IMPORTANCE OF THE AQUATIC DETRITUS FOODWEB IN THE TRANSFER OF RADIONUCLIDES FROM WATER TO HIGHER TROPHIC LEVELS

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Abstract

Uptake of radionuclides from water to decaying elm-leaf discs and their transfer to the amphipod *Gammarus lacustris* was investigated. Uptake by decomposing elm leaves is microbially mediated. Uptake coefficients, *k*, for *G. lacustris* fed contaminated leaf discs were 3.66‧ d^{-1} for ^{60}Co, 4.34‧ d^{-1} for ^{131}I and 9.74‧ d^{-1} for ^{134}Cs, whereas loss rates were -1.08‧ d^{-1} for ^{60}Co, -1.07‧ d^{-1} for ^{131}I and -1.04‧ d^{-1} for ^{134}Cs. Assimilation efficiencies were 11% for leaf material, 53% for ^{60}Co, 55% for ^{131}I and 75% for ^{134}Cs. These results indicate that there is considerable potential for the transfer of radionuclides to higher trophic levels by the detritus-food web.

1. Introduction

Atmospheric weapons tests and the operation of nuclear facilities such as uranium mines and mills, generating stations, fuel reprocessing plants, and waste disposal facilities have resulted in a continual release of low concentrations of radionuclides to the environment. Nuclear accidents can also result in radionuclide releases to the environment. For example, following the Chernobyl accident ^{131}I, ^{134}Cs, and ^{137}Cs were major radionuclides in atmospheric fallout in Europe [1]. The radionuclides ^{129}I and ^{135}Cs are of particular concern to nuclear fuel waste disposal because of their long half-lifes (half-life ($t_{1/2}$) = 1.6 x 10^7 years for ^{129}I and 3.0 x 10^6 years for ^{135}Cs), mobility in the environment and their tendency for uptake by biota [2, 3, 4]. Short-lived radionuclides such as ^{60}Co ($t_{1/2}$ = 5.3 years), ^{131}I ($t_{1/2}$ = 8 days), ^{134}Cs ($t_{1/2}$ = 2.1 years) and ^{137}Cs ($t_{1/2}$ = 30.2 years) are abundant activation or fission products that are present in low concentrations in aqueous discharges from nuclear facilities and are taken up by biota [4, 5, 6, 7]. At uranium mines and mills it is uranium and its decay-chain daughters (^{230}Th, ^{226}Ra, ^{210}Pb and ^{210}Po) that are of primary concern. To protect the environment, it is important to understand the behaviour of these radionuclides in the environment and their transfer in the food chain.

In freshwater ecosystems, considerable energy is cycled through the detritus-food web. The detritus may be of authochonous origin such as decomposing macrophytes and algae or of allochthonous origin such as leaves, wood, bark, etc. The autumnal input of leaves to woodland streams [8] and smaller lakes [9, 10] is an important source of energy to these systems. Because most Canadian Shield lakes are small, with a geometric mean area of only 7 ha [11], allochthonous inputs are important sources of energy to these lakes. For example,

about 65% of the particulate organic carbon (POC) was estimated to be of allochthonous origin in Lake 224, Experimental Lakes Area, northwestern Ontario [12].

Upon entering water, leaves undergo rapid weight loss because of leaching of soluble compounds. The leaves rapidly become colonized by fungi and bacteria. Microbial colonization of the leaves and assimilation of nutrients from the water by the microbes increases their nutrient quality [13]. Microbes make the leaf tissue more palatable to invertebrates by converting leaf tissue into microbial biomass and more digestible material for detritus feeders [14]. The decomposition of macrophytes and their consumption by invertebrates is similar to that of leaf litter, but occurs at a faster rate.

The following studies tested the hypothesis that microbial activity mediates the transfer of radionuclides from water to detritus (leaf litter) and the feeding of benthic invertebrates on the detritus results in their uptake of the radionuclides, which can be subsequently transferred to higher trophic levels. *Gammarus* was studied because of its abundance in freshwater and, where present, its prevalence in the diet of fish. Benthic invertebrates are also important in the diet of waterfowl. This work provides fundamental information on the potential for these radionuclides to be transferred to higher trophic levels (e.g., fish and waterfowl) through the detritus-food chain.

2. Materials and Methods

2.1 Uptake of ^{60}Co, ^{131}I and ^{134}Cs from Water by Decomposing Elm Leaves

American elm (*Ulmus americana* L.) leaf discs were used in the experiments, because they are a fast decomposing leaf species [15]. The leaf discs (14 mm in diameter) were leached for 24 h, dried at 65ºC for 48 h, and placed in groups of 90 into ten polyethylene containers containing 1.5 L of Winnipeg River (soft) water (Table 1) collected near Whiteshell Laboratories, Pinawa,

Table 1. Characteristics of Spring Water and Winnipeg River water.

	Spring Water	Winnipeg River
pH	8.1	7.6
Alkalinity ($mg \cdot L^{-1}$ $CaCO_3$)	250	42
Ca ($mg \cdot L^{-1}$)	65	13.1
Mg ($mg \cdot L^{-1}$)	16	3.9
Fe ($mg \cdot L^{-1}$)	0.03	0.03
Si ($mg \cdot L^{-1}$)	5.1	1.0
S ($mg \cdot L^{-1}$)	3.1	1.8
Sr ($mg \cdot L^{-1}$)	-	0.025
Na ($mg \cdot L^{-1}$)	4.4	2.3
K ($mg \cdot L^{-1}$)	38	1.0

- data not available

Manitoba. The leaf discs were allowed to decompose for up to five weeks over the study period. Two treatments were used: microbially enhanced (ME) and microbially inhibited (MI), with five replicates per treatment [16]. The ME treatment involved spiking each container of water with 50 mL of a foam inoculum collected from the outflow of a beaver pond and adding nutrients (5 mg P $^{-1}$as K_2HPO_4 and 20 mg N L^{-1} as $(NH_4)_2SO_4$) to the water to enhance microbial growth. Foam is known to be efficient in trapping fungal spores and bacteria and is an excellent inoculum [17]. Inhibition of microbes involved sterilizing the dry leaf discs and water with gamma irradiation (1.7 Gy s^{-1} for 4 h) and the addition of fungicide (100 mg L^{-1} of nystatin) and bactericide (3.0 mg L^{-1} each of streptomycin and penicillin) to the water. The MI treatment will not remain sterile but the growth of microbes would be greatly reduced compared to that in the ME treatment.

The water in each container was spiked with radionuclides and handled as described in Bird and Schwartz [16]. Fifteen-leaf discs were collected from each container at weekly intervals for five weeks, dried a 60ºC for 24 h, weighed, then placed in 10 mL of NCS-II tissue solubilizer (Amersham Canada Limited, Oakville, Ontario) in a 22 mL vial and digested overnight, before being counted for radioactivity as described by Bird and Schwartz [16].

2.2 Conditioning and Contamination of Elm Leaf Discs for *Gammarus* Feeding Studies

Elm-leaf discs were leached for 24 h, dried at 65°C for 48 h, and placed in groups of 200 into two polyethylene containers containing 2.6 L of Winnipeg River water to which 50 mL of a foam inoculum and nutrients (5 mg P L^{-1} as K_2HPO_4 and 20 mg N L^{-1} as $(NH_4)_2SO_4$) were added to enhance microbial growth. The leaf discs were allowed to decompose for three weeks prior to initiating the feeding studies. One week prior to the feeding study, the water in each container was spiked with 30 kBq of ^{60}Co, 60 kBq of ^{131}I and 30 kBq of ^{134}Cs. Conditioning the leaf discs for two weeks before the addition of radionuclide allowed for microbial colonization of the leaf discs so the radionuclides would be taken up by both the leaf discs and their associated microbial flora. Each container was gently stirred five days per week to mix the clumps of leaf discs to ensure they were all exposed to microbial colonization and radionuclide uptake.

2.3 ^{60}Co, ^{131}I and ^{134}Cs Uptake and Depuration by *Gammarus*

The uptake of ^{60}Co, ^{131}I and ^{134}Cs in feeding studies with *G. lacustris* used hard water (Table 1) from a local spring because survival of amphipods is better in hard water than the soft water. Sixty gammarids were placed in each of five 4-L polypropylene food-pail-feeding chambers and fed twenty contaminated elm leaf discs per day for eight days before they were switched to a diet of uncontaminated-conditioned-leaf discs and fed for an additional 17 days. Leaf discs were conditioned for 21 d as previously described. The gammarids used in the feeding study weighed 5.4 ± 0.6 mg dw individual^{-1} based on the weight of 26-representative animals sacrificed at the start of the study. The feeding chambers had a screen bottom and were raised so that the faeces would fall through the screen. Three leaf discs from each of two containers of contaminated leaf discs were placed in a 20-mL vial, dissolved in 10 mL of NSC and counted for gamma activity on days 1, 3, 5 and 8. On days 1, 3, 5, 8, 9, 12, 14, 17 and 25,

five specimens were sacrificed from each of the feeding chambers, placed in a 20-mL vial, dissolved in 10 mL of NSC and counted for gamma activity.

2.4 Assimilation Efficiency of *Gammarus*

Three gammarids were placed in each of five feeding chambers housed in a 250-mL beaker containing 200 mL of water. The feeding chambers were constructed of acrylic tubing 5 cm in diameter by 9.5 cm in height. Fibreglass screening, 1.0 mm-mesh size, was attached to the bottom of each chamber with a 1-cm base ring, which held the mesh off the bottom of the container. The mesh permitted retention of the animals and leaf discs in the feeding chamber, while faecal material and other fine particulate organic matter (FPOM), e.g., fragments of leaf material, passed through the screen into the container below.

Three leaf-discs per replicate (3 x 5 reps) were counted for gamma activity before being fed to the gammarids. The gammarids were fed three contaminated elm leaf discs per day for two days. After 24 h of feeding, leaf remnants were removed from the feeding chamber, dried, weighed, solubilized in 10 mL of NCS-II tissue solubilizer at ambient room temperature (~22°C) and counted for gamma activity. Faecal material that had passed through the screen was collected onto a preweighed 0.45-μm millipore filter. The filters were dried, reweighed and counted for gamma activity. A 20-mL-water sample from each feeding chamber was also analyzed for gamma activity. The containers (beakers) housing the feeding chambers were rinsed with distilled water, wiped clean with a Kim wipe and fresh water was added. The gammarids in each feeding chamber were counted for gamma activity. Feeding rates were determined gravimetrically from the difference between the weight of control leaf discs and the weight of the leaf remnants remaining after feeding and was expressed as the weight of leaf ingested per gammarid per day. The assimilation efficiency (AE) of leaf material, ^{60}Co, ^{131}I and ^{134}Cs ingested by *G. lacustris* was calculated using the equation:

$$AE = (\text{ingestion} - \text{egestion})/\text{ingestion per gammarid} \quad (1)$$

where:
ingestion is the initial weight or gamma activity of the leaf discs before feeding minus the weight or gamma activity in the leaf disc remnants; and egestion is the weight or gamma activity of the faecal material produced. Since all samples were decay corrected to the start of the study, decay is not considered in the equation.

2.5 Partitioning of ^{60}Co, ^{131}I and ^{134}Cs between Water and *Gammarus* Faeces

The partition coefficient, K_d, is the tendency of the radionuclides to be associated with the solid or liquid phase, in this case faeces and water. To collect faeces for the investigation into the partitioning of ^{60}Co, ^{131}I and ^{134}Cs between water and faeces, three *G. lacustris* were housed in three feeding chambers containing uncontaminated hard water and fed six conditioned elm-leaf discs for 24 h. The faeces were then collected and placed in 25 mL of

contaminated hard water in a 50-mL disposable centrifuge tube for 24 h. This was repeated daily for three days. Faeces were collected from the contaminated water by filtering the contents of the centrifuge tube through a preweighed 0.45-μm cellulose-nitrate filter, which was dried at 60°C, reweighed and counted for gamma activity. A 20-mL water sample was also counted for gamma activity.

2.6 Radiological and Statistical Analysis

All samples were analyzed by counting for at least 20 min in a Nuclear Data 9900 gamma spectrometer using a co-axial germanium detector with a rated relative efficiency of 14% in conjunction with a micro-Vax 4000-460 work station. Gamma emissions for ^{60}Co at 1332 keV energy, ^{131}I at 364 keV and ^{134}Cs at 796 keV were analysed. Counts were for samples corresponding to standard geometries of 10 mL, assuming uniform distribution of the radioactivity throughout the sample. The activities were back-dated to the start of the experiment to account for radioactive decay.

Statistical analysis of the data for radionuclide uptake by decaying elm-leaf discs was by analysis of variance (ANOVA) in combination with Scheffe multiple-comparison test using the SAS PROC ANOVA program. Because the amount of each radionucide added to the containers varied, counts for radionuclides on the leaf discs were standardized to the amount of ^{60}Co added to the containers. Statistical analysis of data to determine uptake and depuration rate coefficients, k (d^{-1}), was by linear regression of the non-transformed data for counts per individual *Gammarus* for uptake rates and the natural log-transformed data depuration rates using the SAS PROC REG program [18]. Radionuclides uptake up by *G. lacustris* from consumption of contaminated leaf discs was normalized to the amount of ^{131}I on the leaf discs. To assess differences in AE among the radionuclides, a cosine transformation was performed on the data and statistical analysis was by analysis of variance (ANOVA) in combination with the Scheffe multiple-comparison test using PROC ANOVA. Probabilities at or below $P = 0.05$ are deemed significant.

3 Results and Discussion

Gammarus is a shredder that feeds on detritus, particularly deciduous leaves, algae and animal remains [19, 20, 21]. They are continuous feeders and have a gut content turnover time of about one hour when continuously feeding. A feeding rate of 4.1 ± 2.1 mg d^{-1}·individual^{-1} was measured for *G. lacustris* in our study which is similar to a feeding rate of 5.1 mg·d^{-1}·individual^{-1} reported for *G. pseudolimneaus* fed conditioned elm-leaf discs in another study [15].

Standardized radionuclide concentrations in the conditioned elm-leaf discs decreased in the order ^{60}Co > ^{134}Cs > ^{131}I [16]. Uptake of ^{60}Co by the leaf discs is relatively rapid, possibly due to adsorption to both leaf surface and microbial biomass (Figure 1). Uptake of ^{131}I and ^{134}Cs by the leaf discs was slower than that of ^{60}Co and increased steadily with the duration of conditioning which strongly suggests that their uptake is primarliy mediated by microbial activity. Previous studies have demonstrated that ^{131}I is readily taken up by algae [16, 22] and that microbes greatly increase the sorption of ^{131}I to sediments [23]. Cations (e.g., ^{60}Co and

^{134}Cs) show a strong affinity for fungal mycelium [24]. In lakes, Co readily binds to organic particles and is rapidly lost to bottom sediments [5, 25]. This is in agreement with the observation of rapid uptake of ^{60}Co by the leaf discs, which supports the conjecture that this is primarily a surface absorption phenomena. In lakes, Cs binds to organic particles less readily than Co and is lost to bottom sediments at a slower rate [25], whereas iodine which is present predominantly as I^- [26, 22] has little tendency to adsorb to sediments [27, 23]. The uptake of ^{134}Cs and ^{131}I by leaf discs is mediated primarily by microbes.

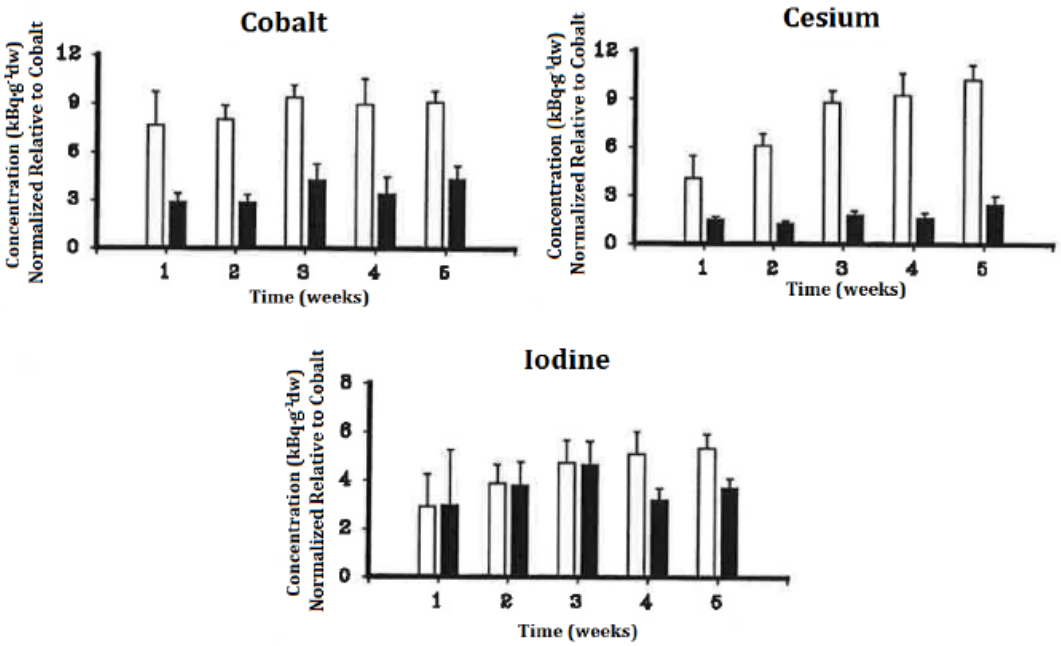

Figure 1 Uptake of ^{60}Co, ^{131}I and ^{134}Cs by elm-leaf discs from water (modified from [16]. Open bars are microbially enhanced; solid bars are microbially inhibited.

3.1 Uptake of ^{60}Co, ^{131}I and ^{134}Cs by *Gammarus*

Radionuclide uptake and depuration from elm-leaf discs are presented in Table 2. Radionuclide uptake from contaminated leaf discs by *G. lacustris* was in the order ^{131}I > ^{134}Cs > ^{60}Co. Uptake *k* values from feeding on contaminated leaf discs were 3.66 d^{-1} for ^{60}Co, 14.34 d^{-1} for ^{131}I and 9.74 d^{-1} for ^{134}Cs (Table 2). Following radionuclide uptake from consumption of contaminated leaf discs, depuration *k* values were -1.08 d^{-1} ($t_{1/2}$ = 8.8 d) for ^{60}Co, -1.07 d^{-1} ($t_{1/2}$ = 9.8 d) for ^{131}I and -1.04 d^{-1} ($t_{1/2}$ = 17.3 d) for ^{134}Cs (Table 2). Thus depuration rates are much slower than uptake rates. The rapid uptake and accumulation of these radionuclides by *G. lacustris* points to the potential importance of benthic invertebrates in transferring contaminants to higher trophic levels.

Copius amounts of faecal material are continuously produced by invertebrates because of their low assimilation efficiencies of 5-20% when feeding on detritus and rapid gastric evacuation rates of 30 minutes to 2 hours. Faecal pellets, especially after microbial growth, represent an important food source quantitatively and qualitatively [8]. For example, the turnover of fine

sediments (<63 μm) in 71-102 days by defecation by Simuliidae and *Gammarus pulex* and reuse
by Tubificidae [28] is suggestive of the importance of faecal matter in streams. Increased microbial activity in faecal material enhances nutrient (and contaminant) content of the faeces resulting in food of higher quality than the original fresh faeces. The use of faecal material by detritivores enhances elemental turnover rates. The partitioning of aqueous radionuclides to faeces in the present study, with GM K_d values of about 2700 $L \cdot kg^{-1}$ for ^{60}Co, 1150 $L \cdot kg^{-1}$ for ^{131}I and 700 $L \cdot kg^{-1}$ for ^{134}Cs (Table 3) indicates that considerable recycling of contaminants may occur through detritivore activity.

Table 2. Uptake Rate Coefficients, *k* (d^{-1}), as the Slope of the Data for Counts (Bq) per Individual *Gammarus* Fed Contaminated Elm-leaf Discs versus Time and Depuration *k*s as the Slope of the Anti-log of the Natural Log-transformed Data.

Uptake (n = 17)				
	k	SE	Probability	R^2
^{60}Co	3.66	0.56	0.0001	0.81
^{131}I	14.34	1.66	0.0001	0.88
^{134}Cs	9.74	1.01	0.0001	0.90
Depuration (n =11)				
	k	SE	Probability	R^2
^{60}Co	-1.08	0.016	0.0007	0.70
^{131}I	-1.07	0.012	0.0002	0.77
^{134}Cs	-1.04	0.012	0.008	0.52

Increasing the duration of microbial conditioning of the leaf discs substantially increases the amount eaten by *G. pseudolimnaeus* and the production of both fine particulate organic matter and faecal material [15]. In the present study, faecal production of 0.7 ± 0.4 $mg \cdot mg^{-1}$ $dw \cdot d^{-1}$ is in the range of 0.02 to 1.2 $mg \cdot mg^{-1}$ $dw \cdot d^{-1}$ documented for other freshwater invertebrates [8].

As the duration of conditioning of elm-leaf discs increases from 1 to 4 weeks, the AE of *G. pseudolimnaeus* decreases from about 40% to 10% [15]. The AE of 9% measured in the present study for *G. lacustris* feeding on leaf discs conditioned for three weeks is similar to the AE of 10% reported for *G. pseudolimnaeus* feeding on leaf discs conditioned for 4 weeks. In our study, *G. lacustris* had an AE of about 53% for ^{60}Co, 55% for ^{131}I and 75% for ^{134}Cs (Table 4), which accounts for the rapid uptake of these radionuclides by *G. lacustris*. These AE values are much greater than the value of 1.4% reported for the assimilation of Zn by *G. pulex* fed conditioned horse chestnut leaves (*Aesculus hippocastanum*) [29]. The low AE of Zn may be because Zn is a regulated element and because Zn uptake is primarily from water rather than from its food [29]. Co and I are also essential elements and their uptake is regulated in humans. In contrast, Cs is not required and its uptake is not regulated. Cesium is taken up as an analog of K.

Radionuclides that accumulate in detritus may be transferred to higher trophic levels through the detritus-food web. This may occur despite low assimilation efficiencies (generally < 20%) for
invertebrates feeding on detritus [15], because contaminant concentrations in detritus are usually much greater than in water. Furthermore, high AEs (> 50%) for ^{60}Co, ^{131}I and ^{134}Cs in the present study and for invertebrates feeding on bacteria and fungi in general [15] may enhance this transfer. The accumulation of ^{60}Co and ^{137}Cs in primary consumers and aquatic insects is two to four orders of magnitude greater than that in water [30]. Accumulation of ^{32}P [31] and Zn [29] occurs in amphipods fed contaminated leaves, and substantial accumulation of ^{60}Co, ^{106}Ru and ^{137}Cs occurs in worms, *Limnodrilus hoffmeisteri*, snails, *Physa*, and chironomid larvae, *Stictochironomus annulirus*, fed contaminated detritus [32]. Sombre *et al*. [33] found that the food chain was responsible for 90% of the ^{137}Cs accumulated by the barbel (*Barbus barbus*). The importance of recycling of contaminants through the detritus-food web is illustrated by the fact that about 80% of the primary production in Lawrence Lake, Michigan, was consumed via the detritus food chain [34].

CRs between water and faecal material (L·kg^{-1} dw) (n =3).

	^{60}Co	^{131}I	^{134}Cs
GM*	22600	1200	700
GSD**	1.4	1.8	1.4

CRs between *Gammarus* (Bq·g^{-1})/elm-leaf discs (Bq·g^{-1}) (n = 3).

	^{60}Co	^{131}I	^{134}Cs
GM*	0.004	0.25	0.025
GSD**	1.1	1.1	1.1

CRs between *Gammarus* faeces (Bq·g^{-1}) and elm-leaf discs (Bq·g^{-1}) (n = 10)

	^{60}Co	^{131}I	^{134}Cs
GM*	0.22	0.30	0.17
GSD**	1.3	1.3	1.6

Assimilation efficiency of *G. lacustris* fed contaminated elm-leaf discs (mean % ± SD, n = 10).

Leaf material	^{60}Co	^{131}I	^{134}Cs
8.3 ± 6.1[a]	52.7 ± 12.5[b]	55.1 ± 10.6[b]	74.5 ± 3.7[c]

[a,b,c] Statistical analysis was by ANOVA on cosine transformed data in combination with the Scheffe multiple-range test using SAS (1989). Values with different superscripts are significantly different at $P < 0.05$.
GM* = geometric mean
GSD** = geometric standard deviation

Table 3. Summary of Concentration Ratios (CRs) and Assimilation Efficiencies Measured in the *Gammarus* Feeding Studies.

In the present study, concentration factors between water and *G. lacustris* (L·kg^{-1} dw *G. lacustris*) of 9,800 for ^{60}Co, 2,800 for ^{131}I and 3,100 for ^{134}Cs were calculated. These values are consistent with a CF of 6600 for ^{60}Co in *Hyalella azteca* in a Canadian Shield lake [35],

6,000 for *Gammarus* in the laboratory and 1,400 in the field [36]. In our study, we did not differentiate between surface adsorption and assimilation from water. However, based on the radioactivity measured in a single sample of three exuvia pooled together, radioactivity in the exoskeleton represented about 23% of the ^{60}Co, 26% of the ^{131}I and <4% of the ^{134}Cs taken up by the animals. Uptake of the radionuclides from water by *G. lacustris* may be via the pleopods in respiration or due to adsorption to the exoskeleton. Surface adsorption to the exoskeleton is an important process when aqueous contaminant concentrations are relatively high. For example, surface adsorption accounted for about 32% of the Ni, 46% of the Mn and 27% of the Cd total body burden of chironomid larvae collected from a low pH (5.4) Shield lake in Ontario [37].

Concentration ratios (Bq·kg^{-1} dw *G. lacustris* / Bq·kg^{-1} dw leaf) between *G. lacustris* and the elm-leaf discs were 0.004 for ^{60}Co, 0.250 for ^{131}I and 0.025 for ^{134}Cs. Fresh faeces had lower radionuclide concentrations than the contaminated elm-leaf discs from which they were derived. Concentration ratios between faeces and leaf discs were about 0.220 for ^{60}Co, 0.300 for ^{131}I and 0.170 for ^{134}Cs (Table 3). For comparison, a concentration ratio of about 0.01 was reported for carp (*Cyprinus carpio*) fed ^{60}Co contaminated snails (*Lymnaea stadnalis*) [38], which indicates that concentrations decrease between a primary consumer and the secondary consumer. Because radionuclides may reach much higher concentrations in detritus than in water and the AE of the detritivore *G. lacustris* in the present study is high, there is the potential for substantial transfer of radionuclides to higher trophic levels through the detritus food web and the subsequent exposure of aquatic biota to radiation.

This study shows that radionuclides are readily taken up by decaying detritus and can be transferred to benthic invertebrates feeding on the decaying organic material. Contamination of benthic invertebrates can lead to the transfer of radionuclides to higher trophic levels that feed on benthic invertebrates such as fish and ducks. Further information is required on the transfer of other radionuclides such as ^{nat}U, ^{230}Th, ^{226}Ra, ^{210}Pb and ^{210}Po to detritus and their uptake by benthic inverebrates and subsequently to higher trophic levels. We know that the uptake of ^{nat}U and ^{230}Th via the gut in humans is low (generally <5%), whereas that of ^{210}Po is high (50 – 75%). However, we do not know whether this trend is applicable to benthic invertebrates or other aquatic organisms at higher trophic levels, e.g., fish and waterfowl. This requires further investigation.

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5.0 References

[1] P.H. Santschi, S. Bollhalder, S. Zingg, A. Lück and K. Farrenkothen, “The self-cleaning capacity of surface waters after radioactive fallout. Evidence from European waters after Chernobyl, 1986-1988”, Environ. Sci. Technol.,Vol. 24, 1990, pp.519-527.

[2] G.M. Desmet, L.R. Van Loon and B.J. Howard, "Chemical speciation and bioavailability of elements in the environment and their relevance to radioecology", Sci. Total Environ., Vol. 100, 1991, pp.105-124.

[3] H. Elderfield and V.W. Truesdale, "On the biophilic nature of iodine in seawater". Earth Planet Sci. Lett., Vol. 50, 1980, pp.105-114.

[4] G.A. Bird, M. Motycka, J. Rosentreter, W.J. Schwartz and P.Vilks, "Behaviour of ^{125}I added to limnocorrals in two Canadian Shield lakes of differing trophic states", Sci. Tot. Environ., Vol. 166, 1995, pp.161-177.

[5] G.A. Bird, W.J. Schwartz and M. Motycka, " Behavior of ^{60}Co and ^{134}Cs in a Canadian Shield lake over 5 years", Sci. Tot. Environ., Vol. 212, 1997, pp.115-135.

[6] S. Kolehmainen, "The balance of ^{137}Cs, stable cesium and potassium of bluegill (*Lepomis macrochirus* Raf.) and other fish in White Oak lake", Health Physics, Vol. 23, 1972, pp.301-315.

[7] D. Miškovic, Lj. Conkic, B. Dalmacija and M. Gantar, "Removal of some radionuclides from water by bioaccumulation", Wat. Sci. Tech., Vol. 26, 1992, pp.2129-2132.

[8] G.A. Bird and N.K. Kaushik, "Coarse particulate organic matter in streams", In: M.A. Lock & D.D. Williams (eds.), Perspectives in Running Water Ecology, Plenum Press, New York, 1981, pp.41-68.

[9] W.E. Odum and R.T. Prentki, "Analysis of five North American lake ecosystems IV. Allochthonous carbon inputs", Verh. Internat. Verein. Limnol., Vol. 20, 1978, pp.574-580.

[10] E. Pieczynska, " Detritus and nutrient dynamics in the shore zone of lakes: a review", Hydrobiologia, Vol. 251, 1993, pp.49-58.

[11] G.A.Bird, M. Stephenson and R.J. Cornett, "The surface water model for assessing Canada's nuclear fuel waste disposal concept", Waste Mngt., Vol. 13, 1993, pp.153-170.

[12] R.H. Hesslein, W.S. Broecker and D.W. Schindler, " Fates of metal radiotracers added to a whole lake: sediment-water interactions", Can. J. Fish. Aquat. Sci., Vol. 37, 1980, pp.378-386.

[13] G.A. Bird and N.K. Kaushik, "Invertebrate colonization and processing of maple leaf litter in a forested and an agricultural reach of a stream", Hydrobiologia, Vol. 234, 1992, pp.65-77.

[14] L.G. Willoughby, "Decomposition of litter in freshwater", In: C.H. Dickinson and J.F. Pugh (eds), Biology of Plant Litter Decomposition. Academic Press, London, 1974, pp. 658-681.

[15] G.A. Bird and N.K. Kaushik, "Processing of elm and maple leaf discs by collectors and shredders in laboratory feeding studies", Hydrobiologia, Vol. 126, 1985, pp.109-120.

[16] G.A. Bird and W. Schwartz, "Effect of microbes on the uptake of ^{60}Co, ^{85}Sr, ^{95m}Tc, ^{131}I and ^{134}Cs by decomposing elm leaves in aquatic microcosms" Hydrobiologia, Vol. 330, 1996, pp.57-62.

[17] J. Michaelides and B. Kendrick, "An investigation of factors retarding colonization of conifer needles by amphibious hypomycetes in streams", Mycologia, Vol 70, 1978, pp.419-430.

[18] SAS (Statistical Analysis System, Inc.), "Statistical analysis user's guide: Statistics", SAS Institute, Cary, NC., 1989.

[19] H.B.N. Hynes, "The ecology of *Gammarus duebeni* Lilljeborg and its occuence in fresh waters in Western Britian", J. Animal Ecol. Vol. 23, 1954, pp.38-84.

[20] J.W. Moore, "The role of algae in the diet of *Asellus aquaticus* L. and *Gammarus pulex* L.", J. Animal. Ecol.,Vol. 44, 1975, pp.719-730.

[21] L.G. Willoughby and D.W. Sutcliffe, "Experiments on feeding and growth of the amphipod *Gammarus pulex* (L.) related to the distribution in the River Duddon", Freshwater Biology, Vol. 6, 1976, 577-586.

[22] K. Sugawara and K. Terada, "Iodine assimulation by a marine *Navicula* sp. and the production of iodate accompanied by the growth of the algae", Inf. Bull. Planktology Jpn., Commem. Number of Dr. Y. Matsue, 1967, pp.213-218.

[23] G.A. Bird and W. Schwartz, "Distribution coefficients, K_ds, for iodine in Canadian Shield lake sediments under oxic and anoxic conditions", J. Environ. Radioactivity Vol. 35, 1996, pp.261-279.

[24] J. Bender, R.F. Lee and P. Phillips, "Uptake and transformation of metals and metalloids by microbial mats and their use in bioremediation". J. Industrial Microbiol. Vol. 14, 1995, pp.113-118.

[25] R.H. Hesslein, "Whole-lake metal radiotracer movement in fertilized lake basins", Can. J. Fish. Aquat. Sci., Vol. 44, 1987, pp.74-82.

[26] R. Fuge and B. Brehler, "Iodine section 57", In: Handbook of Geochemistry, Part 4, Springer, Vol. 7, 1977.

[27] G.A. Bird, W.J. Schwartz and J. Rosentreter, "Evolution of ^{131}I from freshwater and its partitioning in simple aquatic microcosms", Sci. Tot. Environ., Vol. 164, 1995, pp.151-159.

[28] M. Ladle and B.S. Griffiths, "A study on the faeces of some chalk stream invertebrates", Hydrobiologia, Vol. 74, 1980, pp. 161-171.

[29] Q. Xu and D. Pascoe, "The importance of food and water as sources of zinc during exposure of *Gammarus pulex* (Amphipoda)", Arch. Environ. Contam. Toxicol., Vol. 26, 1994, pp.459-465.

[30] J.R. Voshell, J.S. Eldridge and T.W. Oakes, "Transfer of ^{137}Cs and ^{60}Co in a waste retention pond with emphasis on aquatic insects", Health Physics, Vol. 49, 1985, pp.777-789.

[31] M.L. Costantini and L. Rossi, "^{32}Phosphorus transfer in systems of fish and amphipods exploiting detritus particles", Hydrobiologia, Vol. 302, 1995, pp.81-87.

[32] J.L. Wilhm, "Transfer of radionuclides between detritus and benthic macroinvertebrates in laboratory microecosystems", Health Phys., Vol. 18, 1970, 277-284.

[33] L. Sombre, Y. Thiry and C. Myttenaere, "The radiocesium transfer in a freshwater foodchain (water - algae - mussels -fish - fish)", J. Radioecol., Vol. 1, 1993, pp.21-27.

[34] R.G. Wetzel, P.H. Rich, M.C. Miller and H.L. Allen, "Metabolism of dissolved and particulate detrital carbon in a temperate hard-water lake", Mem. 1st. Ital. Idrobiol. Suppl., Vol. 29, 1972, pp.185-243.

[35] G.A. Bird, W.J. Schwartz and M. Motycka, "Fate of ^{60}Co and ^{134}Cs added to the hypolimnion of a Canadian Shield lake: Accumulation in biota", Can. J. Fish. Aquat. Sci. Vol. 55, 1998, pp.987-998.

[36] Z.F. Short, R.F. Palumbo, P.R. Olson and J.R. Donaldson, "The uptake of I^{131} by the biota of Fern Lake, Washington, in a laboratory and a field experiment", Ecology Vol. 50, 1969, pp.979-989.

[37] G. Krantzberg and P.M. Stokes, "The importance of surface adsorption and pH metal accumulation by chironomids", Environ. Toxicol. Chem., Vol. 7, 1988, pp.653-670.

[38] J.P. Baudin and A.F. Fritsch, "Retention of ingested ^{60}Co by a freshwater fish", Wat. Air Soil Pollut., Vol. 36, 1987, pp.207-217.