 1999 and references therein).

Dragonflies are an aquatic order of insect (Odonata: Anisoptera), found in both lentic and lotic habitats (two-thirds:one-third) (Hilsenhoff 1991). Although life-cycles may be as long as one to four years, especially in cooler or more northern locations of North America, two generations per year may occur in warmer southern areas where daytime water temperatures may approach 30 °C. Anisoptera nymphs are considered voracious predators.

Stoneflies, another order of aquatic insect (Plecoptera), occur primarily in cool or cold lotic habitats. While most stoneflies are univoltine, *C. sabulosa* (e.g., Allan 1982) and some populations of *M. signata* (Taylor et al. 1999) may take two years to complete their life cycles. Most stonefly nymphs are herbivores, however, those of *Claassenia* (family Perlidae) and *Megarcys* (family Perlodidae) are primarily predaceous, feeding largely on other aquatic insects (Ward and Kondratieff 1992).

Crayfish are another crustacean, order Decapoda. Like the other invertebrates in this study, this order is fairly ubiquitous in the environment, inhabiting a variety of lentic and lotic habitats. Individuals may live as long as eight years (Hobbs 1991). Crayfish are omnivorous, consuming a range of foods from algae to other macroinvertebrates.

Gammarus lacustris were collected from Middle Creedmore Lake, Colorado in May 1998. The water temperature was about 19 °C at the time of collection. Anisoptera nymphs were purchased from Carolina Biological Supply. The temperature of the shipping water was about 20 °C. *Claassenia sabulosa* were collected from the Cache la Poudre River, Colorado in May 1998. The water temperature was about 12 °C at the time

of collection. *Megarcys signata* were collected from the East Fork of the Arkansas River, Colorado in November 1999. The water temperature was about 1 °C at time of collection. *Orconectes* were collected from Watson Lake, Colorado in November 1997 and maintained in the laboratory under ambient conditions. Water temperature at the collection times was about 12 °C.

Experimental design

The invertebrates were maintained at their environmental temperatures for several days before being acclimated to experimental conditions. Experiments were conducted at a potassium concentration of 1 $mg \cdot L^{-1}$ in artificial water constructed by adding 87 mg of synthetic sea salt, Instant Ocean, to 1 L of distilled water. During the acclimation period, *G. lacustris*, Anisoptera and *C. sabulosa* were fed oligochaete worms *Tubifex* sp. to satiation once per week, while *M. signata* were fed diet items consisting of mayfly nymphs of the genera *Baetis*, *Rhithrogena* and *Ameletus*, and *Orconectes* were fed earthworms.

As the primary objective of this study was to evaluate the effect of water temperature on ^{134}Cs elimination, six water temperature treatments were utilized: 3.5, 10, 15, 20, 25 and 30 °C (Table 2). *Gammarus lacustris* were maintained at temperatures from 10 to 25 °C; Anisoptera were maintained at temperatures from 10 to 30 °C; *C. sabulosa* were maintained at temperatures of 3.5, 10 and 15 °C; *M. signata* were maintained at 2.5 °C as an aside to the main study; and *Orconectes* were maintained at temperatures from 3.5 to 30 °C. Three individuals of each taxon, with the exception of

TABLE 2. Experimental design outlining the number of significant replicates at the end of the study per temperature treatment and the ^{134}Cs labeled food provided on the first day of the experiment.

Taxon	Temperature (°C)						^{134}Cs Labeled Food
	2.5-3.5	10	15	20	25	30	
Megarcys signata nymphs	9						Mayfly nymphs (*Baetis*, *Rhithrogena*, *Ameletus* spp.)
Gammarus lacustris		2	3	2	3		Oligochaete worms (*Tubifex* sp.)
Anisoptera sp. nymphs		3	1	2	3	3	Oligochaete worms (*Tubifex* sp.)
Claassenia sabulosa nymphs	2	2	3				Oligochaete worms (*Tubifex* sp.)
Orconectes sp.		5	3	3	3	5	Algae (*Cladophora* sp.)

change per day. *Gammarus lacustris* did not survive acclimation at 3.5 and 30 °C; Anisoptera did not survive acclimation at 3.5 °C; *C. sabulosa* did not survive acclimation at temperatures above 15 °C; *M. signata* did not survive acclimation above 2.5 °C; *Orconectes* survived at 3.5 °C, but not sufficiently long to obtain reliable estimates of elimination rates.

Temperature treatments from 3.5 to 20 °C were carried out in covered 70 L plastic tubs (1 tub per treatment). Tubs were maintained at the following temperatures ± 1 SEM: 3.5 ± 0.0 °C, 10.1 ± 0.1 °C, 15.2 ± 0.1 °C, 20.1 ± 0.1 °C). The 2.5°C treatment for *M. signata* was carried out in one covered 36 L glass aquarium. The water was cooled using West Coast Aquatics chillers and circulated using Tecumseh pumps (AE170AL-165-P2). The 25 and 30 °C treatments were carried out in covered 36 L glass aquaria (3 aquaria per treatment: 24.8 ± 0.1 °C, 24.8 ± 0.2 °C, 24.9 ± 0.1 °C, 30.2 ± 0.0 °C, 29.9 ± 0.0 °C). The water was heated using PENN PLAX heaters (110-120 V, 50-60 Hz) and circulated by power filters (Whisper Power Filter and Tetra/Second Nature:115 V, 60 Hz). Each organism was housed in a polyvinylchlorinated (PVC) tube (5-cm diameter x 15 cm) covered at each end with a secured piece of nylon screen. Each tube was suspended horizontally to permit circulation of water. Each 70 L tub contained all three replicates per taxon, while each aquarium contained one replicate per taxon, with the exception of the *M. signata* experiment in which all ten replicates were held in the one aquarium. In order to reduce liquid waste, 1 kg of zeolite contained in a nylon screen bag was placed in each treatment to adsorb ^{134}Cs eliminated by the invertebrates. ^{134}Cs was never detected in gamma measurements of treatment waters during the experiment.

Cesium labeled foods for the invertebrates (Table 2) consisted of *Tubifex* purchased from a local pet store (for *G. lacustris*, Anisoptera and *C. sabulosa*), mayfly nymphs of the genera *Baetis*, *Rhithrogena* and *Ameletus* collected from the Arkansas R. (diet items of *M. signata*), and filamentous algae *Cladophora* sp. collected from Watson Lake and cultured in the lab (diet item of *Orconectes*). The foods were labeled with ^{134}Cs as follows. 3.7×10^4 Bq of ^{134}Cs was added to 100 ml of artificial water and adjusted to pH 7 using 1 M NaOH. Phytoplankton (1 g) was added to the labeled solution as food for *Tubifex* (2g) and mayfly nymphs, and left for one week until the ^{134}Cs levels in *Tubifex* and mayfly nymphs were sufficient for analytical needs. *Cladophora* was labeled by simply adding the algae to labeled solution. Prior to feeding the invertebrates, the labeled foods were thoroughly rinsed 5 times to remove any external ^{134}Cs. This ensured that dissolved ^{134}Cs would not be present during the feeding phase of the experiment.

At the start of the experiment (day 0), each invertebrate was weighed and then fed labeled food to satiation in individual beakers of experimental water. After feeding, each invertebrate was rinsed three times to remove any external contamination. Each invertebrate, with the exception of *Orconectes*, was placed in a 14 x 51 mm plastic counting vial along with enough experimental water to cover it. The same amount of water was used each time for each individual in order to keep counting geometry constant throughout the experiment. ^{134}Cs activity (net counts per second, net cps) of each invertebrate was immediately measured in a low background, high-purity germanium well photon detector system (EG&G ORTEC, model number GWL-200240-S, 100 Midland Rd, Oak Ridge, TN, 37830). *Orconectes* individuals were too large for the small vials, and therefore were placed in 20 ml plastic scintillation vials, which in turn were placed in

a larger container in a set position to keep counting geometry constant. ^{134}Cs activity of *Orconectes* was measured in a coaxial high-purity germanium well detector (EG&G ORTEC, model number GMX-80230-S). The net cps for the 0.605 and 0.796 MeV ^{134}Cs gamma peaks were averaged for data analysis. The ^{134}Cs activity of each invertebrate was subsequently measured on days 1, 2, 4 and 7 following the initial measurement and then approximately every week thereafter until either the slow component of the elimination rate remained constant or the invertebrate died, whichever came first. Experiments ranged between 7 and 135 days. The invertebrates were fed to satiation weekly with unlabeled food (*Tubifex* or chironomids for *G. lacustris*, Anisoptera and *C. sabulosa*; mayfly nymphs for *M. signata*; earthworms for *Orconectes*) throughout the experiment. Most invertebrates were weighed before ^{134}Cs activity measurements were made, and body sizes remained relatively constant over the course of the experiment. Occasionally, invertebrates molted, and molted exoskeletons were retained for ^{134}Cs analysis, as this is another possible means of eliminating radiocesium.

Assimilation efficiencies and elimination rate constants of ^{134}Cs were estimated for each invertebrate by performing non-linear regression of the fraction of remaining ^{134}Cs activity on time using SYSTAT computer software (Wilkinson 1997). The following three component exponential equation, which best describes the loss kinetics of cesium in fish (Rowan and Rasmussen 1995), was used as the starting point:

$$A_t/A_0 = \alpha_1 e^{-k_1 t} + \alpha_2 e^{-k_2 t} + \alpha_3 e^{-k_3 t} \qquad \text{eqn 1}$$

where A_0 = initial ^{134}Cs activity (cps), A_t = ^{134}Cs activity (cps) at time t corrected for physical decay, t = time in days, α_n = fraction of ^{134}Cs in each compartment or pool, and k_n = elimination rate constant (d^{-1}) for each pool. The most rapid component of radiocesium

elimination ($\alpha_1 e^{-k_1 t}$) reflects radiocesium that is not assimilated by the organism (egestion). The other components of elimination reflect radiocesium assimilated by the organism ($\alpha_2 + \alpha_3 - \alpha_1$) and taken up by different tissue compartments. Statistically insignificant exponential terms ($p > 0.05$) were removed and regressions re-run until only statistically significant exponential terms remained.

Only those results which were considered to be statistically and biologically significant are provided in the results section. The results were considered to be significant if the following two conditions were met: 1) the mathematical model and parameters (i.e., assimilation efficiency and elimination rate constant) were statistically significant ($p \leq 0.05$); and, 2) the elimination rate of assimilated ^{134}Cs was relatively constant through time. This latter condition required that the experiment be carried out for a sufficiently long time and that a sufficient number of ^{134}Cs activity measurements be obtained for a given invertebrate. By estimating the elimination rate constants as new data were collected, it was possible to determine if the elimination rates had become constant in time. As temperature increased, fewer measurements were necessary to satisfy the criterion because ^{134}Cs elimination rates were faster.

For each taxon, assimilation efficiencies and elimination rate constants were regressed on temperature and body size using appropriate linear or non-linear models. Data were transformed using the natural logarithm (ln) if results of studentized residual plots indicated heterogeneity of variance. Analysis of variance (ANOVA) was used to test the hypothesis that mean assimilation efficiencies differed among taxa using SAS computer software (SAS Institute Inc. 1999). A general invertebrate cesium elimination model, with elimination rate as the dependent variable and temperature and body size as

independent variables, was investigated using linear (in SAS) and non-linear (in SYSTAT) regression techniques.

For comparison with data from this experiment, published biological half-times (T_b, d) were converted to elimination rate constants (k, d^{-1}) using the equation:

$$k = \ln 2 / T_b \qquad \text{eqn 2}$$

Biological half-time of a radioisotope is, by definition, the time required for an organism to eliminate one-half of its body burden of the radioisotope.

Results and Discussion

Estimating ^{134}Cs assimilation efficiencies and elimination rate constants

For each invertebrate, the loss of ^{134}Cs over time (i.e., graphically represented as the fraction of initial ^{134}Cs activity versus time) following an acute intake of ^{134}Cs exhibited non-linear, first-order kinetics (Appendices A through E). The data for the majority of invertebrates (36 of 57) were mathematically best described by the following two component exponential model:

$$A_t/A_0 = \alpha_1 e^{-k_1 t} + \alpha_2 e^{-k_2 t} \qquad \text{eqn 3}$$

where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t corrected for physical decay, t = time in days (d), α_1 = unassimilated fraction of ^{134}Cs, k_1 = elimination rate constant of unassimilated ^{134}Cs (d^{-1}), α_2 = assimilated fraction of ^{134}Cs (i.e., assimilation efficiency), and k_2 = elimination rate constant of assimilated ^{134}Cs (d^{-1}). The first component is assumed to represent the short term or fast pool of ^{134}Cs, in other words, the ^{134}Cs that is not assimilated by the organism, but rather is egested. The second component is taken to represent the longer term or slower pool, that is, the ^{134}Cs that is

assimilated by the organism and taken up into tissues before being excreted. No data conformed to a three component model, suggesting that ^{134}Cs is eliminated from a single dominant tissue pool in these aquatic invertebrates. Fig. 1 shows a typical set of ^{134}Cs loss data. These results are supported by the studies of Guthrie and Brust (1969) on *L. americanus* nymphs and adults, and Gerking et al. (1976) on *C. plumosus*. Three component cesium elimination models are typical for fish (Rowan and Rasmussen 1995), indicating that different tissue pools with different rates of cesium elimination are likely involved in the overall elimination of cesium for fish.

One component exponential models were utilized for the remaining invertebrates. In most cases, two exponential curves were evident, but use of two component models with SYSTAT was not appropriate for reasons that follow. In three cases (two *C. sabulosa* at 3.5 and one at 10 °C), the ^{134}Cs activity levels unexpectedly remained constant for the initial few days of the experiment. This may have occurred because radiolabeled food was attached to the external surface of the invertebrate during the initial few days despite the thorough rinsing of the invertebrate. Alternatively, the invertebrate may not have cleared its gut for several days. For these cases, one component exponential models were utilized after removing data from days 0, 1 and sometimes 2, and no assimilation efficiencies were estimated. In one case (Anisoptera at 10 °C), the uneveness of the initial data points resulted in an underestimation of the slope of the second component (i.e., k_2), using a two component model with SYSTAT. Use of a one component model, starting at day 29, eliminated this bias. In four cases (three *G. lacustris* at 25 °C, one Anisoptera at 30 °C), there were too few points to obtain the overall statistics for a two component model. Since these cases were at higher

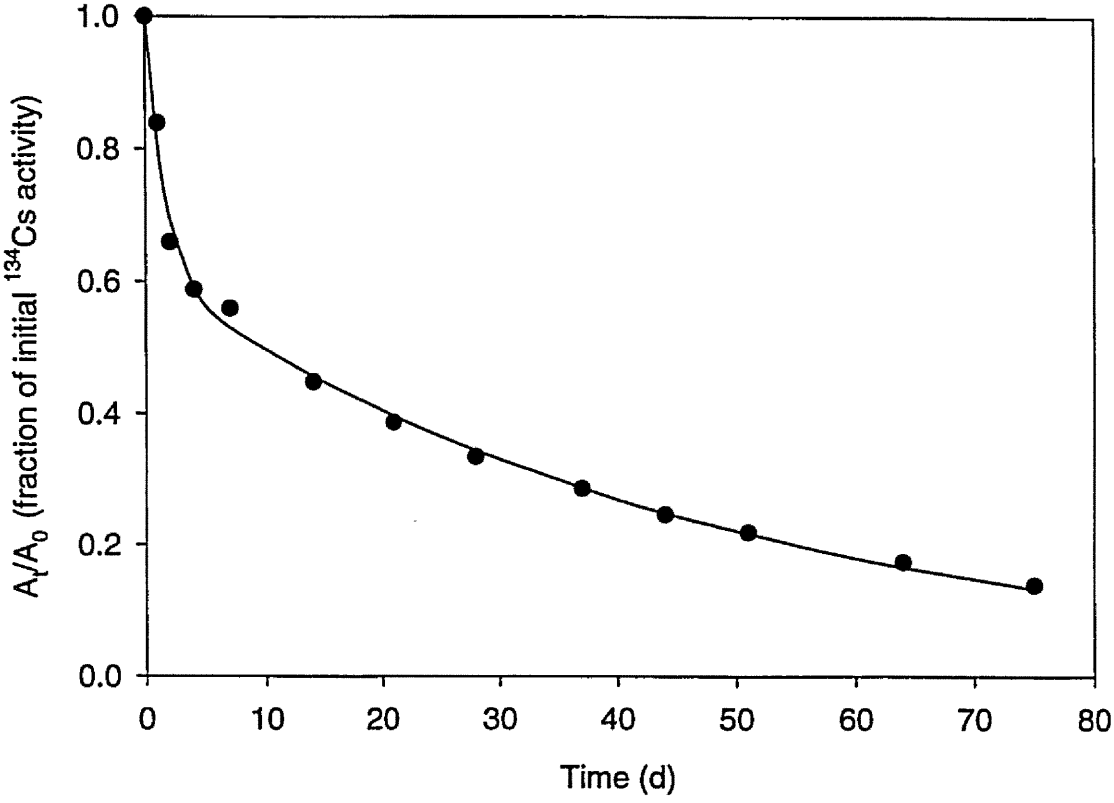

Fig. 1. Typical ^{134}Cs elimination data for freshwater invertebrates represented by a *Claassenia sabulosa* nymph at 15 °C (CL-3-2). The data (•) are best described by a two component exponential model (——) of the form: $A_t/A_0 = \alpha_1 e^{-k_1 t} + \alpha_2 e^{-k_2 t}$, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d), α_1 = unassimilated fraction of ^{134}Cs, k_1 = elimination rate constant of unassimilated ^{134}Cs (d^{-1}), α_2 = assimilation efficiency of ^{134}Cs, and k_2 = elimination rate constant of assimilated ^{134}Cs (d^{-1}).

temperatures where gut clearance was observed to be more rapid, one component models were used after removing day 0 data. For *M. signata*, gut clearance was so rapid and assimilation of ^{134}C so low (e.g., < 0.3), that use of the two component model with SYSTAT resulted in an underestimation of the slope of the second component (i.e., k_2). Use of one component models starting after the observed gut clearance times (usually around day 14) resolved this problem. One component models were utilized for six crayfish which were moved to different temperature treatments later in the experiment (three from 25 to 10 °C, three from 20 to 30 °C) to eliminate the correlation between temperature and body size. The elimination of ^{134}Cs at the new temperatures was represented by one component elimination models since these crayfish were not fed labeled food again, but simply continued to eliminate the initial uptake of ^{134}Cs. It is possible that the elimination rates at the new temperatures were slightly slower than they would have been directly following an acute uptake, since the rates may decline over a long period of time; however, a third component was not evident for any of the invertebrates in this study. Estimated ^{134}Cs elimination rate constants and assimilation efficiencies are listed in Table 3.

^{134}Cs assimilation efficiencies

Estimated assimilation efficiencies of ^{134}Cs from *Tubifex* ranged from 0.47 to 0.98 for *G. lacustris* (mean ± 1 SEM: 0.77 ± 0.06), 0.27 to 0.97 for Anisoptera (mean ± 1 SEM: 0.78 ± 0.05), and 0.61 to 0.76 for *C. sabulosa* (mean ± 1 SEM: 0.70 ± 0.03). The estimated assimilation efficiencies were not significantly related to temperature (with the exception of *G. lacustris*) or body size within each taxon, nor were they related to body

TABLE 3. ^{134}Cs assimilation efficiencies and elimination rate constants (k, d^{-1}) of freshwater invertebrates at different temperatures, along with the number of data points (n) and mean corrected R^2 for the one (*) or two (default) exponential model describing the loss of cesium activity over time.

Taxon (mean weight ± 1 SEM, g)	Temperature °C	Mean Weight ± 1 SEM (g)	n	Assimilation Efficiency	k (d^{-1})	Mean Corrected R^2
Gammarus	10	0.073 ± 0.002	13	0.64	0.014	0.998
lacustris	10	0.074	14	0.49	0.013	0.996
(0.062 ±	15	0.045 ± 0.002	11	0.77	0.053	0.999
0.002 g)	15	0.054 ± 0.002	11	0.95	0.043	0.999
	15	0.053 ± 0.002	11	0.47	0.032	0.997
	20	0.060 ± 0.003	6	0.77	0.085	0.996
	20	0.061 ± 0.003	8	0.87	0.063	0.999
	25	0.061 ± 0.001	4	0.97	0.067 *	0.990
	25	0.071 ± 0.001	4	0.98	0.125 *	0.998
	25	0.070 ± 0.001	4	0.84	0.113 *	0.974
Anisoptera sp.	10	0.213 ± 0.001	17	0.95	0.002	0.991
nymphs	10	0.198 ± 0.001	17	0.97	0.002	0.977
(0.162 ±	10	0.103 ± 0.001	10	0.83	0.003 *	0.977
0.013 g)	15	0.174 ± 0.002	17	0.77	0.004	0.976
	20	0.152 ± 0.002	17	0.90	0.007	0.997
	20	0.203 ± 0.011	17	0.74	0.007	0.981
	25	0.148 ± 0.002	13	0.70	0.016	0.995
	25	0.140 ± 0.001	13	0.77	0.011	0.995
	25	0.139 ± 0.001	14	0.27	0.011	0.995
	30	0.144 ± 0.002	4	0.75	0.037 *	0.915
	30	0.201 ± 0.005	7	0.95	0.013	0.998
	30	0.130 ± 0.128	6	0.77	0.032	0.995
Claassenia	3.5	0.138 ± 0.002	13	0.72	0.003	0.996
sabulosa	3.5	0.120 ± 0.004	8	-	0.005 *	0.989
nymphs	10	0.208 ± 0.007	13	0.71	0.012	0.994
(0.192 ±	10	0.158 ± 0.006	8	-	0.017 *	0.999
0.005 g)	15	0.235 ± 0.013	13	0.76	0.015	0.994

	15	0.240 ± 0.004	13	0.61	0.019	0.996
	15	0.242 ± 0.001	9	-	0.018 *	0.983
Megarcys signata nymphs (0.041 ± 0.007 g)	2.5	0.024	5	0.15	0.013 *	0.984
	2.5	0.040	4	0.23	0.012 *	0.981
	2.5	0.063	4	0.25	0.012 *	0.999
	2.5	0.036	8	0.16	0.012 *	0.992
	2.5	0.040	6	0.13	0.012 *	0.991
	2.5	0.033	6	0.18	0.014 *	0.998
	2.5	0.028	6	0.27	0.012 *	0.978
	2.5	0.022	8	0.22	0.013 *	0.993
	2.5	0.083	5	0.19	0.012 *	0.985
Orconectes sp. (2.468 ± 0.220 g)	10	3.270	12	0.79	0.005	0.980
	10	3.252	12	0.70	0.004	0.984
	10	1.783	7	-	0.005	0.976
	10	1.227	6	-	0.003 *	0.974
	10	1.209	6	-	0.004 *	0.926
	15	1.978	12	0.74	0.007	0.993
	15	2.063	12	0.83	0.007	0.996
	15	2.071	12	0.71	0.005	0.967
	20	2.775	12	0.87	0.004	0.985
	20	2.410	12	0.75	0.006	0.986
	20	3.913	12	0.64	0.007	0.991
	25	1.908	12	0.76	0.009	0.996
	25	1.118	12	0.91	0.011	0.998
	25	1.009	12	0.99	0.008	0.995
	30	1.930	8	0.84	0.016	0.994
	30	2.013	8	0.95	0.013	0.993
	30	1.548	9	0.78	0.019	0.998
	30	3.216	7	-	0.010 *	0.988
	30	3.622	7	-	0.008 *	0.975

size across taxa. For *G. lacustris*, a weak positive relationship existed between assimilation efficiency and temperature (adjusted $R^2 = 0.48$, temperature coefficient $p = 0.02$). Mean assimilation efficiencies for *G. lacustris*, Anisoptera and *C. sabulosa* did not differ significantly among taxa, based on one-way ANOVA ($p = 0.72$). Since the assumption of constant variances was violated in this test and no suitable transformation of the assimilation efficiency was possible, a nonparametric alternative, the Kruskal-Wallis test, was used and yielded the same result of no significant difference ($p = 0.23$). Thus, the ^{134}Cs assimilation efficiencies obtained in this study for easily digestible material of animal origin can be represented by an overall mean assimilation efficiency ± 1 SEM of 0.77 ± 0.03. Assimilation efficiencies of ^{134}Cs from *Cladophora* for crayfish were similar to those estimated from *Tubifex*, ranging from 0.64 to 0.99 (mean ± 1 SEM: 0.80 ± 0.03).

The estimated average ^{134}Cs assimilation efficiency of 0.78 from *Tubifex* and 0.80 for *Cladophora* are in the range of expected values for easily digestible foods that do not contain cesium binding materials such as sediment. The data of Guthrie and Brust (1969) for *L. americanus*, which consumed tadpoles containing ^{137}Cs, indicate that the assimilation efficiency would have been less than 0.42. No information was provided regarding the quality of the labeled food (e.g., whether or not the tadpoles contained sediment). Reichle (1967) reported cesium assimilation efficiencies ranging between 0.70 and 0.94 for four species of terrestrial isopods that consumed cesium labeled lettuce. Assimilation efficiencies of radiocesium from food for fish on average have low variability, ranging between about 0.64 from invertebrate tissue, to about 0.69 from fish tissue (Rowan and Rasmussen 1996); however, values for individual invertebrate dietary

items have a wider range of variability, ranging from 0.23 to 0.82 (Forseth et al. 1992; Hewett and Jefferies 1978; Kolehmainen 1972). Similar assimilation efficiencies for fish from algae (0.8, Kevern 1965; 0.687, Kolehmainen 1972) have been obtained.

Kevern et al. (1964) reported much lower ^{134}Cs assimilation efficiencies for aquatic invertebrates which consumed organic detritus (0.17 for *E. varia* nymphs, 0.30 for *C. commutatus* larvae). Similarly, lower ^{137}Cs assimilation efficiencies for fish have been obtained from detritus (0.03, Kolehmainen 1972; 0.07, Kevern 1966), and from sediment fed *Chironomus* larvae (0.07 to 0.16, Kolehmainen 1972) reflecting the very high partition coefficient (k_d) of radiocesium between sediment and water (10^1 to 10^5 in freshwater; IAEA 1994). Gerking et al.'s (1976) data indicates ^{134}Cs assimilation efficiencies less than 0.05 for *C. plumosus* fed ^{134}Cs contaminated sediment. It appears that mineral bound cesium is largely unavailable for biological uptake (Kolehmainen 1972; Eyman and Kitchings 1975).

In sharp contrast, the assimilation efficiencies of ^{134}Cs labeled mayfly nymphs by *M. signata* were much lower than those for ^{134}Cs labeled *Tubifex* or *Cladophora*, ranging from 0.13 to 0.27, with a mean $\pm$ 1 SEM of 0.20 ± 0.02. It is interesting to note that Forseth et al. (1992) also found low assimilation efficiencies (0.23) of ^{134}Cs for mayfly nymphs fed to trout. The reasons for such distinct differences between the assimilation efficiencies of ^{134}Cs from *Tubifex* and *Cladophora*, and those from mayfly nymphs are not known. Residual sediment in the mayfly nymphs could account for minimal ^{134}Cs being available for uptake by consumer organisms; however, the mayfly nymphs in this study were kept in filtered water three days before being labeled with ^{134}Cs, and analyses of gut contents indicated that their guts had cleared completely prior to labeling. Given

that uptake by exoskeleton was not observed in any of the taxa, it is unlikely that the labeled mayfly nymphs had incorporated any ^{134}Cs into exoskeleton.

^{134}Cs elimination rate constants

Elimination rate constants of ^{134}Cs increased with temperature for *G. lacustris*, Anisoptera, *C. sabulosa*, and *Orconectes*. These findings are consistent with those by Gerking et al. (1976) for aquatic *C. plumosus*, Reichle and Crossley (1965), Crossley (1966) and Reichle (1967) for terrestrial arthropods, and by many studies on fish (see review by Rowan and Rasmussen 1995). *Gammarus lacustris* displayed the fastest elimination rate constants of the taxa, ranging from 0.010 to 0.125 d^{-1} (T_b of 67 to 6 d) for temperatures 10 to 25 °C. The elimination rate constants for *C. sabulosa* were slower, ranging from 0.003 to 0.019 d^{-1} (T_b of 224 to 36 d) for temperatures from 3.5 to 15 °C. Anisoptera and *Orconectes* exhibited the slowest elimination rate constants of the taxa, ranging from 0.002 to 0.037 d^{-1} (T_b of 423 to 19 d) for the former and from 0.003 to 0.019 d^{-1} (T_b of 258 to 37 d) for the latter, for temperatures 10 to 30 °C. The elimination rate constants for *M. signata* ranged from 0.012 to 0.014 d^{-1} (T_b of 60 to 48 d) at 2.5 °C.

Within each taxon, elimination rates were not significantly related to body size. Size differences in this study were likely too small to be incorporated into the statistical models (Table 3). However, within each taxon, elimination rates were significantly related to temperature (Figure 2), using the following linear regression of the ln of the elimination rate constant (k, d^{-1}) on temperature (T,°C):

$$\ln k = \beta_1 + \beta_2 T \qquad \text{eqn 4}$$

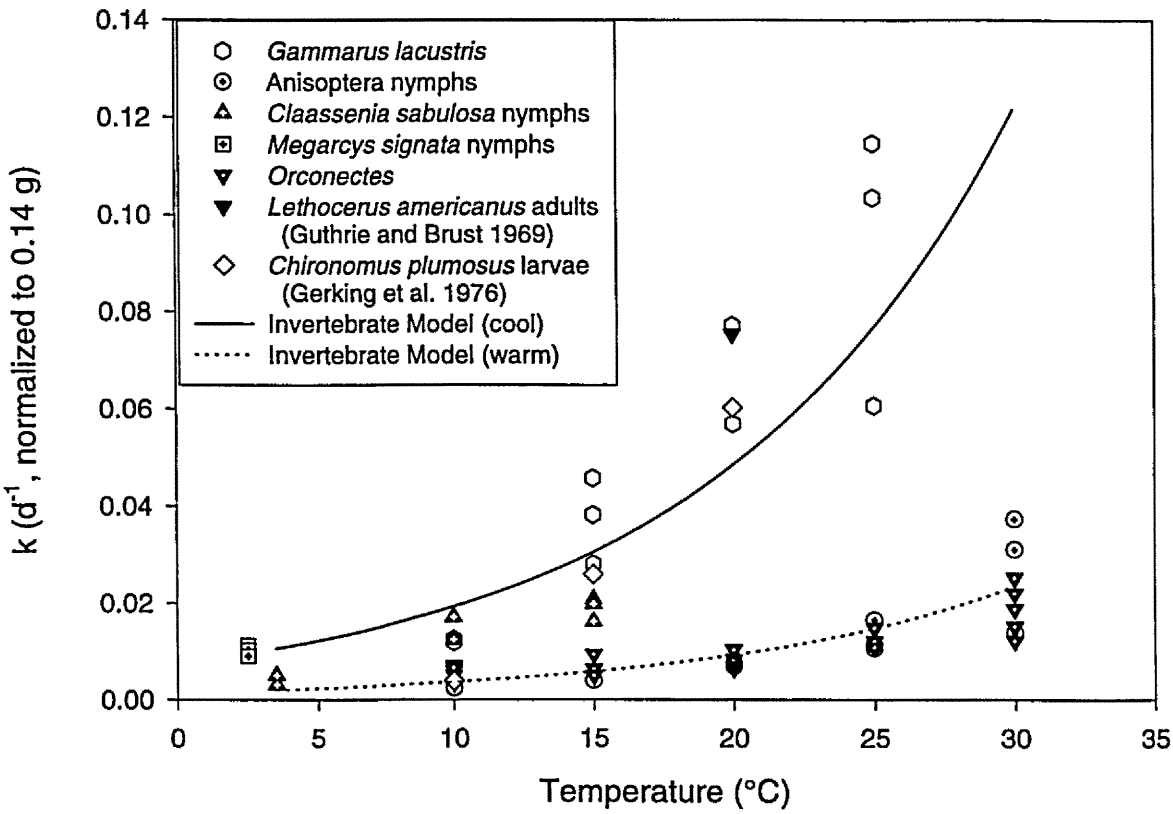

Fig. 2. ^{134}Cs elimination rate constants (k, d^{-1}) of freshwater invertebrates, normalized to a body size of 0.14 g, plotted in relation to temperature and predictions of the back-transformed curve of the general ^{134}Cs elimination model for freshwater invertebrates for 0.14 g body size: $\ln k = -5.187 + 0.092\,T - 0.126 \ln W - 1.650\,OP$, where T is temperature (°C), W is body size (g), and OP is a categorical variable for thermal optima (1 for warmwater, 0 for cool-water adapted taxa). Data for *Chironomus plumosus* larvae (Gerking et al. 1976) were not included in the general invertebrate model, but are provided in the graph for comparative purposes.

where β_1 and β_2 are fitted model coefficients. A transformation of the form ln k was used to meet the assumption of constant variance. Since ^{134}Cs was not detected in exoskeletons collected from molting invertebrates, this possible mode of elimination was not included in the elimination models. The models were all highly significant, as were the coefficients ($p \leq 0.05$) (Table 4). The similarities in the slopes and intercepts of the models led to the investigation and development of a general cesium elimination model for freshwater invertebrates.

General cesium elimination rate constant model for freshwater invertebrates

Published radiocesium elimination rate constants for freshwater invertebrates were evaluated for their inclusion in a general radiocesium elimination model for freshwater invertebrates. Harvey (1969) carried out ^{137}Cs elimination studies on the freshwater clam *Lampsilis radiata* under natural stream conditions where temperature was not a controlled factor. Kevern et al. (1964) reported ^{134}Cs biological half-times of 3.5 d (elimination rate constant of 0.198 d^{-1}) for a midge larva *C. commutatus* and 8.3 d (elimination rate constant of 0.084 d^{-1}) for the mayfly nymph *E. varia*, but neither temperature, body size, nor duration of the study were provided. Furthermore, no raw data were provided to evaluate the adequacy of the results. Thus, the results of these two studies were not utilized.

Guthrie and Brust (1969) estimated ^{137}Cs half-times of 4.5 days (elimination rate constant of 0.154 d^{-1}) for fourth instar *L. americanus* nymphs, and 10.8 days (elimination rate constant of 0.0.064 d^{-1}) for adult *L. americanus* kept at temperatures between 17 and 20 °C. The nymph value was obtained from a one component elimination curve.

TABLE 4. ^{134}Cs elimination rate constant (k, d^{-1}) models for freshwater invertebrates as a function of temperature (T, °C), along with the number of data points (n), model R^2 and p-values.

Taxon	Model	Adjusted R^2	n	Model p-value
Gammarus lacustris	$\ln k = -5.273 + 0.124T$	0.828	10	0.0002
Anisoptera sp. nymphs	$\ln k = -7.251 + 0.117T$	0.916	12	<0.0001
Claassenia sabulosa nymphs	$\ln k = -5.834 + 0.127T$	0.810	7	0.0036
Orconectes sp.	$\ln k = -6.200 + 0.060T$	0.766	18	<0.0001

However, it appears that the latter few points on the ^{137}Cs elimination curve for the nymphs were leveling off, and therefore, the elimination rate constant may have been slower than reported. Since the experiment was terminated early (16 days) due to molting, no conclusion can be drawn regarding the reliability of the estimated elimination rate constant. Experiments which were not conducted for a sufficiently long period of time would report elimination rate constants which were too fast. The estimated elimination rate constant for the adult appears reliable. However, it should be noted that it is unlikely that the nymphs and adults were in equilibrium with the ^{137}Cs in their food source at the start of the elimination phase of the experiment as assumed. Likely more than seven days would have been required to reach equilibrium, since it takes approximately five biological half-times to achieve equilibrium conditions (97 %, Whicker and Schultz 1982).

Gerking et al. (1976) estimated ^{134}Cs elimination rate constants for *C. plumosus* larvae at 10, 15, and 20 °C from three component elimination models that were fit by eye. Contrary to the authors' interpretation of the components, the first two components of the elimination curves likely represented the ^{134}Cs in sediment, which passed through the gut unabsorbed, while the third component represented the assimilated ^{134}Cs. Furthermore, contrary to Gerking et al.'s (1976) interpretation of the data, *C. plumosus* were not likely in equilibrium with the ^{134}Cs in the sediment after only 40 to 70 hours of exposure. Their estimated times to equilibrium correspond to the apparent time for gut clearance evident from inspection of the elimination curves in their study. Thus, the observed time to equilibrium likely represented the time for the larvae to fill their guts with sediment. It

appears that the study was terminated too early, in particular, the 15 and 20 °C treatments, to obtain reliable estimates of elimination.

Thus, the elimination rate constants obtained in this study for *G. lacustris*, Anisoptera, *C. sabulosa*, *M. signata*, and *Orconectes*, together with one datum point from Guthrie and Brust (1969) for adult *L. americanus* at 20 °C (body size of 0.4 g assumed), were combined into a general model for freshwater invertebrates with the following result (SE in parentheses):

$$\ln k = -5.187\ (0.163) + 0.092\ (0.007)T - 0.126\ (0.047)\ln W - 1.650\ (0.157)OP$$

eqn 5

adjusted $R^2 = 0.845$, $P < 0.0001$, $n = 58$

where T is temperature (°C), W is body size (g), and OP is a categorical variable for thermal optimum (1 for warmwater adapted, 0 for cool-water adapted taxa). While little variation in body size existed within taxa (Table 3), across taxa there was a wide range of body sizes, and therefore body size was tested as a predictor in the general model. Although it was found to be significant ($p = 0.0089$), its inclusion in the model resulted in only a small increase in the adjusted R^2 from 0.827 to 0.845, and thus may be considered a weak predictor. The Anisoptera and *Orconectes* were considered to be warmwater adapted invertebrates, as they were the only invertebrates to survive the warmest temperature of 30 °C. The remaining taxa, namely *G. lacustris*, *C. sabulosa*, *M. signata* and *L. americanus* were considered to be cool-water adapted species. A categorical variable for cold-water species, represented by *M. signata*, was initially investigated, but was not statistically significant. However, data for cold-water species were limited in this study (i.e., one taxa at one temperature). Cesium elimination rate constants for freshwater

invertebrates, normalized to 0.14 g, are compared with the predictions of the general model in Fig. 2. The reinterpreted results of Gerking et al. (1976) for *C. plumosus* are also provided. Given that the 15 and 20 °C experiments for *C. plumosus* were not likely conducted for a sufficient period of time, it is not surprising to observe that the rate of increase of those elimination rate constants relative to temperature is somewhat higher than would be expected with the general model.

The effect of temperature on a reaction rate is often expressed as a Q_{10}, the factor by which the reaction rate increases with a 10 °C increase in temperature. The Q_{10} of the general model is 2.5.

Thus, across taxa, elimination rate constants were proportional to temperature and inversely proportional to body size as originally hypothesized. Crossley (1963a) observed an inverse relationship between elimination rate and body size for adults of four species of terrestrial insects, and the same relationship was observed for larva and adult beetle *Chrysomela knabi* (Crossley 1963b). Guthrie and Brust (1969) noted that fourth instar *L. americanus* nymphs had a faster ^{137}Cs elimination rate constant than the larger adults at the same temperature, although there are indications that the nymph value may have been smaller had the experiment been allowed to continue longer. Previous studies on fish have shown that cesium elimination rates decrease with increasing size of the fish (see review by Rowan and Rasmussen 1995).

The results of the general freshwater invertebrate model suggest that warmwater adapted species eliminate cesium at 19 % of the rate of cool-water adapted species. Comparative data on ion retention by freshwater invertebrates is lacking, thus it is not known why such differences were observed between cool-water and warmwater adapted

invertebrates. Such differences may suggest an evolutionary advantage to minimizing nutrient loss in warmer temperatures where metabolism is higher, but further research is required to address this issue. Data on cold-water adapted species in this study were limited to one temperature for *M. signata*, but based on my observations that *M. signata* clears radiocesium faster than similar sized cool-water invertebrates (Fig. 2), I hypothesize that cold-water adapted species would eliminate cesium faster than cool-water adapted species.

Other possible modes of ^{134}Cs elimination, such as loss through molted exoskeletons or eggs, were not included in the general invertebrate model. ^{134}Cs was not detected in exoskeletons collected from molting invertebrates. However, because the exoskeletons were already present at the time of ^{134}Cs uptake, further research would be required to determine whether newly formed exoskeletons (i.e., after an uptake of radiocesium) would contain any cesium label.

The general cesium elimination model for freshwater invertebrates (eqn 5) bears a striking resemblance to Rowan and Rasmussen's (1995) cesium elimination model for fish (SE in parentheses):

$$\ln k = -6.583\ (0.181) - 0.111\ (0.018) \ln W + 0.093\ (0.007)T + 0.326\ (0.090)SS \quad \text{eqn 6}$$

where k is elimination rate constant (d^{-1}), W is body size (g), T is temperature (°C), and SS is a categorical variable for exposure (0 for steady-state, 1 for non-steady-state). It is apparent that the coefficients of the invertebrate temperature term (0.092 (0.007)) and body size term (-0.126 (0.047)) are essentially the same as those for fish. Given these similarities in models, it is not surprising that the Q_{10} of the invertebrate model is essentially the same as that for the fish model (2.5 vs 2.4). The predictions of the general

invertebrate model are compared with those of the fish model for a body size of 0.14 g in Fig. 3.

Application of ^{134}Cs assimilation efficiencies and elimination rate constants

This study significantly improves the body of information on cesium uptake and elimination kinetics in freshwater invertebrates. Knowledge of cesium assimilation efficiencies and elimination rates of freshwater invertebrates allows, for the first time, development of a mechanistic model describing cesium kinetics in fish dietary items. The observations of Elliot et al. (1992) on ^{137}Cs levels in wild fish populations versus stocked fish in two lakes in the United Kingdom provide strong evidence that the food chain is the main route of ^{137}Cs transfer to the fish. In addition, the authors observed a lag between ^{137}Cs maxima in water and fish in two lakes in the United Kingdom, which they presumed was due to the time required for ^{137}Cs transport through the sediments and food chain. Hammar et al. (1991) suggest that certain aquatic invertebrates may create a system of recycling and maintenance of high levels of radiocesium in fish. Based on a model of linear regressions, they showed that the opposum shrimp *Mysis relicta*, which effectively transferred ^{137}Cs from both zooplankton and detritus to Arctic char *Salvelinus alpinus* and brown trout *S. trutta* in Swedish lakes, increased the ecological half-time of cesium in these fish populations by another two years.

However, most predictions of radiocesium (e.g., ^{134}Cs and ^{137}Cs) levels in fish and subsequent doses to humans are based on **steady-state** bioaccumulation or bioconcentration factors for water to fish. While this approach may be adequate for systems which are truly at steady-state with respect to radiocesium levels, it clearly is not

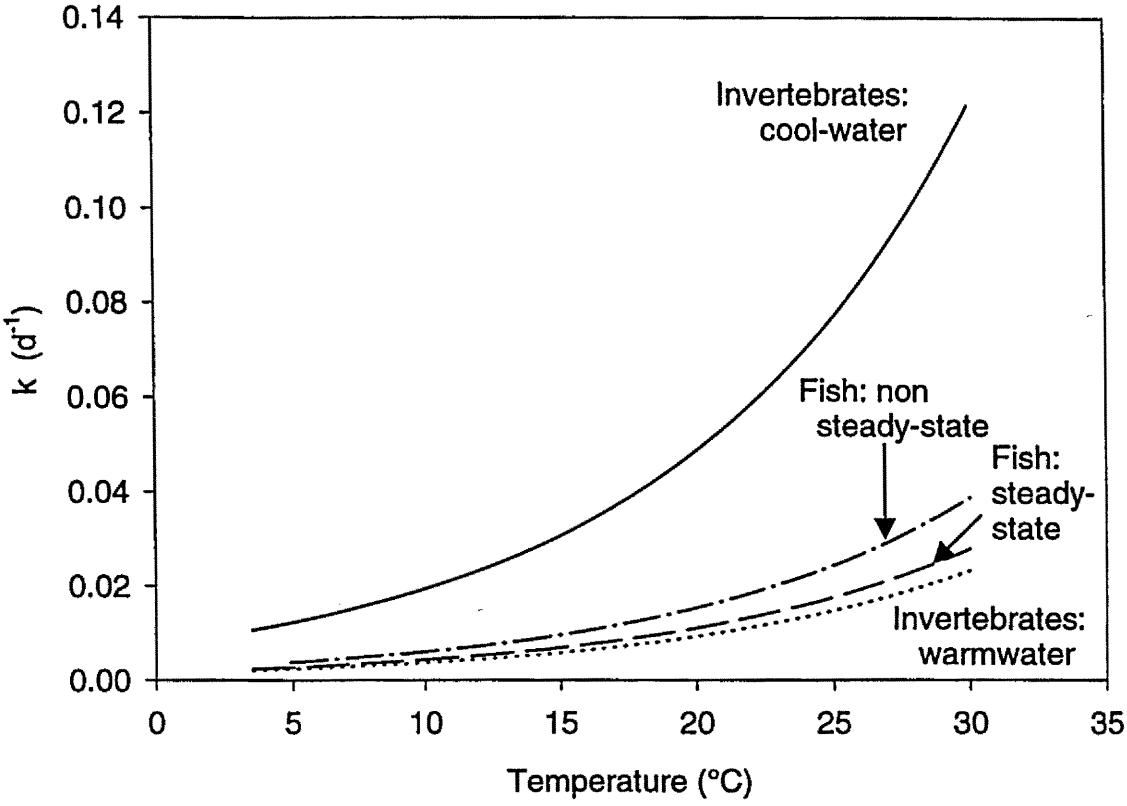

Fig.3. Comparison of predictions of general ^{134}Cs elimination model for freshwater invertebrates with radiocesium elimination model for fish (Rowan and Rasmussen 1995). Invertebrate model: $\ln k = -5.187 + 0.092\,T - 0.126 \ln W - 1.650\,OP$, where k is elimination rate constant (d^{-1}), T is temperature (°C), W is body size (g), and OP is a categorical variable for thermal optima (1 for warmwater adapted taxa, 0 for cool-water adapted taxa). Fish model: $\ln k = -6.583 - 0.111 \ln W + 0.093\,T + 0.326\,SS$, where SS is a categorical variable for exposure (0 for steady-state, 1 for non-steady-state). Note the similarity in the predictions of the general invertebrate model for warmwater taxa with the predictions of the fish model for steady-state exposure.

appropriate for dynamic conditions, for example, following a pulse release or for fluctuating levels of cesium in an aquatic system. Alternatively, Nordlinder et al. 1993 incorporated freshwater invertebrates (*G. lacustris*, *M. relicta* and zooplankton) into their model of ^{137}Cs transport in Swedish lakes in order to simulate ^{137}Cs levels in two sympatric salmonid species following the Chernobyl accident of 1986. However, they used bioaccumulation factors to estimate ^{137}Cs levels in the invertebrates. The bioaccumulation factors and biological half-times were estimated from the observed field data. In their study, they stated that the bioaccumulation factors for the zooplankton and benthos were one of two main parameters contributing to uncertainty estimates in the first year. The results of the simulation study indicated that biological parameters, such as the turnover of cesium in fish and their prey items, are the most important factors affecting the precision of the estimate of cesium in fish muscle during the first years following an acute pulse release when cesium concentrations are the highest in biological compartments. Although this latter approach is an improvement to past steady-state type models, it still does not represent a truly dynamic model.

Development of a mechanistic model describing cesium kinetics of aquatic invertebrates also requires quantification of the invertebrate food consumption rates. Such rates may be estimated using the obtained assimilation efficiencies and elimination rates, along with knowledge of the cesium levels in the diet items. ^{137}Cs can be detected in many ecosystems in the world due to low-level cesium contamination resulting from atmospheric nuclear weapons testing. ICP mass spectrometry makes possible the use of stable cesium as a tracer where ^{137}Cs levels are too low to measure. A few of the past consumption studies on invertebrates were limited to laboratory feeding experiments on

cesium labeled foods (Reichle 1967; Gerking et al. 1976) or were conducted in cesium labeled environments (Reichle and Crossley 1965). Others were conducted in areas previously contaminated with cesium (Crossley and Howden 1961; Crossley 1963a, 1963b, 1966). In addition, consumption rates of fish have been estimated in numerous studies using ^{137}Cs tracer (e.g., Kevern 1965, Forseth et al 1992) and Rowan and Rasmussen (1996) developed a model to measure *in situ* the bioenergetic cost of fish activity using ^{137}Cs as a tracer. Thus, the ability to obtain assimilation efficiencies and elimination rates of aquatic invertebrates in this study allows for the extension of the fish bioenergetic technique to aquatic invertebrates in their natural environment.

Conclusions

This study provides a detailed investigation of cesium assimilation and elimination by freshwater invertebrates. A general model of cesium elimination by freshwater invertebrates is proposed where elimination rate constants are a function of temperature, body size and a categorical variable for thermal optima (warmwater adapted and cool-water adapted taxa). Cesium elimination rate constants were found to increase with temperature, decrease with body size, and be much lower for warm water adapted invertebrates than cool-water adapted invertebrates. Both the assimilation efficiencies for a variety of food types and the general model of cesium elimination rate constants for freshwater invertebrates are in excellent agreement with those for fish. Quantification of cesium assimilation efficiencies and elimination rate constants by freshwater invertebrates allows, for the first time, development of dynamic cesium models for

aquatic food webs for risk assessment studies, and it enables the *in situ* quantification of invertebrate feeding rates and other bioenergetic parameters.

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APPENDIX A

Gammarus lacustris Data

TABLE A.1. Fraction of initial ^{134}Cs activity over time for individual *Gammarus lacustris* at 10 °C.

Time (d)	G-1-1	G-1-3
0	1	1
1	0.965459721	0.858577021
2	0.904045549	0.816841261
4	0.817826616	0.750903146
7	0.712562098	0.64172458
14	0.541304285	0.470351765
21	0.472623402	0.397419386
28	0.444806149	0.330201193
36	0.392161081	0.293717189
45	0.337165205	0.263334486
52	0.314562181	0.239352997
59	0.256385374	0.225072017
72	0.209392756	0.180811641
84	-	0.145970364

TABLE A.2. Fraction of initial ^{134}Cs activity over time for individual *Gammarus lacustris* at 15 °C.

Time (d)	G-3-1	G-3-2	G-3-3
0	1	1	1
1	0.817067646	0.905999654	0.904356527
2	0.748409851	0.871524512	0.778020731
4	0.632247099	0.799533592	0.577766416
7	0.524336249	0.681830671	0.425516704
14	0.348725124	0.508731728	0.318390856
21	0.248659938	0.375674461	0.251192558
28	0.178179205	0.284771728	0.193900746
38	0.09191801	0.181964636	0.145886414
45	0.071654101	0.122968675	0.096230174
52	0.055082552	0.085513783	0.06476179

TABLE A.3. Fraction of initial ^{134}Cs activity over time for individual *Gammarus lacustris* at 20 °C.

Time (d)	G-4-1	G-4-2
0	1	1
1	0.806032509	0.862187081
2	0.695021139	0.781979205
4	0.578461483	0.689147943
7	0.393498003	0.541220218
13	0.263912699	-
14	-	0.357344847
21	-	0.213294708
28	-	0.160524501

TABLE A.4. Fraction of initial ^{134}Cs activity over time for individual *Gammarus lacustris* at 25 °C.

Time (d)	G-5	G-6	G-7
0	1	1	1
1	0.916612356	0.85413073	0.766092264
2	0.839071758	0.773932962	0.662321736
4	0.721271753	0.590101496	0.500943997
7	0.611797259	0.403626399	0.404625696

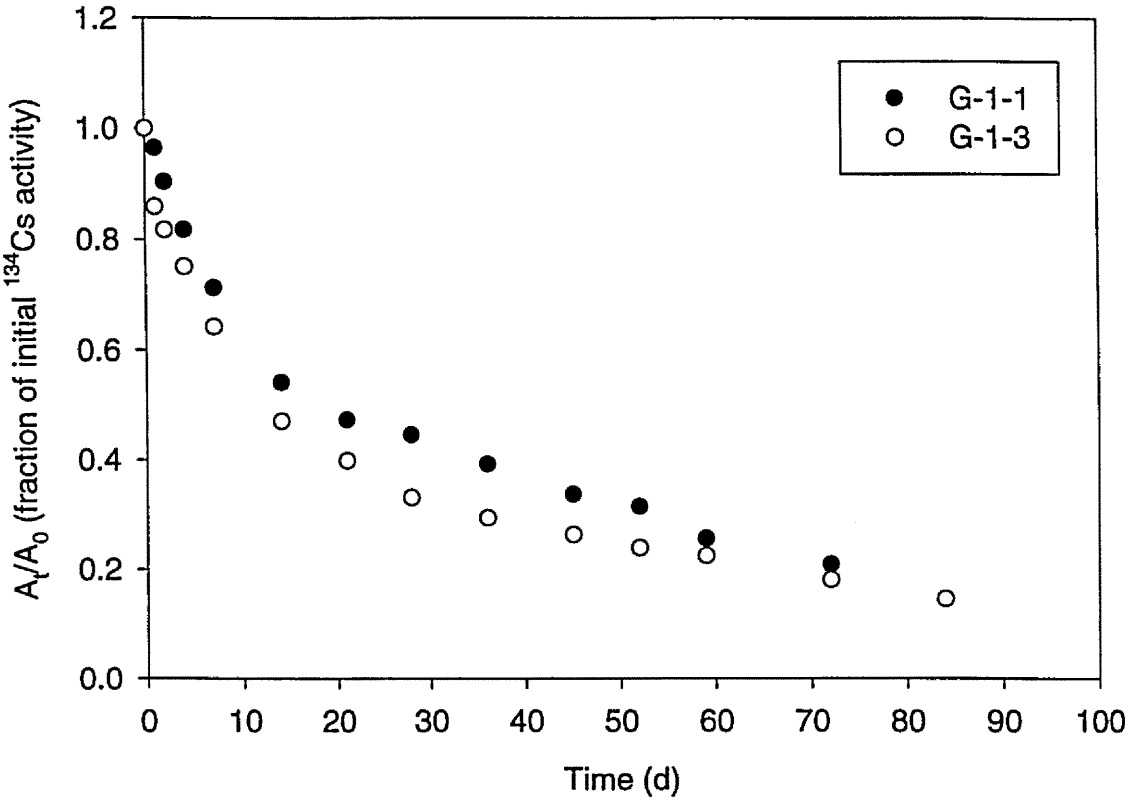


Fig. A.1. Elimination of ^{134}Cs by individual *Gammarus lacustris* (G-1-1, G-1-3) at 10 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

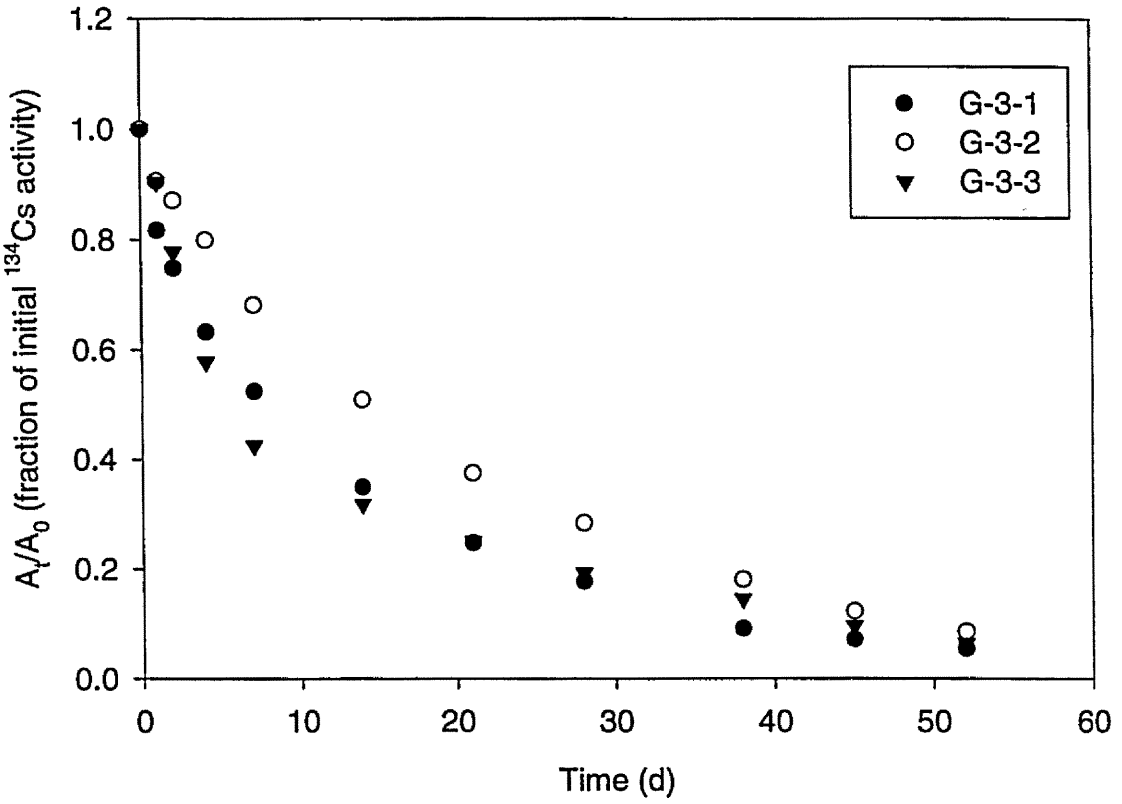


Fig. A.2. Elimination of ^{134}Cs by individual *Gammarus lacustris* (G-3-1, G-3-2, G-3-3) at 15 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

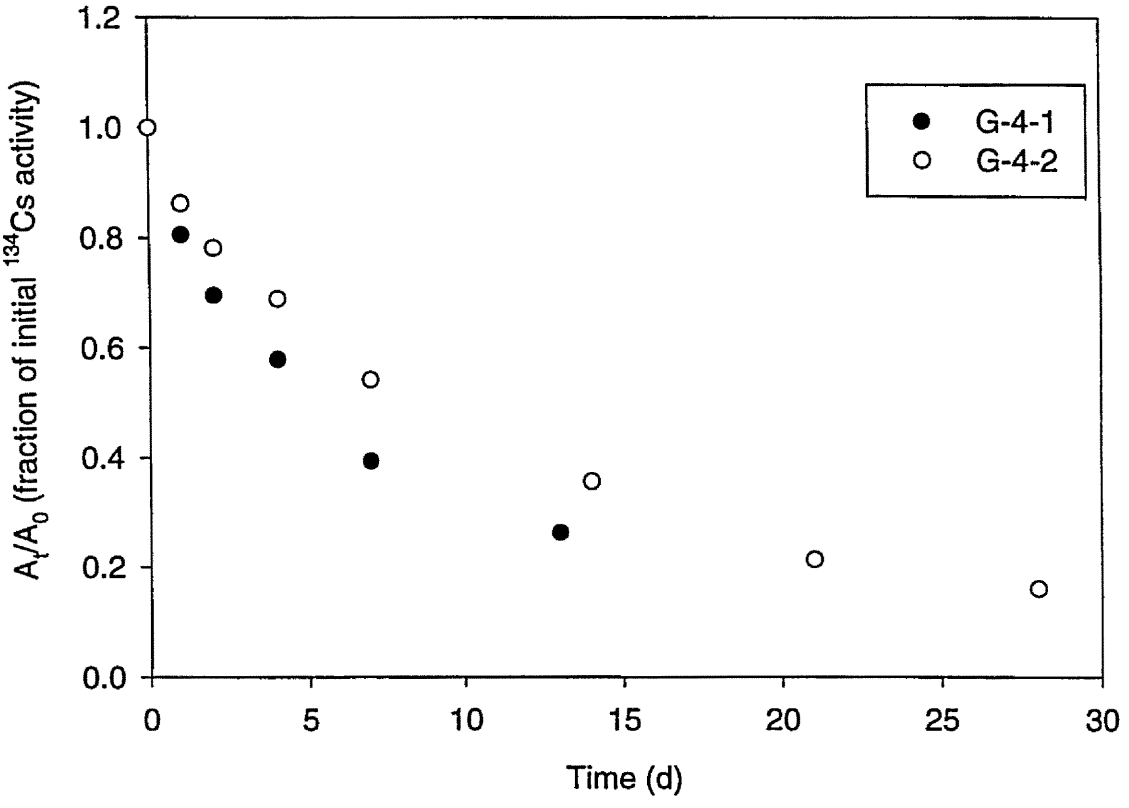


Fig. A.3. Elimination of ^{134}Cs by individual *Gammarus lacustris* (G-4-1, G-4-2) at 20 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

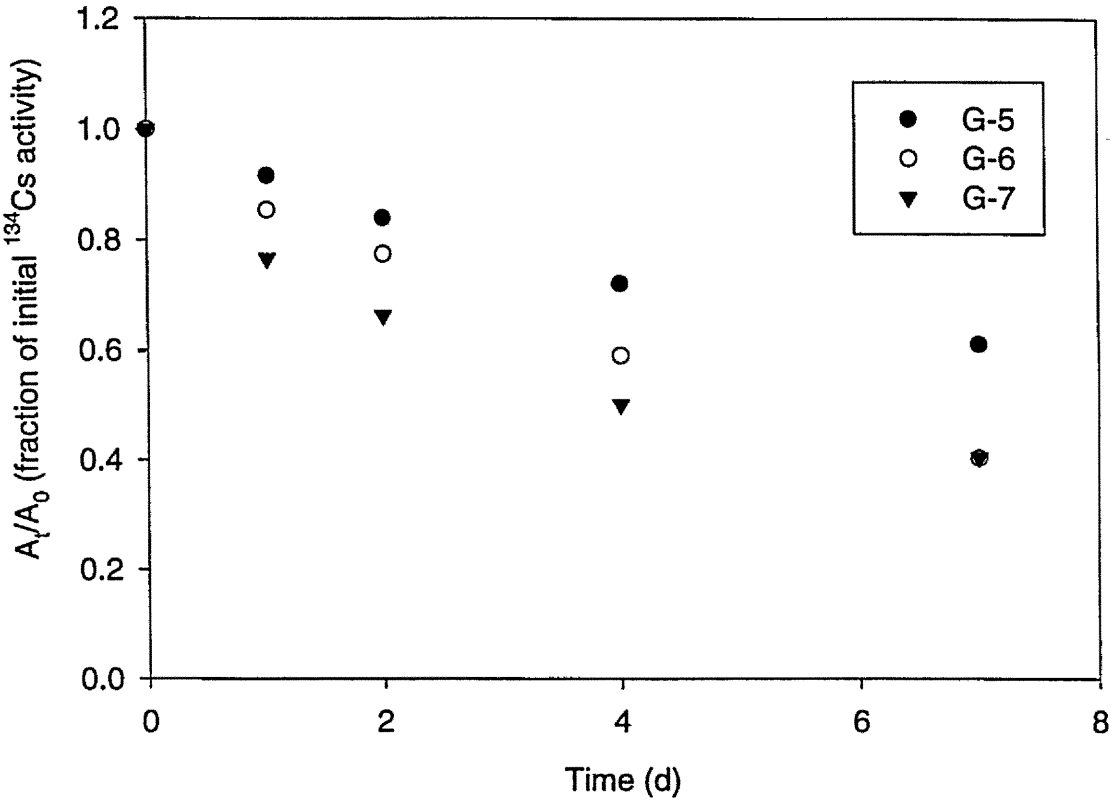


Fig. A.4. Elimination of ^{134}Cs by individual *Gammarus lacustris* (G-5, G-6, G-7) at 25 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

APPENDIX B

Anisoptera Data

TABLE B.1. Fraction of initial ^{134}Cs activity over time for individual Anisoptera nymphs at 10 °C.

Time (d)	DF-1-1	DF-1-2	DF-1-3
0	1	1	1
1	0.976796417	1.006898785	0.938958752
2	0.975775456	0.966703572	0.990305348
4	0.932454733	0.991365952	0.87589258
7	-	0.984841067	-
8	0.941394579	-	0.776183695
15	0.898233673	0.919100178	0.671170215
21	0.878358413	0.905913853	0.717689217
28	-	0.890766709	-
29	0.871526842	-	0.743109845
36	0.86223287	0.834725605	0.74116367
43	0.82729518	0.856512411	0.695778368
50		0.842755564	0.68962226
51	0.818174119	-	-
56	-	0.795867708	0.682547348
58	0.787815158	-	-
63	-	-	0.678092954
64	0.790933774	0.795854294	-
71	0.771062487	0.798090341	0.657561873
86	0.72564963	0.748861314	0.614985329
102	0.672687671	0.703152526	0.579724386
116	0.649929644	0.644703577	0.541920719

TABLE B.2. Fraction of initial ^{134}Cs activity over time for individual Anisoptera nymph at 15 °C.

Time (d)	DF-3-2
0	1
1	1.046784294
2	0.880239535
4	0.8077197
7	0.787354706
14	0.724626795
21	0.684824772
28	0.675412188
35	0.652829375
43	0.629692833
50	0.611481946
57	0.604442462
64	0.583206839
69	0.560584454
86	0.47866742
102	0.477713525
116	0.436772256

TABLE B.3. Fraction of initial ^{134}Cs activity over time for individual Anisoptera nymphs at 20 °C.

Time (d)	DF-4-1	DF-4-3
0	1	1
1	0.961992152	0.899947961
2	0.922026799	0.784363064
4	0.880008346	0.837824591
7	0.868069779	0.77870674
14	0.80169073	0.659653388
21	0.770892915	0.61960018
28	0.684156888	-
29	-	0.583173098
35	0.650975935	0.565416225
42	-	0.55071152
43	0.632553783	-
50	0.59880617	-
51	-	0.503140105
56	0.572839546	-
58	-	0.470492965
63	0.530889114	-
65	-	0.451225831
70	0.506502015	0.414652156
86	0.443102455	0.37825659
102	0.389298342	0.349425596
116	0.324274602	0.324028989

TABLE B.4. Fraction of initial ^{134}Cs activity over time for individual Anisoptera nymphs at 25 °C.

Time (d)	DF-5	DF-6	DF-7
0	1	1	1
1	0.89067088	0.878319594	0.516122558
2	0.756591883	0.822813611	0.282283333
4	0.659964837	0.744610502	0.262533515
7	0.644360181	0.689190222	0.258679999
14	0.557621673	0.675897177	-
15	-	-	0.228691264
21	0.475212588	0.636054285	0.215818791
28	0.426768211	-	-
29	-	0.559864008	0.190163357
35	0.394496562	0.514406394	-
36	-	-	0.170163554
42	-	0.468561707	-
43	0.339100219	-	0.15651216
49	0.307300852	-	-
50	-	0.424692409	-
51	-	-	0.142477911
56	-	0.407530642	-
57	0.26787947	-	-
58	-	-	0.133515032
63	-	0.377118931	-
64	0.206296026	-	-
65	-	-	0.114648007
71	-	-	0.107378692

TABLE B.5. Fraction of initial ^{134}Cs activity over time for individual Anisoptera nymphs at 30 °C.

Time (d)	DF-8	DF-9	DF-10
0	1	1	1
1	0.7516806	0.94356676	0.801003486
2	0.6784593	0.927933221	0.710200073
4	0.630173323	0.889806878	0.692902714
7	-	0.863682081	0.604954838
8	0.568549018	-	-
15	-	0.759463127	0.467381136
21	-	0.707579033	-

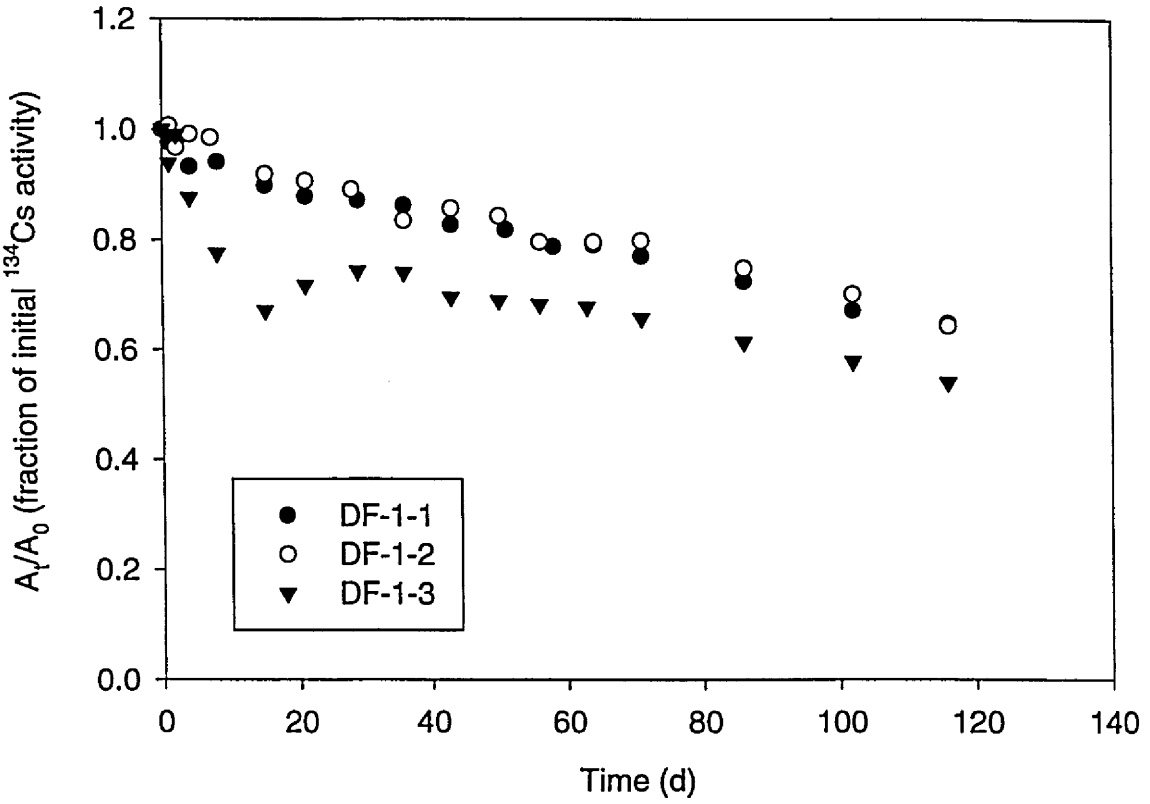


Fig. B.1. Elimination of ^{134}Cs by individual Anisoptera nymphs (DF-1-1, DF-1-2, DF-1-3) at 10 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

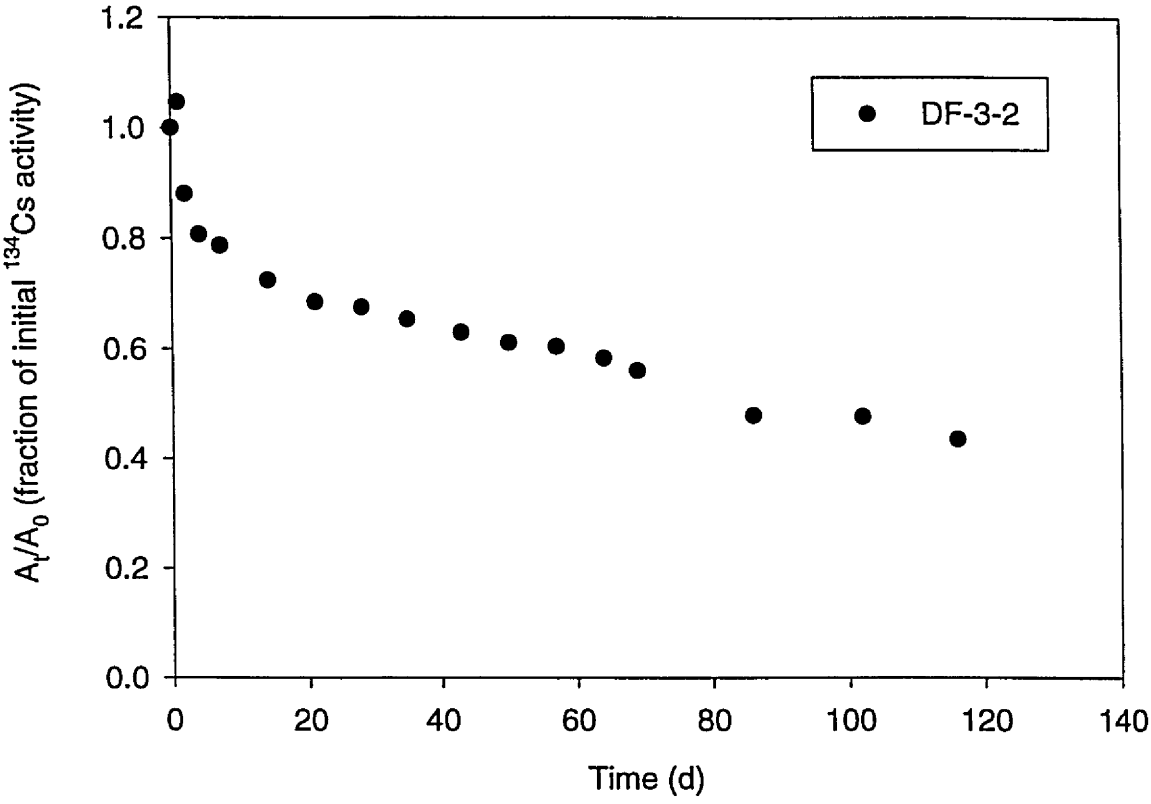


Fig. B.2. Elimination of ^{134}Cs by individual Anisoptera nymph (DF-3-2) at 15 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

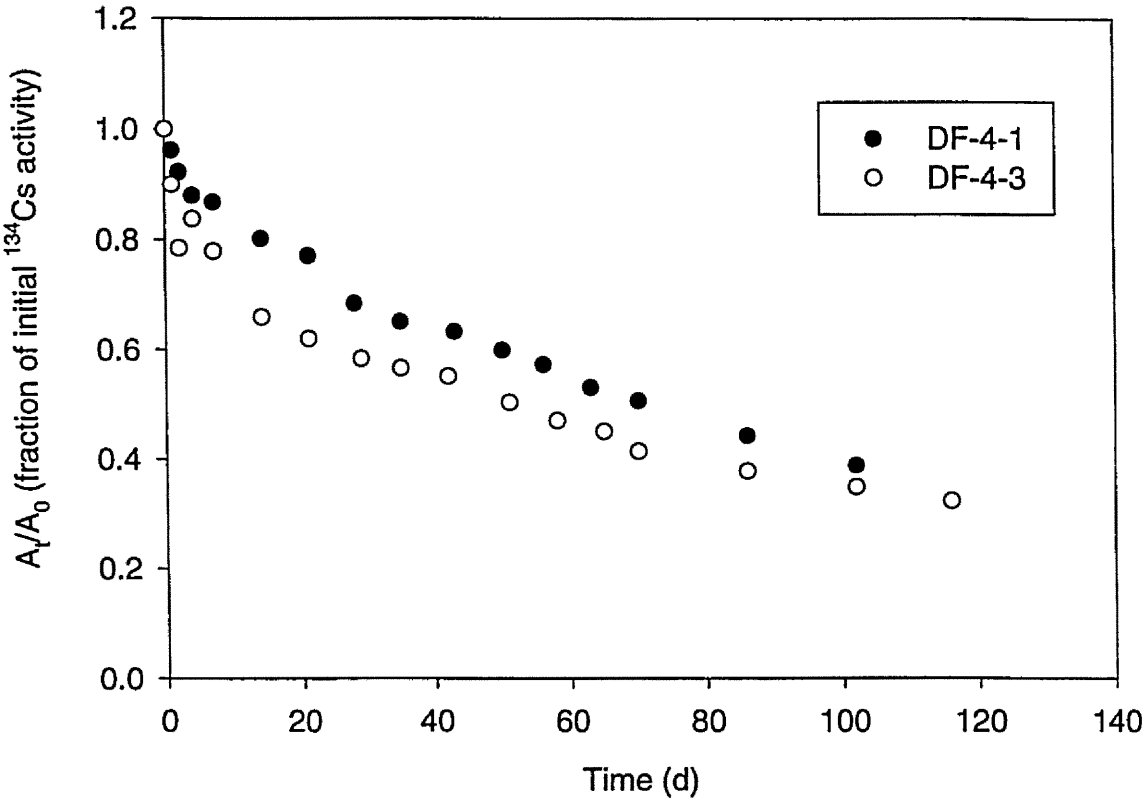


Fig. B.3. Elimination of ^{134}Cs by individual Anisoptera nymphs (DF-4-1, DF-4-3) at 20 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

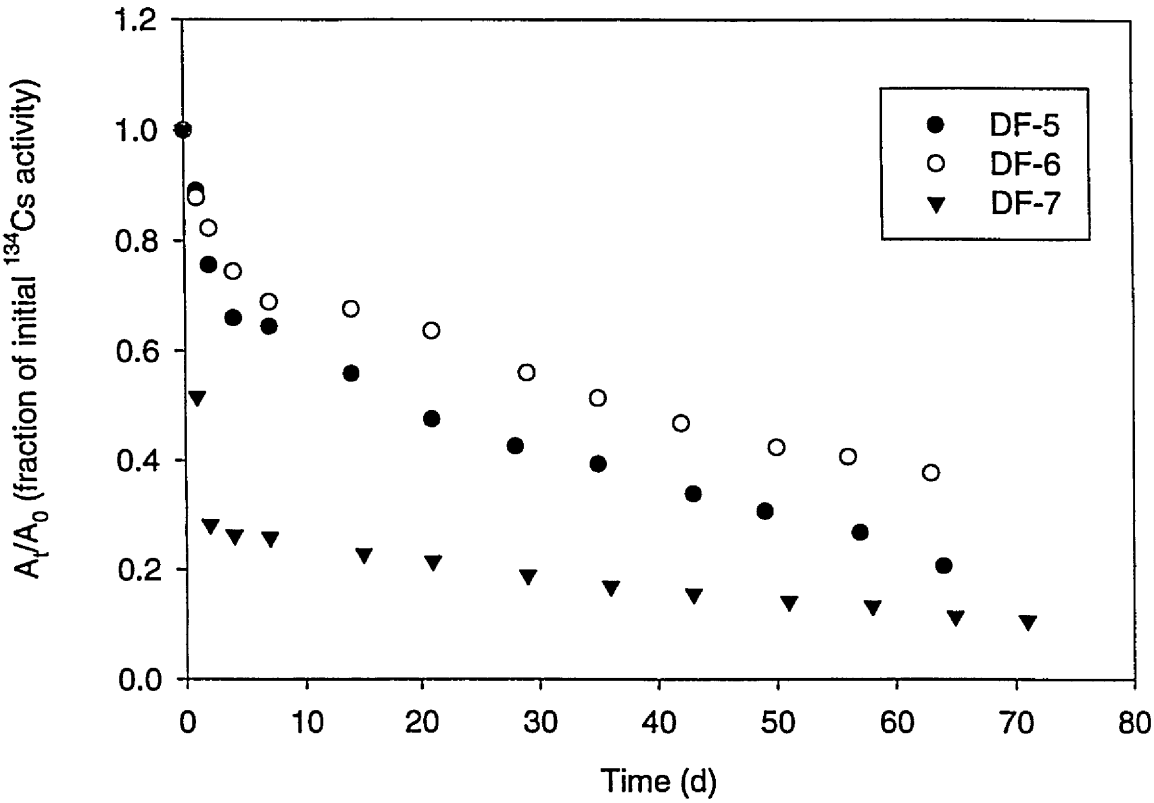


Fig. B.4. Elimination of ^{134}Cs by individual Anisoptera nymphs (DF-5, DF-6, DF-7) at 25 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

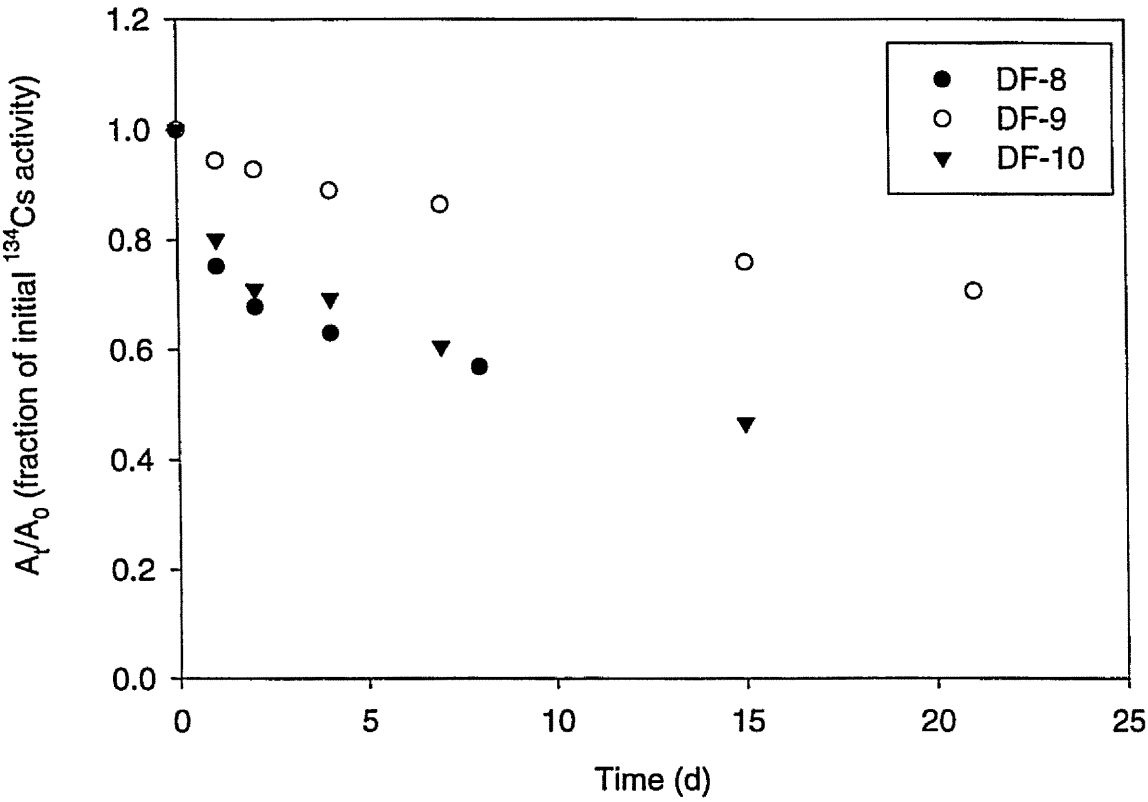


Fig. B.5. Elimination of ^{134}Cs by individual Anisoptera nymphs (DF-8, DF-9, DF-10) at 30 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

APPENDIX C

Claassenia sabulosa Data

TABLE C.1. Fraction of initial ^{134}Cs activity over time for individual *Claassenia sabulosa* nymphs at 3.5 °C.

Time (d)	CL-2-1	CL-2-3
0	1	1
1	0.990704404	1.015088448
2	0.978143177	1.020766945
4	0.944099516	0.369017066
7	0.868143675	0.344959867
14	0.754766165	0.321136468
21	0.712219633	0.30758673
28	0.682367347	0.294519911
37	0.638092903	0.27964809
44	0.611727288	0.273546551
51	0.591095225	0.259926599
64	0.559179633	0.242112294
75	0.528712002	0.216179526

TABLE C.2. Fraction of initial ^{134}Cs activity over time for individual *Claassenia sabulosa* nymphs at 10 °C.

Time (d)	CL-1-1	CL-1-3
0	1	1
1	0.990179143	0.997454254
2	0.918867017	0.098693169
4	0.791048096	0.093423482
7	0.693168616	0.08989051
14	0.609998627	-
15	-	0.075325384
21	0.547893749	0.066783807
28	0.492601422	0.060259365
37	0.452514979	0.051483224
44	0.414915536	0.045881578
51	0.391188016	0.040205152
64	0.300877664	0.03241095
75	0.255440199	0.028360457

TABLE C.3. Fraction of initial ^{134}Cs activity over time for individual *Claassenia sabulosa* nymphs at 15 °C.

Time (d)	CF-3-1	CF-3-2	CF-3-3
0	1	1	1
1	0.867739139	0.839540859	0.070650098
2	0.764131139	0.65965112	0.072055433
4	0.71802603	0.587778265	0.066780738
7	0.675320347	0.55947632	0.064491427
14	0.592817144	0.448263636	-
15	-	-	0.05740536
21	0.5582728	0.385571284	-
22	-	-	0.051583219
28	0.506446529	0.333444242	0.044655536
37	0.451703475	0.284997168	0.037517994
44	0.385114385	0.245884443	0.031364713
51	0.344458564	0.218463716	0.023418725
64	0.248831635	0.172874895	-
75	0.197142421	0.138159667	-

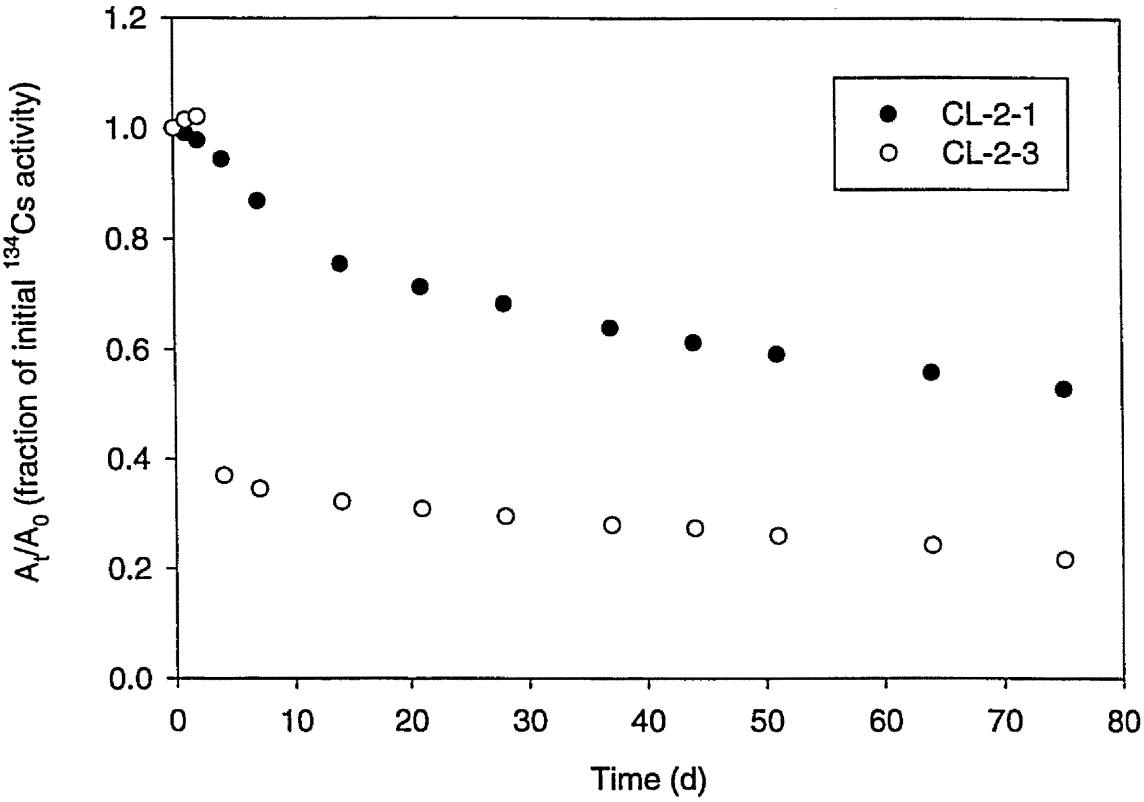


Fig. C.1. Elimination of ^{134}Cs by individual *Claassenia sabulosa* nymphs (CL-2-1, CL-2-3) at 3.5 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

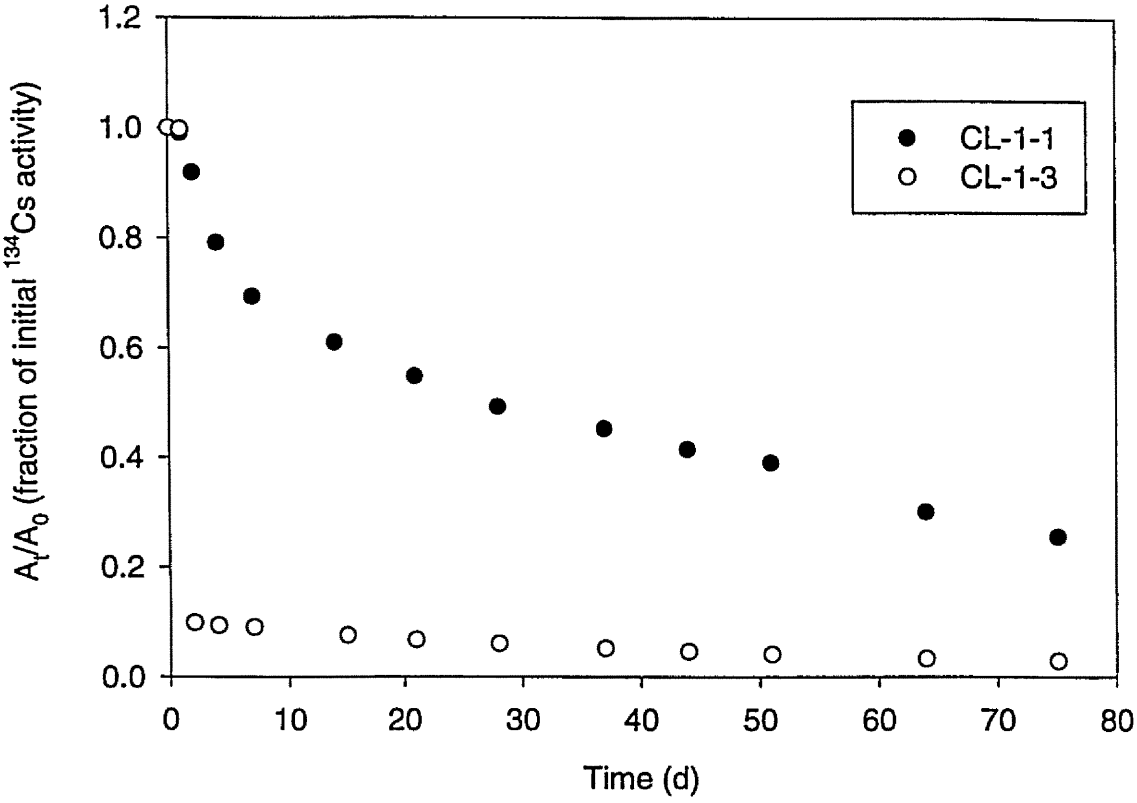


Fig. C.2. Elimination of ^{134}Cs by individual *Claassenia sabulosa* nymphs (CL-1-1, CL-1-3) at 10 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time(d).

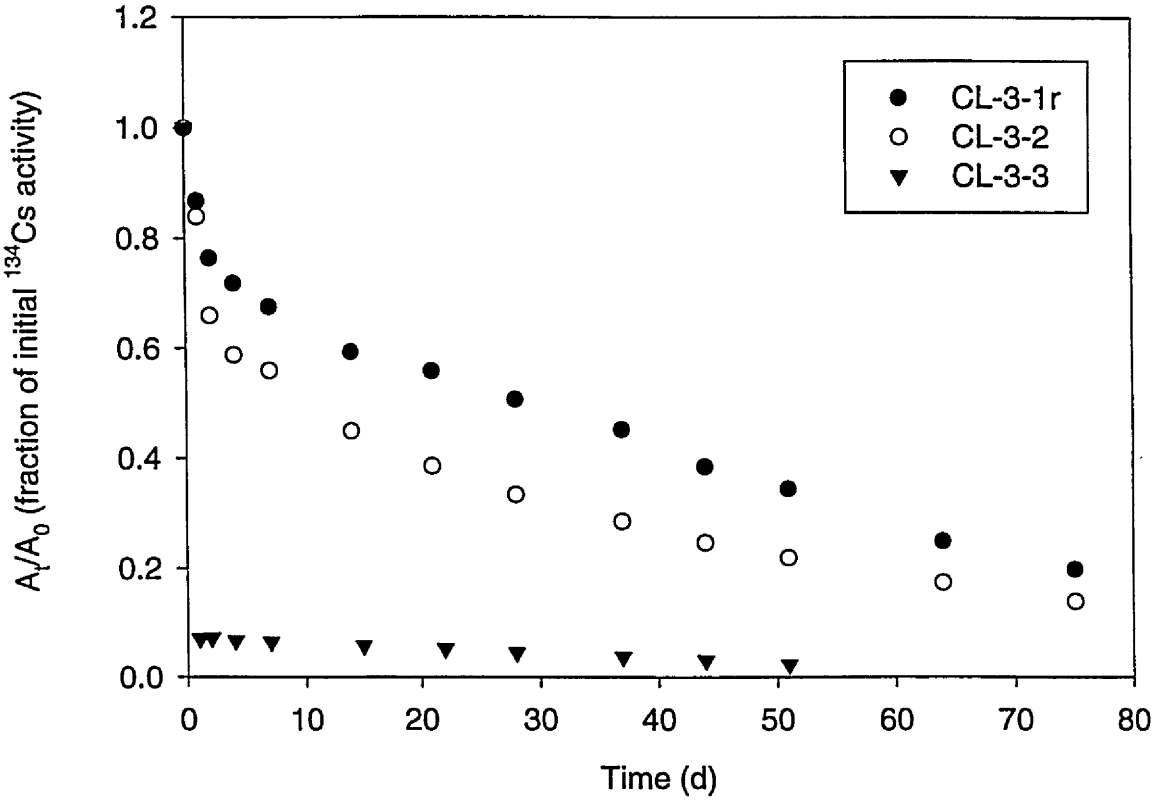


Fig. C.3. Elimination of ^{134}Cs by individual *Claassenia sabulosa* nymphs (CL-3-1, CL-3-2, CL-3-3) at 15 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

APPENDIX D

Megarcys signata Data

TABLE D.1. Fraction of initial ^{134}Cs activity over time for individual *Megarcys signata* nymphs at 2.5 °C.

Time (d)	M-1	M-2	M-3	M-4	M-5	M-6	M-7	M-8	M-10
0	1	1	1	1	1	1	1	1	1
1	0.874776482	0.943990533	0.966481116	0.904750495	0.63837284	0.917762475	0.914106933	0.852814882	0.911099771
2	0.791529124	0.905954891	0.942786061	0.85314038	0.606758967	0.891167928	0.842609221	0.804960007	0.813039628
5	0.558431806	0.774415985	0.853709094	0.153434754	0.152030196	0.220848077	0.738893282	0.201370703	0.607145733
8	0.21054384	0.229853451	0.761756	0.14848102	0.118982119	0.167981659	0.264914729	0.197598462	0.317615859
14	0.132458294	0.190410937	0.203496378	0.126399647	0.104377066	0.144625746	0.234642208	0.169678783	0.190581427
20	0.112306937	0.164125418	0.190632653	0.120127569	0.09647483	0.129008519	0.210640031	0.159463814	0.151777379
41	0.086897651	0.124733224	0.143759007	0.091858024	0.073619857	0.094207335	0.145992664	0.123087994	0.109000445
57	0.071797575	0.105276265	0.115341902	0.076687592	0.063664757	0.072918758	0.123988786	0.100290811	0.089700733
78	0.055865105	0.080065728	-	0.06006781	0.047982621	0.052194716	0.09986561	0.07525424	0.072063512
104	-	-	-	0.0357	-	0.036017	0.07483	0.037057	0.052146

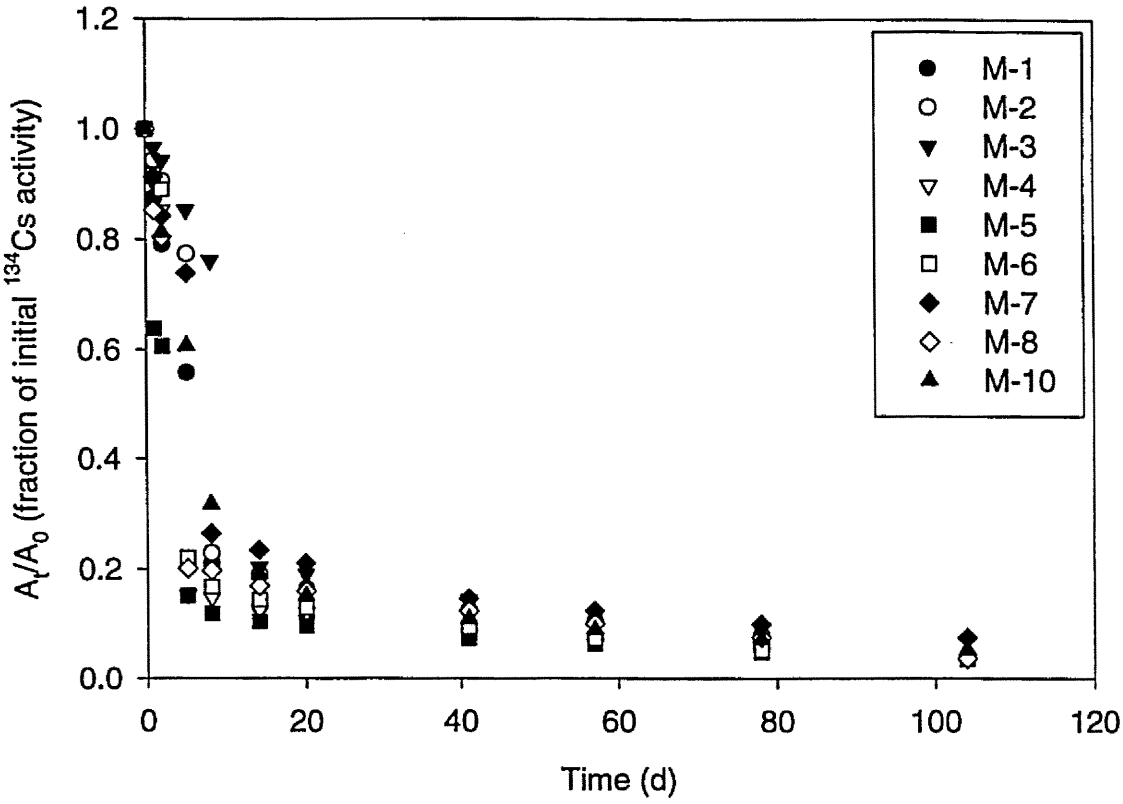


Fig. D.1. Elimination of ^{134}Cs by individual *Megarcys signata* nymphs (M-1 to M-8, M-10) at 2.5 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

APPENDIX E

Orconectes sp. Data

TABLE E.1. Fraction of initial ^{134}Cs activity over time for individual *Orconectes* at 10 °C. a. Individuals fed ^{134}Cs labeled food on day 0. b. Individuals previously labeled with ^{134}Cs transferred from 25 °C.

a.

Time (d)	CF-1-1	CF-1-3
0	1	1
1	0.938282259	0.91198336
2	0.830252056	0.887148226
4	0.795997604	0.753329607
16	0.772331177	0.700311099
23	0.655937138	0.606841051
32	0.648852015	0.610488126
46	0.573749271	0.512378393
61	0.581719834	0.509858081
79	0.538154051	0.460901035
105	0.419852574	0.420632367
135	0.368394212	0.383647232

b.

Time (d)	CF-1-5	CF-1-6	CF-1-7
0	1	1	1
15	0.992612899	0.98017906	0.863145187
30	0.942786869	0.933537457	0.814701519
41	0.879405241	0.917460524	0.796343396
52	0.877683437	0.85629925	0.726995512
65	0.826595929	0.806757994	0.685800452
83	0.689509795	0.778269407	0.590096948
85			0.591184909

TABLE E.2. Fraction of initial ^{134}Cs activity over time for individual *Orconectes* at 15 °C.

Time (d)	CF-3-1	CF-3-2	CF-3-3
0	1	1	1
1	0.766863744	0.949376956	1.032626257
2	0.764553615	0.947576426	0.905103913
4	0.739956851	0.913558352	0.903532473
16	0.651272011	0.787509296	0.793675306
23	0.612329986	0.732965067	0.631675633
32	0.563047051	0.701918295	0.604609053
46	0.50119196	0.666080183	0.592421346
61	0.4533553	0.588906472	0.602100132
79	0.401839272	0.511636109	0.449175999
105	0.343808673	0.462965416	0.45821484
135	0.294638971	0.415506378	0.383271278

TABLE E.3. Fraction of initial ^{134}Cs activity over time for individual *Orconectes* at 20 °C.

Time (d)	CF-4-1	CF-4-2	CF-4-3
0	1	1	1
1	0.911235825	0.820229765	0.680571099
2	0.927457533	0.80252287	0.660721944
4	0.875108818	0.798287596	0.614246399
16	0.795494357	0.689324597	0.554818708
23	0.759124528	0.625787507	0.55330799
32	0.674817948	0.617354959	0.494125264
46	0.681818499	0.530933644	0.462444035
61	0.570515572	0.509533742	0.354333465
79	0.575484989	0.455553601	0.334650553
105	0.485385261	0.389701733	0.29795575
135	0.413300948	0.33603288	0.250706345

TABLE E.4. Fraction of initial ^{134}Cs activity over time for individual *Orconectes* at 25 °C.

Time (d)	CF-5	CF-6	CF-7
0	1	1	1
1	0.87643533	0.893547383	0.795741894
2	0.85201742	0.882032057	0.769714776
4	0.832904666	0.887016451	0.75665247
16	0.719690069	0.751720906	0.649757831
23	0.631403481	0.675323809	0.593939788
32	0.591899692	0.605299962	0.531576205
46	0.531484681	0.497113587	0.481936813
61	0.477930349	0.424423151	0.431366536
79	0.398461752	0.363163509	0.338730324
105	0.324091118	0.254649061	0.28287417
135	0.238741557	0.189592251	0.215267252

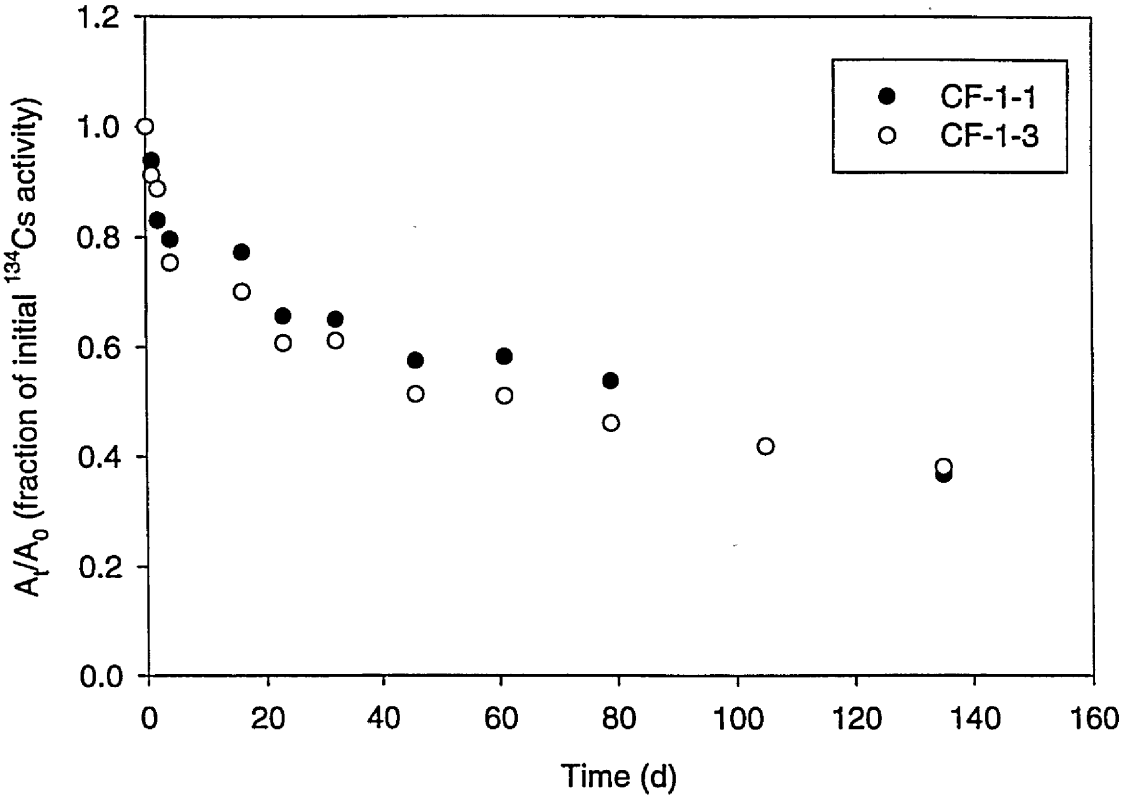
TABLE E.5. Fraction of initial ^{134}Cs activity over time for individual *Orconectes* at 30 °C. (a) Individuals fed ^{134}Cs labeled food on day 0. (b) Individuals previously labeled with ^{134}Cs transferred from 20 °C.

(a)

Time (d)	CF-8	CF-9	CF-10
0	1	1	1
1	0.835058046	0.963281856	0.841468716
2	0.78461792	0.907372136	0.794369799
4	0.711847932	0.902787791	0.794507619
16	0.592408092	0.740036408	0.66383227
23	0.486028456	0.710385868	0.555583091
32	0.42135618	0.586776399	0.469955275
46	0.306026813	0.487526291	0.404512807
61	0.24607984	-	-

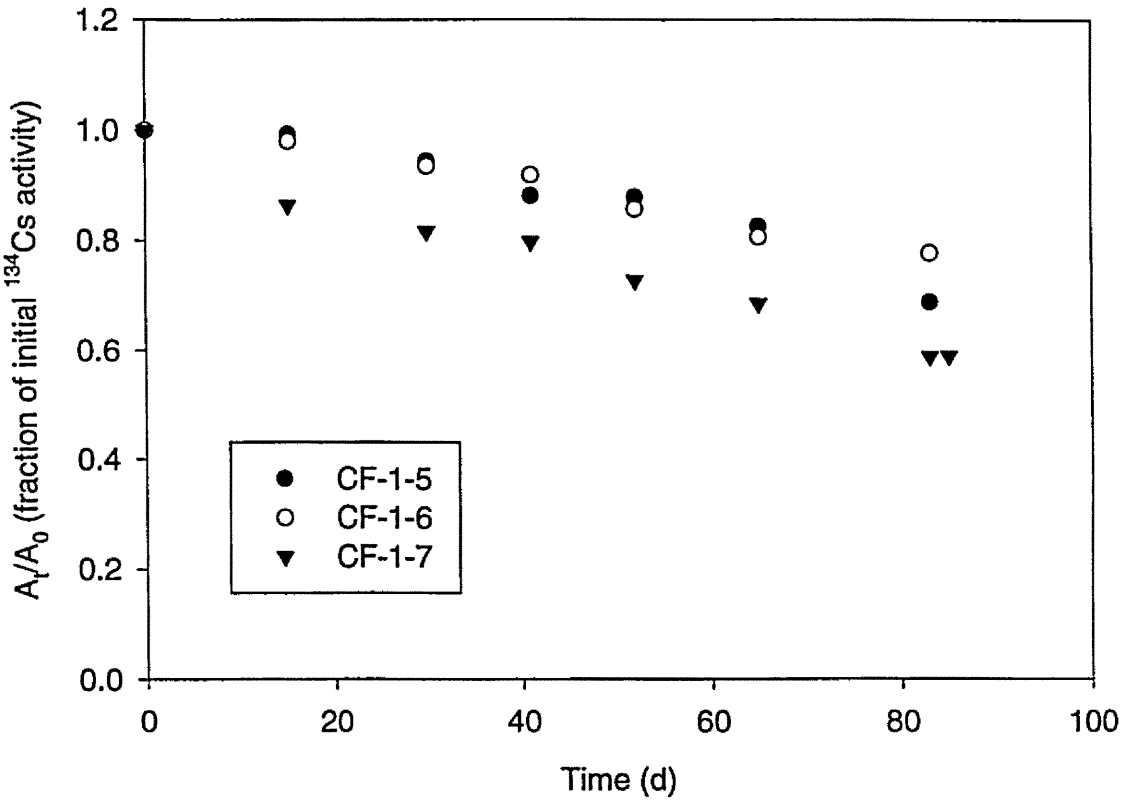
(b)

Time (d)	CF-30-41	CF-30-43
0	1	1
15	0.881599216	0.789941041
30	0.752262148	0.729519019
41	0.685568039	0.658866681
52	0.556625476	0.599573013
65	0.473572384	0.535690016
83	0.401961953	0.480529501



(a)

Fig. E.1. Elimination of ^{134}Cs by individual *Orconectes* at 10 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d). (a) Individuals (CF-1-1, CF-1-3) fed ^{134}Cs labeled food on day 0. (b) Individuals (CF1-5, CF-1-6, CF-1-7) previously labeled with ^{134}Cs transferred from 25 °C.


1.2
1.0
0.8
0.6
0.4
0.2
0.0
A_t/A_0 (fraction of initial ^{134}Cs activity)
0
20
40
60
80
100
Time (d)
CF-1-5
CF-1-6
CF-1-7

(b)

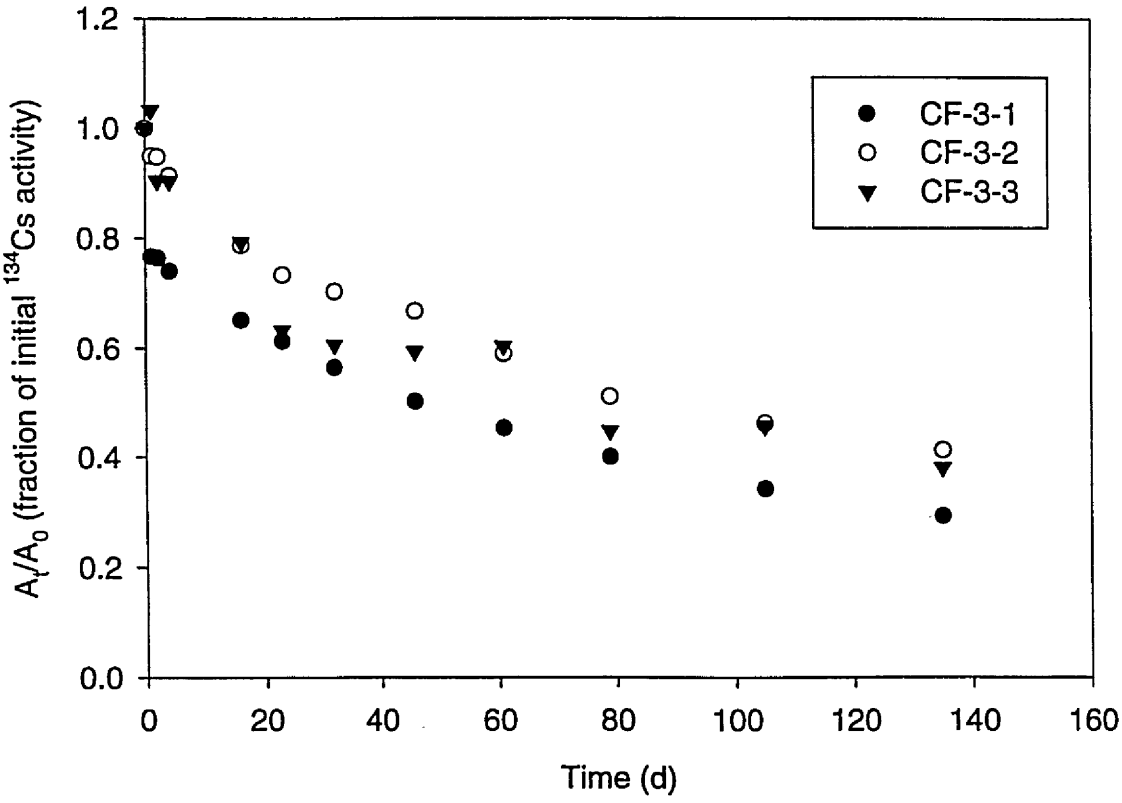


Fig. E.2. Elimination of ^{134}Cs by individual *Orconectes* (CF-3-1, CF-3-2, CF-3-3) at 15 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

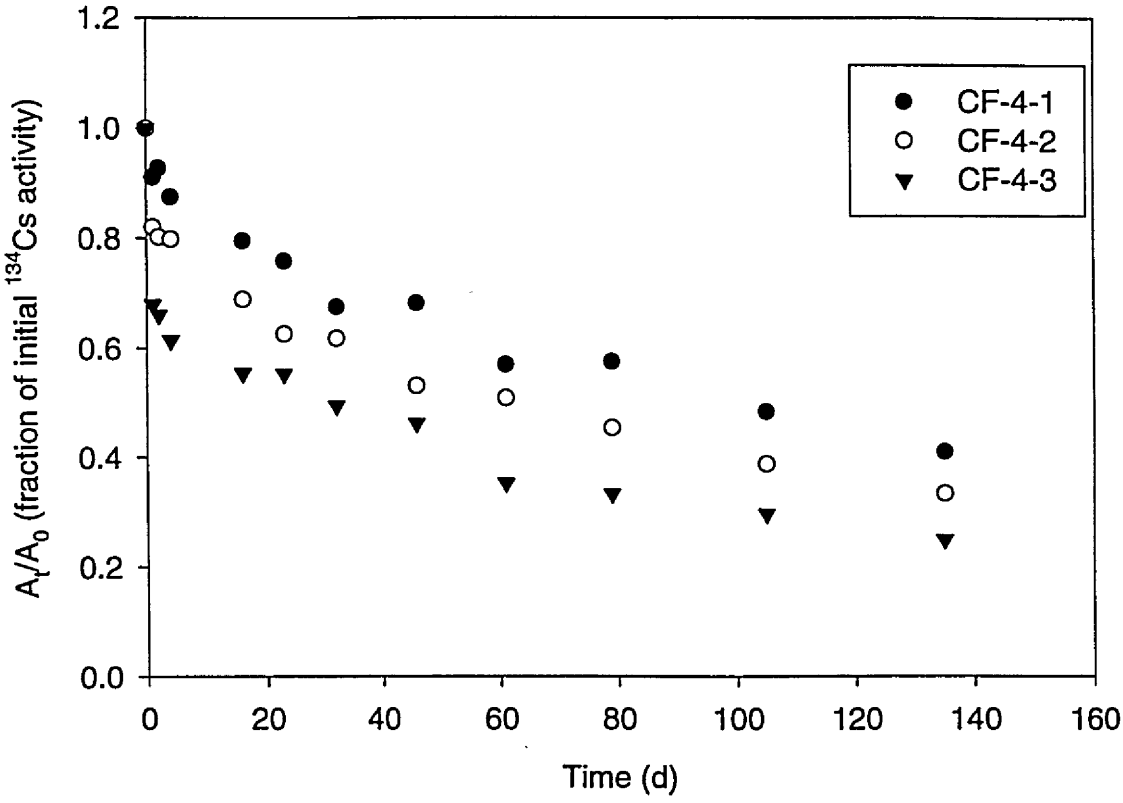


Fig. E.3. Elimination of ^{134}Cs by individual *Orconectes* (CF-4-1, CF-4-2, CF-4-3) at 20 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).

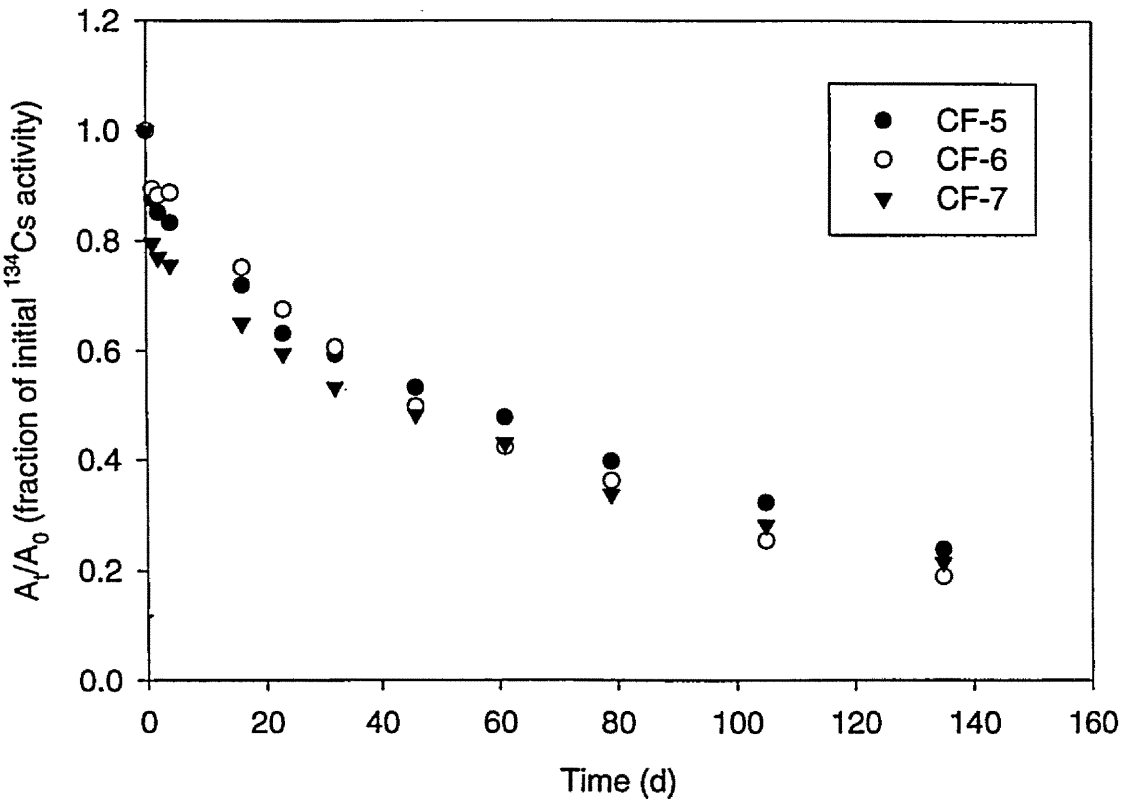
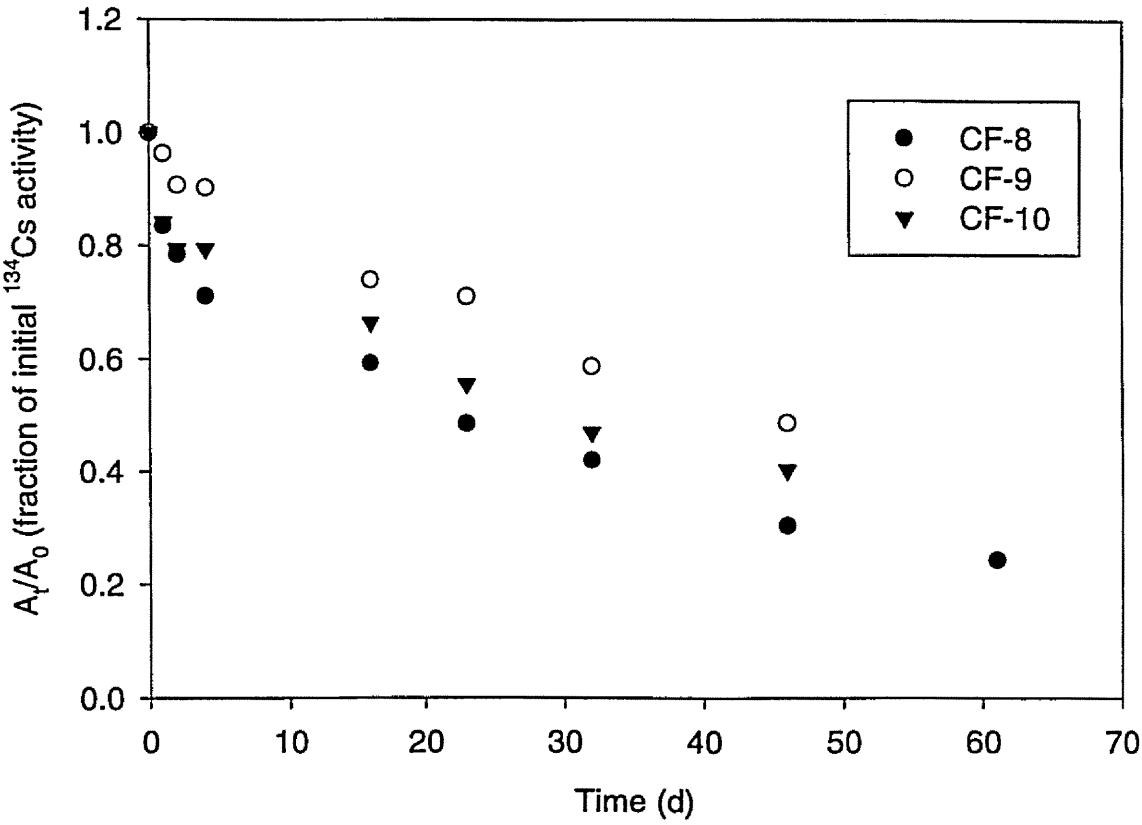
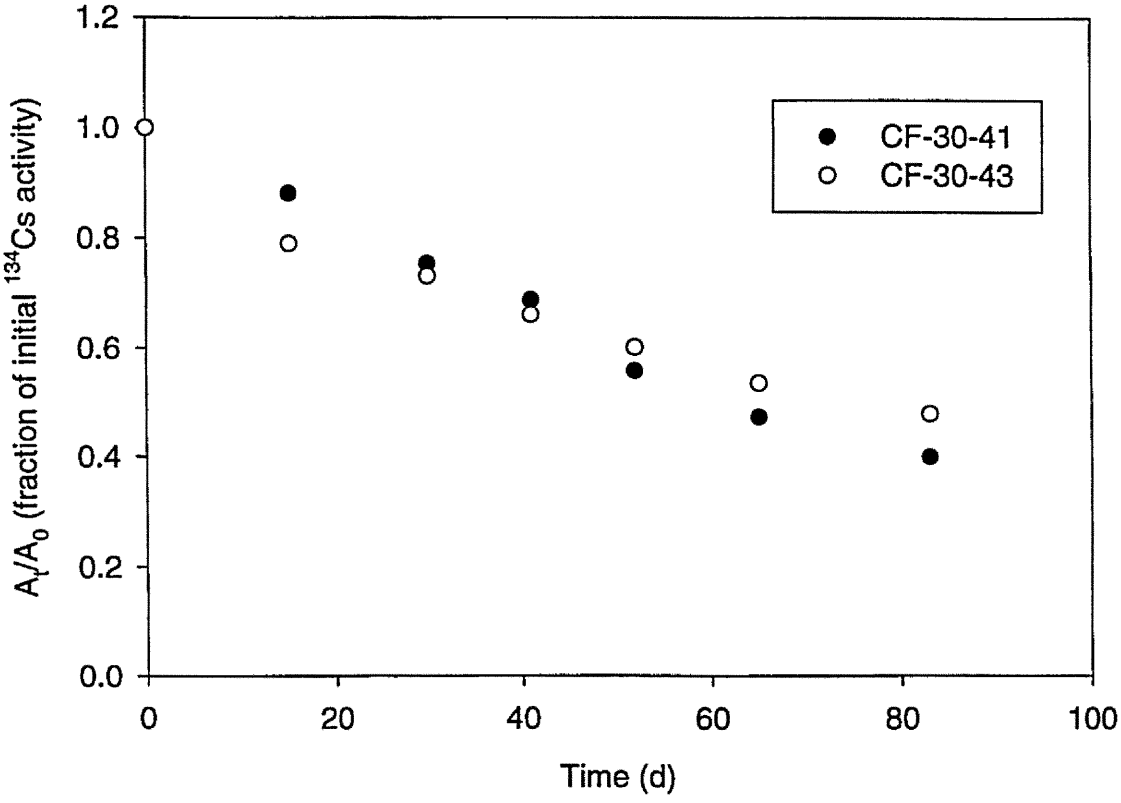


Fig. E.4. Elimination of ^{134}Cs by individual *Orconectes* (CF-5, CF-6, CF-7) at 25 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d).



(a)

Fig. E.5. Elimination of ^{134}Cs by individual *Orconectes* at 30 °C represented as fraction of initial ^{134}Cs activity (A_t/A_0) over time, where A_0 = initial ^{134}Cs activity (cps) on day 0, A_t = ^{134}Cs activity (cps) at time t, t = time (d). (a) Individuals (CF-8, CF-9, CF-10) fed ^{134}Cs labeled food on day 0. (b) Individuals (CF-30-41, CF-30-43) previously labeled with ^{134}Cs transferred from 20 °C.


1.2
1.0
0.8
0.6
0.4
0.2
0.0
A_t/A_0 (fraction of initial ^{134}Cs activity)
0
20
40
60
80
100
Time (d)
CF-30-41
CF-30-43

(b)