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Uptake from Water, Internal Distribution and Bioaccumulation of Selenium in *Scenedesmus obliquus*, *Unio mancus* and *Rattus norvegicus*: Part B

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Abstract ^{75}Se-selenite transfer was investigated in a phytoplankton-mussel-rat food chain model consisting of *Scenedesmus obliquus* (Turpin) Kützing, *Unio mancus* Lamark and *Rattus norvegicus* Berkenhout. ^{75}Se-metabolized forms were investigated in order to identify potential critical steps in the food chain, as well as its relative bioavailability looking also at intracellular, cellular and organ partitioning. Tissue and intracellular distribution of ^{75}Se in mussels fed with ^{75}Se-*S. obliquus* was different compared to those exposed only to inorganic ^{75}Se-selenite. The intracellular distribution of ^{75}Se in the hepatopancreas and mantle of mussels fed ^{75}Se-microalgae was similar to hepatic and renal distributions in rats, suggesting that their stomach dissociated larger ^{75}Se-containing molecules. The ^{75}Se partitioned from water (culture medium) to microalgae showing a bioconcentration factor of 435. The bottleneck in the trophic transfer of ^{75}Se occurred between *S. obliquus–U. mancus*. From microalgae to mussels and subsequently to rats no bioaccumulation was verified.

Keywords Selenium · Microalgae · Mussel · Rat · Food chain · Biomagnification

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In recent years, the problem of elevated levels of selenium (Se) in certain areas has become a major concern, especially to wildlife. Mainly, body burdens of Se accumulate either through food or dissolved Se uptake. Dietary exposure represents the most relevant pattern of Se uptake in terrestrial predators (Ohlendorf et al. 1998; Chapman et al. 2010; Polettini et al. 2014). Simplified laboratory food chain models have been used to study Se bioavailability and biomagnification. These have included food chains involving bacteria and the ciliated protozoan *Paramecium putrinum* (Sanders and Gilmour 1994), the alga *Scenedesmus obliquus* and the cladoceran *Daphnia magna* (Yu and Wang 2004), and the insect *Acheta domestica* and lizard *Sceloporus occidentalis* (Hopkins et al. 2005). The transfer of Se has also been investigated in various fish species fed invertebrates containing radiolabelled Se (Reinfelder and Fisher 1994; Baines et al. 2002; Xu and Wang 2002). Studies about the sensitivity and effects of Se to organisms are limited to a small number of animal groups (Chapman et al. 2010).

The aim of the present study was to investigate the nature of the transfer of Se through a simplified phytoplankton-mussel-rat food chain model, mainly focusing on its absorption, retention, intracellular and protein distribution in tissues and excreta. Mammals were included, thus providing data to integrate existing ecosystem-scale modeling activities (Presser and Luoma 2010). Exposure scenarios took into consideration elemental Se as selenite [Se(IV)] (Boisson et al. 1995; Takayanagi 2001), starting from the considerations reported in Polettini et al. (2014). The combined use of radiotracers and biochemical techniques supported the analytical characterization within and between the various identified trophic levels.

Materials and Methods

An alga (*S. obliquus*), mussel (*Unio mancus*), and rat (*Rattus norvegicus*) were used in the various exposure scenarios of the study. Spiking conditions and analyses were the same described in Polettini et al. (2014). Microalgae or mussels were spiked with ^{75}Se-selenite from water; mussels were contaminated with water-spiked-microalgae and rats per os (p.o.) with both spiked microalgae and mussels (spiked in both ways from water and microalgae). A 200 mL culture of freshwater green alga *S. obliquus* was prepared and spiked (105 ng Se mL^{-1} at pH 7.14 ± 0.01 and 24.5 ± 0.5°C). After 4 days of continuous culture growth, the whole culture was centrifuged at 6,000×g for 5 min and the residue washed twice with $NaHCO_3$ solution (15 µg L^{-1}). After suspending cells in 10 mL of the same solution, microalgae were counted for radioactivity.

A population of five freshwater mussels (*U. mancus)* was maintained in a 10 L tank containing 7.5 L aerated and filtered (Millipore GS 0.22 µm) Lake Maggiore (Italy) water (pH 7.2 ± 0.1, conductivity 142.0 ± 1.5 µs cm^{-1}, temperature 22.0 ± 0.5°C). Mussels were fed with the above ^{75}Se-spiked algal suspension containing about 1.9 mg of *S. obliquus* cells and a total content of 19.8 ng Se dry wt. The mussel tank water was continuously and gently stirred with a mixer to ensure a uniform treatment during the 24 h of exposure. After the exposure period, mussels were taken out for dissection. Removed tissues were rinsed in demineralized water, wet weighed and counted for ^{75}Se content. The hepatopancreas and mantle of all five animals were pooled and homogenized. Subcellular fractions, including nuclei, mitochondria, lysosome and microsomal cytoplasmic fractions were obtained as previously described (Polettini et al. submitted). The soluble cytoplasmatic fraction (cytosol) of hepatopancreas and mantle were chromatographed on Sephadex G-150 columns (1 × 100 cm), previously calibrated with proteins of known molecular weights and equilibrated with 10 mM ammonium acetate buffer (pH 7.1 ± 0.1). The UV profile of the eluate was continuously monitored using a Lambda 25 spectrometer (Perkin-Elmer, Waltham, MA, USA), and the ^{75}Se content was measured in all biological fractions.

The Sprague–Dawley male albino rat (*R. norvegicus*, 350–380 g) was considered as the top consumer. Three exposure scenarios were investigated: (1) rats fed p.o. with microalgae grown in ^{75}Se-spiked water; (2) rats fed with mussels exposed to ^{75}Se-spiked water; (3) Rats fed with mussels exposed to ^{75}Se-spiked water fed with ^{75}Se contaminated microalgae. Three rats that had been held without food for 24 h were treated p.o. with a ^{75}Se-spiked microalgae suspension obtained as previously mentioned. Each suspension contained about 0.7 mg of cells and 44.9 ng Se in 0.75 mL $NaHCO_3$. The animals were separately placed in metabolic cages with free access to food and water for urine and feces collection. A population of six mussels (*U. mancus*) were exposed to 105 ng Se mL^{-1}. After 3 days of exposure, they were dissected and their soft parts taken out and counted for radioactivity. They were divided into three groups of relatively uniform weight and ^{75}Se content, and used to feed the three groups of rats. Thus, each rat received a range of 8–10 g of mussel tissue containing about 2.000 ng Se. A volume of 400 mL of microalgae culture was prepared as described above with a ^{75}Se-selenite concentration of 105 ng Se mL^{-1}. After 4 days of algal growth in this medium, the cells were separated, resuspended in 20 mL $NaHCO_3$ and counted for radioactivity. An aliquot of about 9.7 mg cells corresponding to 443.1 ng of Se was distributed in a tank containing 50 L of lake water and nine mussels (*U. mancus*). After 24 h exposure, the mussels were removed; their soft parts were taken out, weighed and counted for radioactivity. They were grouped in three parts with a relative uniform weight (13.8 ± 0.3 g) and Se content (28.0 ± 0.5 ng). Three rats were fed with one group of mussel tissue each and separately placed for 24 h in metabolic cages for separate collection of their urine and feces. After 24 h, the rats were sacrificed by heart puncture under ether anaesthesia. The analysis took into account various direct and indirect organisms' components (tissues and excreta): kidney, liver, testis, epididymis, brain, heart, lung, spleen, pancreas, stomach, small intestine, large intestine, blood, plasma, red blood cells (RBC), feces and urine. Blood was taken with heparinized syringes. The tissues were then dissected out, washed, weighed and counted for ^{75}Se radioactivity. Blood was centrifuged at 2,500×*g* for 15 min to separate plasma and RBC. To obtain the respective intracellular distribution of liver and kidney, they were homogenized in 10 mM ammonium acetate buffer solution (pH 7.1). These subcellular fractions were

differently centrifuged as previously mentioned. The cytosols of liver and kidney were chromatographed under the same conditions used for mussels. Statistical analysis was performed using the Student's *t* test or the analysis of variance (ANOVA) considering a significance threshold level always set at 5 %. When ANOVA revealed significant differences among treatments, post hoc analyses were conducted using Dunnett's and Tukey's methods. Statistical analyses were performed using Microsoft® Excel 2013/XLSTAT©-Pro (Version 7.2, 2003, Addinsoft, Inc., Brooklyn, NY, USA).

Results and Discussion

The distribution of ^{75}Se in mussel tissues (wet weight) following uptake of microalgae that were exposed to ^{75}Se followed the decreasing order (in ng g^{-1}): hepatopancreas (20.5 ± 7.5), visceral residue (6.4 ± 1.6), mantle (4.2 ± 1.0), gills (2.5 ± 0.6), foot (1.9 ± 0.7), adductor muscle (1.4 ± 0.2) and shell (0.2 ± 0.1). The hepatopancreas showed the highest Se concentration, followed by the whole soft parts, with the shell having the lowest amount. The intracellular ^{75}Se distribution in hepatopancreas and mantle was displayed in Fig. 1. ^{75}Selenium occurred in all subcellular fractions, but the hepatopancreas cytosol showed the highest amount (about 40 % of ^{75}Se in the total homogenate) followed by nuclei and mitochondria (20 % total relative concentration). Less than 10 % was found in lysosomes and microsomes. In the mantle, more than 50 % of ^{75}Se was found in the nuclear fraction and about 28 % in the cytosol. ^{75}Se content in mantle mitochondria was much lower than in the hepatopancreas, accounting for only 5 % of the total homogenate.

The ^{75}Se content in rat tissues (wet wt, n = 3) after p.o. treatment with ^{75}Se-water spiked *S. obliquus* was as follows in decreasing order in ng g^{-1} or ng mL^{-1}: kidney (0.71 ± 0.07), small intestine (0.35 ± 0.05), liver (0.35 ± 0.02), pancreas (0.17 ± 0.03), spleen (0.15 ± 0.01), large intestine (0.14 ± 0.02), stomach (0.14 ± 0.02), testis (0.14 ± 0.02), lung (0.13 ± 0.02), heart (0.09 ± 0.01), epididymis (0.08 ± 0.01) and brain (0.03 ± 0.01), blood (0.21 ± 0.03) (mainly composed of plasma and RBC), plasma (0.16 ± 0.01) and RBC (0.05 ± 0.02). For excreta (rat wet wt, n = 3), the ^{75}Se levels were 2.97 ± 0.96 ng g^{-1} in feces and 0.23 ± 0.05 ng mL^{-1} in urine. The highest ^{75}Se concentration was in the kidneys, whereas most of the elimination occurred via the feces. Similar trends were observed between the rat liver (Fig. 2) and mussel hepatopancreas (Fig. 1) in the distribution of ^{75}Se in the cellular compartments, with the cytosol containing the highest levels in both species. The rat liver cytosol contained about 45 % of the ^{75}Se that was present in the total homogenate. ^{75}Selenium was equally distributed between nuclear and mitochondrial fractions (≈20 %). Compared to its distribution in the liver, its concentration in kidneys increased up to 50 % in the nuclear fraction and decreased to 20 % in the cytosolic fraction.

^{75}Selenium content in rat tissues after feeding them with mussels that had accumulated ^{75}Se from ^{75}Se-spiked water (n = 3, doses per rat: 2,050 ± 97 ng Se in 8.63 ± 0.83 g mussel flesh) exhibited the following decreasing concentrations (ng g^{-1}, wet wt, or ng mL^{-1}): kidney (18.8 ± 0.52), small intestine (10.4 ± 1.52), liver (7.82 ± 0.74), lung (3.15 ± 0.04), stomach (2.74 ± 0.24), spleen

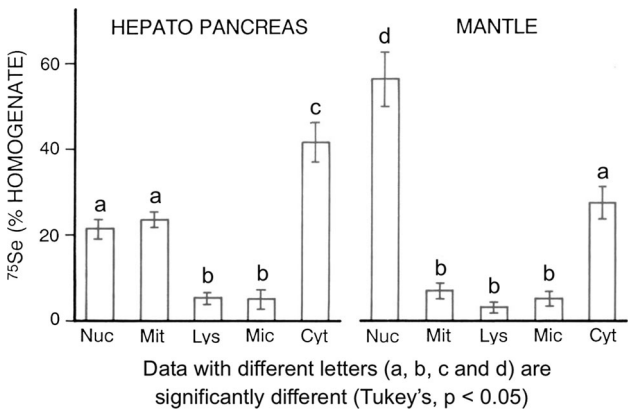

Fig. 1 Intracellular distribution of ^{75}Se in the hepatopancreas and mantle of mussels 24 h after the administration of *S. obliquus* grown in ^{75}Se-spiked water. Results expressed as % of radioactivity of the total respective homogenate ± SD. *Nuc* nuclear fraction, *Mit* mitochondrial fraction, *Lys* lysosomal fraction, *Mic* microsomal fraction, *Cyt* cytosolic fractions

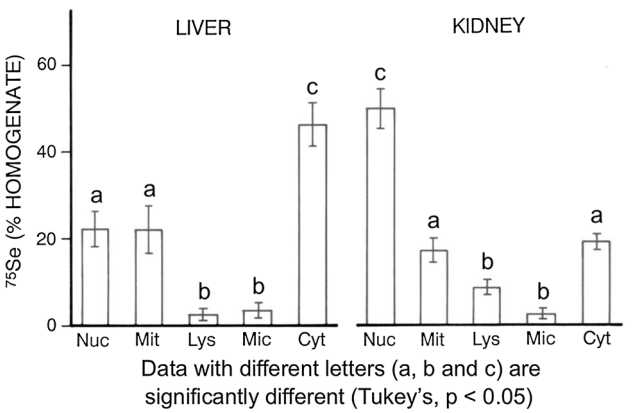

Fig. 2 Intracellular distribution of ^{75}Se in the liver and kidney of rats 24 h after p.o. administration of *S. obliquus* grown in ^{75}Se-spiked water. Results expressed as % of radioactivity of the total respective homogenate ± SD. Nuc nuclear fraction, *Mit* mitochondrial fraction, *Lys* lysosomal fraction, *Mic* microsomal fraction, *Cyt* cytosolic fractions

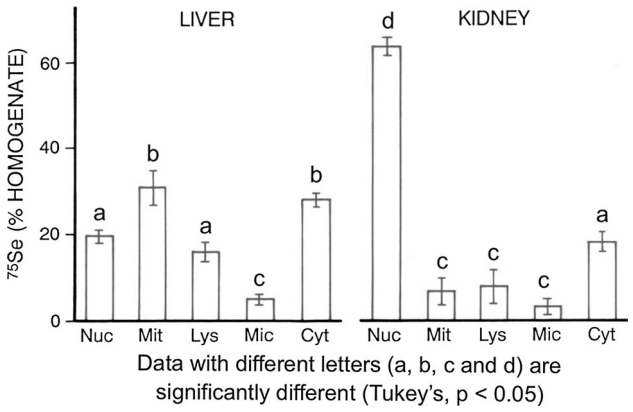

Fig. 3 Intracellular distribution of ^{75}Se in the liver and kidney of rats 24 h after the administration of *U. mancus* exposed to ^{75}Se-spiked water. Results expressed as % of radioactivity of the total respective homogenate ± SD. *Nuc* nuclear fraction, *Mit* mitochondrial fraction, *Lys* lysosomal fraction, *Mic* microsomal fraction, *Cyt* cytosolic fractions

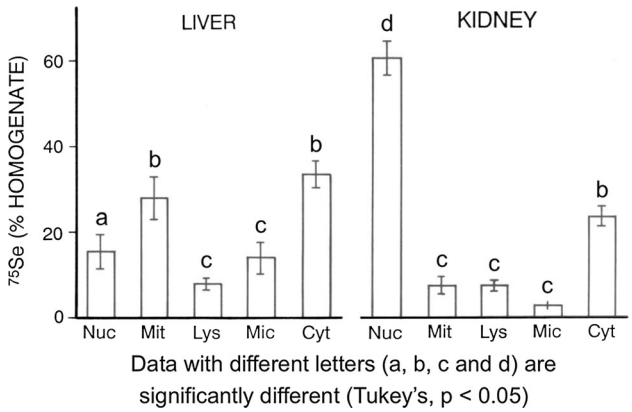

Fig. 4 Intracellular distribution of ^{75}Se in the liver and kidney of rats 24 h after the administration of *U. mancus* previously fed with *S. obliquus* grown in ^{75}Se-spiked water. Results expressed as % of radioactivity of the total respective homogenate ± SD. *Nuc* nuclear fraction, *Mit* mitochondrial fraction, *Lys* lysosomal fraction; *Mic* microsomal fraction, *Cyt* cytosolic fractions

(2.67 ± 0.08), testis (2.50 ± 0.09), heart (1.94 ± 0.08), epididymis (1.48 ± 0.12), pancreas (1.43 ± 0.75), large intestine (0.63 ± 0.32) and brain (0.36 ± 0.02), blood (5.96 ± 1.13), plasma (3.6 ± 0.67), and RBC (1.22 ± 1.14). Feces and urine contained 65.6 ± 5.6 ng g^{-1} and 18.9 ± 1.74 ng mL^{-1}, respectively. Kidney and brain showed the highest and the lowest ^{75}Se content, respectively. It was verified that feces represented the main route of excretion. The intracellular ^{75}Se distribution in liver (Fig. 3) was slightly different from the one in rats fed with microalgae, since the amounts found in nuclei and cytosol were smaller than previously. Its distribution in the kidney was similar for both exposure routes, being lower only in the mitochondrial fraction (10 % of total homogenate) in Fig. 3.

The ^{75}Se content (ng g^{-1} or ng mL^{-1}) in rat tissues 24 h after being fed with mussels contaminated by *S. obliquus* exposed to ^{75}Se-spiked water (105 ng Se mL^{-1}) was as follows in decreasing order: kidney (0.48 ± 0.02), small intestine (0.18 ± 0.04), liver (0.18 ± 0.02), lung (0.07 ± 0.01), stomach (0.08 ± 0.01), spleen (0.09 ± 0.02), testis (0.08 ± 0.01), heart (0.04 ± 0.01), epididymis (0.05 ± 0.02), pancreas (1.43 ± 0.75), large intestine (0.07 ± 0.01) and brain (0.01 ± 0.01), blood (0.12 ± 0.02), plasma (0.10 ± 0.02), and RBC (0.02 ± 0.01). For excreta, the feces and urine contained 1.02 ± 0.63 ng g^{-1} and 0.29 ± 0.04 ng mL^{-1}, respectively. As previously found, kidney tissue showed the highest ^{75}Se concentration followed by liver, small intestine, testis and lung. Although the administered ^{75}Se doses were different in the three experimental treatments involving rats, its tissue uptake expressed as dose percentage did not significantly vary, presenting little standard deviation values as well. The intracellular distribution pattern as displayed in Fig. 4 was similar to the one obtained in Fig. 3.

After feeding mussels with ^{75}Se-microalgae, their hepatopancreas showed the highest Se concentration. This is in contrast to the observation on mussels exposed to inorganic ^{75}Se as simple selenite ions (Polettini et al. 2014). Indeed, the gills were the main targets presenting the highest content, suggesting the possible existence of an indirect interaction on how ^{75}Se would be incorporated in gills after intestinal absorption of the element, differentiating the manner by which it is taken up. Water and dietary exposures were shown to accumulate in distinct target tissues differently, indicating variable ^{75}Se bioavailability. In mussels, the ^{75}Se intracellular distribution in both hepatopancreas and mantle (Fig. 1) showed that it was distributed among the fractions in a different way than after exposure to ^{75}Se in the form of simple inorganic selenite ions (Polettini et al. 2014). In the hepatopancreas, the mitochondrial fraction contained nearly twice the amount. In the mantle, the ^{75}Se content of the nuclear fraction was above 50 % of total homogenate, whereas it was about 30 % when considering the exposure just to the inorganic element (Polettini et al. 2014). This could suggest that the element in the mussel mantle may be bound more strongly when it is taken in via the diet, such as in this case of ^{75}Se-*S. obliquus*.

Data from Table 1 showed that in rats fed with ^{75}Se-microalgae (water exposed) or with ^{75}Se-mussels (exposed via feeding with ^{75}Se-microalgae), the distributions of ^{75}Se were in both cases similar to that of inorganic Se (Polettini et al. 2014). Thus, rats seemed to be able to metabolize various forms of Se, as it was additionally demonstrated by its presence in urine.

Table 1 Selenium content in rat tissues and excreta 24 h after treatment with: (A) inorganic ^{75}Se (5 μg rat^{-1}); (B) *S. obliquus* after contamination with ^{75}Se-spiked water (45 ng Se-microalgae rat^{-1}); (C) *U. mancus* contaminated with ^{75}Se-spiked water (2 μg Se-mussel rat^{-1}); (D) *U. mancus* fed microalgae grown in ^{75}Se-spiked water (28 μg Se-mussel rat^{-1})

Tissue/excreta	% Dose g^{-1} or mL^{-1} wet weight (mean ± SD)			
	A[a]	B[a]	C[a]	D[a]
Kidney	1.8 ± 0.5	2.1 ± 0.4	0.1 ± 0.2	1.8 ± 0.5
Liver	2.5 ± 1.2	1.3 ± 0.8	0.4 ± 0.1	0.7 ± 0.1
Testis	0.30 ± 0.01	0.40 ± 0.02	0.10 ± 0.01	0.30 ± 0.02
Epididymis	0.20 ± 0.01	0.30 ± 0.02	0.10 ± 0.01	0.30 ± 0.02
Brain	0.10 ± 0.01	0.10 ± 0.01	0.02 ± 0.01	0.10 ± 0.01
Heart	0.30 ± 0.02	0.20 ± 0.02	0.10 ± 0.02	0.10 ± 0.02
Lung	0.50 ± 0.01	0.30 ± 0.01	0.20 ± 0.01	0.30 ± 0.01
Spleen	0.50 ± 0.05	0.30 ± 0.01	0.10 ± 0.02	0.30 ± 0.01
Stomach	0.5 ± 0.1	0.5 ± 0.1	0.10 ± 0.03	0.3 ± 0.1
Small intestine	0.7 ± 0.1	0.8 ± 0.1	0.5 ± 0.1	0.6 ± 0.1
Large intestine	0.6 ± 0.3	0.3 ± 0.1	0.4 ± 0.2	0.3 ± 0.9
Blood[b]	0.6 ± 0.3	0.5 ± 0.3	0.3 ± 0.1	0.4 ± 0.4
Plasma[c]	63.7 ± 4.3	82.0 ± 6.2	83.5 ± 5.3	89.5 ± 5.6
RBC[c]	36.3 ± 4.3	18.0 ± 6.2	16.1 ± 5.3	10.5 ± 5.6
Feces	1.8 ± 0.7	6.6 ± 2.2	3.3 ± 1.0	3.6 ± 1.5
Urine	0.1 ± 0.1	0.5 ± 0.2	1.0 ± 0.3	1.0 ± 0.3

[a] Mean of: (A) 5; (B) 3 (C); 3; and (D) 9 animals

[b] % in the total blood

[c] % of the blood

In mussels fed with ^{75}Se-microalgae, the intracellular Se distribution in both hepatopancreas and mantle was very similar to the concentration in liver and kidney of rats fed with the same mussels. It could be supposed that rats were able to dissociate larger ^{75}Se-containing molecules at the stomach pH, so that after intestinal absorption these compounds would have similar metabolic pathways in the body. In this case, its amount was lower than in the case of exposure to by ^{75}Se-spiked water, indicating that ^{75}Se incorporated into mussels was not readily available to rats. This could also be appraised by its intracellular distribution in both liver and kidney, showing a different pattern mainly in the nuclear and cytosolic fractions of the liver, where the ^{75}Se amount was lower than before. Interestingly, the relative distribution of ^{75}Se between RBC and plasma was different in the case of exposure of rats directly to inorganic selenite compared to those of animals fed with metabolized ^{75}Se (Table 1). A significantly higher amount of Se within 10–18 % was recovered in RBC of rats treated with the inorganic form (more than 35 % of Se in whole blood), compared to that of animals treated with metabolized ^{75}Se. This suggested that the dissociation in the stomach of the ^{75}Se in its metabolized form(s) might lead to bioavailable Se species, which would interact with blood components in a different way from the Se absorbed after exposure of rats to the simple inorganic selenite form.

From a quantitative point of view, the ^{75}Se transfer up the model food chain was summarized in Fig. 5 considering the average whole content in water per unit volume and the following average uptake per unit mass (wet wt) in *S. obliquus*, *U. mancus* and *R. norvegicus* including all tested

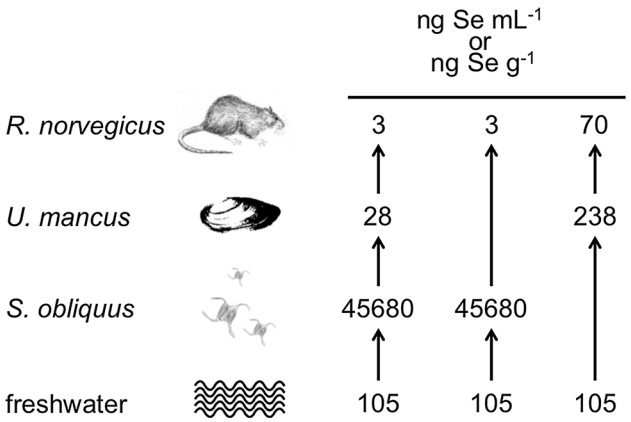

Fig. 5 Uptake of ^{75}Se-selenite in the selected phytoplankton-mussel-rat food chain model; numbers represent the average whole amount of ^{75}Se present in water per unit volume or uptaken by the target biological model per unit mass (wet wt)

scenarios. The trophic transfer of Se presented its main critical step between *S. obliquus–U. mancus*. The ^{75}Se partitioned from water (culture medium) to microalgae showing a bioconcentration factor of 435. Conversely, from microalgae to mussels and subsequently to rats no bioaccumulation was verified. Rats fed with mussels exposed to ^{75}Se-spiked water presented a higher rate of ^{75}Se accumulation compared to its uptake through the whole food chain (microalgae-mussel-rat). This study evidenced the existence of some preferential target organs in rats for Se bioaccumulation such as liver, kidney, intestine, lung and spleen (Table 1). Selenite gastro-intestinal absorption in rats has been shown to be up to 92 %

(WHO 1987). Thus, when it is taken up through the diet, Se is readily bioavailable and can partition into specific target organs. However, ^{75}Se was not subjected to bioaccumulation/biomagnification in the modelled food chain system.

According to Fig. 5, it was evidenced that the bioconcentration of Se is more likely to occur than bioaccumulation. As reported by Luoma and Presser (2009), trophic transfer factors can be more variable among invertebrate species than among fishes mainly due to physiological distinctions in assimilation efficiency and variable elimination rate constants for Se. Thus, this makes the ecological risk characterization of Se in aquatic environments difficult, as may be seen in the regulatory requirements for water quality of various countries worldwide (Luoma and Presser 2009). This study has confirmed observations from previous studies (e.g., Lemly 1985; Luoma et al. 1992; Wang et al. 1996) that Se uptake in animals through bioaccumulation is slow, but faster with aquatic microalgae due to Se bioconcentration from water (Polettini et al. 2014). As suggested by Luoma and Presser (2009), the environmental impact of Se is really species-specific. High exposures of organisms in the environment are determined more by their feeding habits and the ability of potential aquatic or terrestrial species that serve as food to bioconcentrate Se, rather than bioaccumulation of the element through the food chain.

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References

Baines SB, Fisher NS, Stewart R (2002) Assimilation and retention of selenium and other trace elements from crustacean food by juvenile striped bass (*Morone saxatilis*). Limnol Oceanogr 43:646–655

Boisson F, Gnassia-Barelli M, Romeo M (1995) Toxicity and accumulation of selenite and selenate in the unicellular marine alga *Cricosphaera elongate*. Arch Environ Contam Toxicol 28:487–493. doi:10.1007/BF00211631

Chapman PM, Adams WJ, Brooks ML et al (2010) Ecological assessment of selenium in the aquatic environment. SETAC Press, Pensacola, FL

Hopkins WA, Staub BP, Baionno JA et al (2005) Transfer of selenium from prey to predators in a simulated terrestrial food chain. Environ Poll 134:447–456. doi:10.1016/j.envpol.2004.09.010

Lemly AD (1985) Toxicology of selenium in a freshwater reservoir: implications for environmental hazard evaluation and safety. Ecotoxicol Environ Saf 10:314–338

Luoma SN, Presser TN (2009) Emerging opportunities in management of selenium contamination. Environ Sci Technol 43:8483–8487. doi:10.1021/es900828h

Luoma SN, Johns C, Fisher NS, Steinberg NA, Oremland RS, Reinfelder J (1992) Determination of selenium bioavailability to a benthic bivalve from particulate and solute pathways. Environ Sci Technol 26:485–491

Ohlendorf HM, Kilness AW, Simmons JL et al (1998) Selenium toxicosis in wild aquatic birds. J Toxicol Environ Health 24:67–92. doi:10.1080/15287398809531141

Polettini AE, Fortaner S, Farina M, Groppi F, Manenti S, Libralato G, Sabbioni E (2014) Uptake from water, internal distribution and bioaccumulation of selenium in *Scenedesmus obliquus*, *Unio mancus* and *Rattus norvegicus*: Part A. Bull Environ Contam Toxicol. doi:10.1007/s00128-014-1407-2

Presser TS, Luoma SN (2010) A methodology for ecosystem-scale modeling of selenium. Integr Environ Assess Manag 6:685–710

Reinfelder JR, Fisher NS (1994) Retention of elements absorbed by juvenile fish (*Menidia menidia*, *Menidia beryllina*) from zooplankton prey. Limnol Oceanogr 39:1783–1789

Sanders RW, Gilmour CC (1994) Accumulation of selenium in a model freshwater microbial food web. Appl Environ Microbiol 60:2677–2683

Takayanagi K (2001) Acute Toxicity of waterborne Se(IV), Se(VI), Sb(III), and Sb(V) on red seabream (*Pargus major*). Bull Environ Contam Toxicol 66:808–813

Wang W-X, Fisher NS, Luoma SN (1996) Kinetic determinations of trace element bioaccumulation in the mussel *Mytilus edulis*. Mar Ecol Prog Ser 140:91–113

WHO (1987) Selenium–environmental health criteria 58—international programme on chemical safety, 1987, Geneva

Xu Y, Wang W-X (2002) Exposure and potential food chain transfer factor of Cd, Se, and Zn in marine fish *Lutjanus argentimaculatus*. Mar Ecol Prog Ser 238:173–186

Yu RQ, Wang WX (2004) Biokinetics of cadmium, selenium and zinc in freshwater alga *Scenedesmus obliquus* under different phosphorus and nitrogen conditions and metal transfer to *Daphnia magna*. Environ Pollut 129:443–456