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Bioaccumulation and Effects of Heavy Metals in Crayfish: A Review

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Abstract Metal pollution is a global problem which represents a growing threat to the environment. Because of bioaccumulation and negative effects of heavy metals, their bioavailability needs to be monitored. Many studies showed accumulation of metals in crayfish tissues as dose- and time-dependent without significant differences in tissue concentration levels comparing males and females. Muscles and exoskeleton were considered as specific for accumulation of mercury and nickel, respectively. Cadmium, zinc, copper, lead, and chromium accumulated mainly in hepatopancreas. By analyzing these specific tissues, it is possible to deduce the bioavailability and, by presumption, the level of environmental pollution by specific metals. However, in the case of zinc and copper, their utility is limited to assessing bioavailability because rapid depuration of these metals renders them less useful for long-term environmental monitoring programs. The literature reporting heavy metal impacts on freshwater crayfish, with reference to accumulation levels, is reviewed and summarized with respect to their suitability as bioindicators. Summarized published data from unpolluted or control localities can be used as referential values in crayfish, and consequently help with evaluation of monitored sites.

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1 Introduction

Environmental pollution by heavy metals is an increasing problem worldwide. Because of the accumulation effect of some heavy metals, especially through the food chain, their bioavailability needs to be monitored. Through analysis of metal concentrations in living organisms, it is possible to deduce the bioavailability and, by presumption, the level of environmental pollution by specific metals. Crayfish readily accumulate heavy metals in tissues and also meet other criteria which make them suitable as bioindicators of heavy metals in the environment. For example, *Astacus astacus* is easily identified (Pöckl et al. 2006); its populations can be abundant and widespread (Holdich et al. 2006), but it does not have a large home range, hence migrations do not influence the level of metals accumulated in its tissues (Bohl 1999; Schütze et al. 1999). Specimens are therefore representative of the locations in which they are caught. They are easily captured (Policar and Kozák 2005), and the total body length of adult males, 60–70 mm (Abrahamsson 1966; Mackevičienė 1999), and adult females, 76–95 mm (Skurdal et al. 1993), provides sufficient tissue for individual analyses.

In general, for all crayfish species, the concentration of metals in the environment is not sufficient to be a

direct cause of death. Furthermore, crayfish are considered to be highly resistant to environmental metal contamination (Del Ramo et al. 1987; Roldan and Shivers 1987; Chambers 1995). The accumulation of metals in their tissues is dose- and time-dependent, and therefore may be reflective of the levels of metals in the environment (Antón et al. 2000; Rowe et al. 2001; Sánchez-López et al. 2004; Alcorlo et al. 2006; Schmitt et al. 2006; Allert et al. 2009). Crayfish fulfill criteria described for bioindicators by Butler et al. (1971), Phillips and Rainbow (1993), and Rainbow (1995).

2 Selected Heavy Metals: Bioaccumulation and Impact in Crayfish

2.1 Mercury

A background level of mercury exists even in aquatic ecosystems that are not directly contaminated by human activity. The background concentration in biota is usually less than 1.0 mg kg^{-1} fresh tissue weight (Eisler 1987). Biomagnification of mercury through the food chain is a well-known phenomenon (Jackson 1998; Simon et al. 2000) and is influenced by various factors (Scheuhammer and Graham 1999; Pennuto et al. 2005). Simon and Boudou (2001) reported that crayfish take up mercury (Hg) and methylmercury (MeHg) from both water and food, with a marked tendency to accumulate MeHg. Experimental exposures of *A. astacus* to Hg as $HgCl_2$ at concentrations of 0.1–0.8 mg l^{-1} have caused cardiac arrhythmia followed by substantial levels of mortality (Styrishave et al. 1995; Styrishave and Depledge 1996). Mercury is known for its inhibitory effects on ovarian maturation in *Procambarus clarkii* (Reddy et al. 1997).

In crayfish inhabiting contaminated waters or waters with a significant background level of mercury, the type of habitat and size of the specimen have an influence on the concentrations in its tissues (Stinson and Eaton 1983; Parks et al. 1991; Pennuto et al. 2005). Generally for metals, including mercury, finding significant differences in tissue concentration levels between males and females is exceptional (Loukola-Ruskeeniemi et al. 2003).

In crayfish, mercury is accumulated largely in muscle (Stinson and Eaton 1983; Simon et al. 2000; Loukola-Ruskeeniemi et al. 2003). However, in *Orconectes propinquus* fed pellets dosed with Hg and MeHg, the relative levels of mercury accumulation in various organs were: hepatopancreas>gills>exoskeleton>abdominal muscle; and for methylmercury: gills>abdominal muscle>hepatopancreas>exoskeleton (Wright et al. 1991). Methylmercury has been reported to represent approximately 90% of the total mercury in crayfish (Pennuto et al. 2005; Hothem et al. 2007).

Reported mean total mercury concentrations in abdominal muscle and hepatopancreas of crayfish are presented in Table 1.

2.2 Cadmium

Cadmium is generally a non-essential element with teratogenic, carcinogenic, and highly nephrotoxic effects on living organisms (Anderson et al. 1978; Eisler 1985). However, an isolated case of its incorporation into an enzyme of the marine diatom *Thalassiosira weissflogii* has been recently reported (Cullen et al. 1999; Lane et al. 2005). It is still considered non-essential for other organisms.

Accumulation of environmental cadmium in crayfish tissues has been reported. Levels of environmental pollution have shown positive correlations with concentrations in tissue samples. Tissue levels were often positively correlated with proximity to the pollution source (Anderson et al. 1978; Bagatto and Alikhan 1987a; Schmitt et al. 2006; Besser et al. 2007). Cadmium has been shown to be taken up and accumulated by crayfish, both from the surrounding water and via food (Giesy et al. 1980; Devi et al. 1996).

Hepatopancreas is the main organ of cadmium accumulation and detoxification in crayfish (Bagatto and Alikhan 1987a; Viikinkoski et al. 1995; Mackevičienė 2002) as well as in other crustaceans (White and Rainbow 1986; Páez-Osuna and Tron-Mayen 1996; Tu et al. 2008a, b; Barrento et al. 2008, 2009). Chambers (1995) showed relative tissue levels of cadmium accumulation in *Cherax tenuimanus* to be: hepatopancreas>gills>muscle. A similar pattern was reported by Bruno et al. (2006) in *Cherax destructor* (hepatopancreas>exoskeleton>muscle). In crustaceans exposed to various cadmium concentrations, highest accumulation has been reported in gills (Mirenda 1986; Meyer et al. 1991; Schuwerack et al. 2001; Martín-Díaz et al. 2006).

Table 1 Mean total mercury concentrations in abdominal muscle and hepatopancreas of crayfish expressed as mg kg^{-1} dry tissue weight

Reference	Species	Country	Abdominal muscle	Hepatopancreas
Vermeer (1972)[a]	*O. virilis*	Canada	0.60[b]	–
Stinson and Eaton (1983)[a]	*P. leniusculus*	USA	0.60[b]	–
France (1987)	*O. virilis*	Canada	0.27[b]	–
Allard and Stokes (1989)[a]	*Cambarus bartoni*	Canada	0.69	–
	C. robustus		0.43	–
	O. obscurus		0.37	–
	O. propinquus		0.34	–
	O. virilis		0.40	–
Finerty et al. (1990)[a]	*P. clarkii and P. a. acutus*	USA	1.37[b]	1.08[b]
Madden et al. (1991)	*P. clarkii*	USA	<2.0[b]	2.1[b,c] and <2.0[b]
Parks et al. (1991)	*O. virilis*	Canada	0.05–0.2[b]	–
Scheuhammer and Graham (1999)	*O. virilis*	Canada	0.17	–
Loukola-Ruskeeniemi et al. (2003)[a]	*A. astacus*	Finsko	0.88[b]	0.24[b]
Pennuto et al. (2005)[a]	*O. virilis*	USA	0.63	–
Hothem et al. (2007)[a]	*P. clarkii*	USA	1.10	–
	Pacifastacus leniusculus		1.11	–

[a] Results originally given as the concentration in a wet weight were recalculated to dry weight with the water content set at 80% for abdominal muscle and 72% for hepatopancreas (Jorhem et al. 1994)

[b] Concentration from an unpolluted (or reference) locality

[c] Values less than the detection limit were replaced with the detection limit in calculation

Bruno et al. (2006) found adult *C. destructor* (weight~50 g) to have more cadmium in muscle and exoskeleton than did juveniles (weight ~10 g). The relatively high amount of cadmium in the exoskeletons of adults compared to juveniles seems to be related to the lower frequency of molting. Significant differences between males and females have not been found, either in the quantity of accumulated cadmium (Bagatto and Alikhan 1987a,b) or in its toxicity (Chambers 1995). However, when *P. clarkii* were placed in high concentration of cadmium (0.03 mg l^{-1}) over a period of 21 days, males showed significantly higher concentrations in hepatopancreas than females (Martín-Díaz et al. 2006).

Reported mean cadmium concentrations in abdominal muscle and hepatopancreas of crayfish are presented in Table 2.

2.3 Zinc

Although zinc is an essential trace element for all living organisms, and is a constituent of more than 200 metalloenzymes and other metabolic compounds ensuring stability of biological molecules such as DNA and structures such as membranes and ribosomes, excess intake can cause a variety of pathological effects (Eisler 1993).

The content of zinc in the body of a crayfish is naturally high (Bagatto and Alikhan 1987c). In crustaceans, generally, zinc is regulated until a threshold of exposure is reached, after which it will accumulate in tissues at higher levels (Bryan 1967; White and Rainbow 1982, 1984; Vijayram and Geraldine 1996). This regulation is often mediated by the detoxifying proteins, metallothioneins (Rainbow 1997). Metallothioneins are non-enzymatic proteins with a low molecular weight which play a role in the homeostatic control of essential metals such as Zn and Cu (Kägi and Schäffer 1988; Amiard et al. 2006).

Mackevičienė (2002) found the order of zinc accumulation in crayfish tissue to be: hepatopancreas>exoskeleton>digestive tract>abdominal muscle. A similar pattern was observed in *Cambarus bartoni* (Bagatto and Alikhan 1987c). Marine decapods such as crabs (*Charybdis longicollis*), lobsters (*Panulirus inflatus*), and shrimp (*Penaeus* sp., *Pleoticus muelleri*, and *Metapenaeus affinis*) appear to have similar zinc accumulation patterns, with the hepatopancreas as the

Table 2 Mean cadmium concentrations in abdominal muscle and hepatopancreas of crayfish expressed as mg kg^{-1} dry tissue weight

Reference	Species	Country	Abdominal muscle	Hepatopancreas
Dickson et al. (1979)	*O. australis australis*	USA	0.4[b]	3.6[b]
	C. tenebrosus		0.1[b]	2.4[b]
Stinson and Eaton (1983)[a]	*P. leniusculus*	USA	5.53[b]	–
Díaz-Mayans et al. (1986)	*P. clarkii*	Spain	0.02[b]	–
Bagatto and Alikhan (1987a)	*C. bartoni*	Canada	1.8[b]	2.4[b]
Bagatto and Alikhan (1987b)	*C. bartoni*	Canada	4.4	30.2 and 32.5
France (1987)	*O. virilis*	Canada	0.16[b]	–
Alikhan et al. (1990)	*C. bartoni*	Canada	–	4.7
Finerty et al. (1990)[a]	*P. clarkii and P. a. acutus*	USA	3.55[b]	0.83[b]
Madden et al. (1991)	*P. clarkii*	USA	0.73[b] and 0.33[b]	0.30[b] and 0.26[b,c]
Madigosky et al. (1991)	*P. clarkii*	USA	0.0005[b]	0.10[b]
Jorhem et al. (1994)[a]	*A. astacus*	Sweden	<0.025[b]	1.39[b]
	P. leniusculus		<0.02[b]	2.54[b]
Schilderman et al. (1999)[a]	*O. limosus*	The Netherlands	–	5.44
Gherardi et al. (2002)	*Austropotamobius pallipes*	Italy	–	1.4
	P. clarkii		–	0.2
Mackevičienė (2002)[a]	*A. astacus*	Lithuania	0.05	0.01
Abd-Allah and Abdallah (2006)[a]	*P. clarkii*	Egypt	1.97	–
Bruno et al. (2006)[a]	*C. destructor* (adults)	Italy	2.25	35.0
Hothem et al. (2007)	*P. clarkii*	USA	0.03	–
	P. leniusculus		0.03	–

[a] Results originally given as the concentration in a wet weight were recalculated to dry weight with the water content set at 80% for abdominal muscle and 72% for hepatopancreas (Jorhem et al. 1994)

[b] Concentration from an unpolluted (or reference) locality

[c] Values less than the detection limit were replaced with the detection limit in calculation

main storage organ (Darmono and Denton 1990; Marcovecchio 2004; Páez-Osuna et al. 1995; Méndez et al. 1997; Pourang and Amini 2001; Pourang et al. 2004; 2005; Firat et al. 2008). Most zinc was accumulated in the gills during laboratory toxicity tests in the crayfish (Lindhjem and Bennet-Chambers 2002; Martín-Díaz et al. 2006).

In a long-term study of zinc content in the hepatopancreas, gills, and abdominal muscle of *C. tenuimanus* of various ages, Bennet-Chambers and Knott (2002) found the highest levels in juveniles. Higher zinc concentration is primarily related to the relatively larger and more permeable body surface of juveniles which renders them unable to regulate zinc content as effectively as adults. Zinc levels in the hepatopancreas and, especially, in muscle, is regulated primarily in specimens older than 12 months. The widest range of measured values has been recorded in the gills. Bruno et al. (2006) also found higher values of zinc in juveniles of *C. destructor*.

Reported mean zinc concentrations in abdominal muscle and hepatopancreas of crayfish are presented in Table 3.

2.4 Copper

Copper is usual in the environment and essential for normal growth and metabolism of all living organisms (Eisler 1998). It is a component of the respiratory metalloprotein–hemocyanin in crustaceans (White and Rainbow 1982; Rainbow 2002); hence, relatively high copper levels are found in tissues of crayfish, especially in hepatopancreas (Bagatto and Alikhan 1987a; Madden et al. 1991; Bruno et al. 2006).

Concentration of copper in the bodies of crustaceans is regulated to an approximately constant level

Table 3 Mean zinc concentrations in abdominal muscle and hepatopancreas of crayfish expressed as mg kg^{-1} dry tissue weight

Reference	Species	Country	Abdominal muscle	Hepatopancreas
Dickson et al. (1979)	*O. australis australis*	USA	91.3[b]	106.6[b]
	C. tenebrosus		127.4[b]	309.9[b]
Bagatto and Alikhan (1987b)	*C. bartoni*	Canada	96.0 and 97.0	149.0 and 166.0
Bagatto and Alikhan (1987c)	*C. bartoni*	Canada	80.0[b]	92.0[b]
France (1987)	*O. virilis*	Canada	61.0[b]	–
Madden et al. (1991)	*P. clarkii*	USA	5.9[b] and 5.3[b]	34.7[b] and 25.1[b]
Jorhem et al. (1994)[a]	*A. astacus*	Sweden	75.0[b]	203.57[b]
	P. leniusculus		75.0[b]	178.57[b]
Schilderman et al. (1999)[a]	*O. limosus*	The Netherlands	–	137.50
Bennet-Chambers and Knott (2002)[a]	*C. tenuimanus*	Australia	76.1[c]	174.4[c]
Gherardi et al. (2002)	*A. pallipes*	Italy	–	180.0
	P. clarkii		–	506.0
Mackevičienė (2002)[a]	*A. astacus*	Lithuania	23.25	35.29
Abd-Allah and Abdallah (2006)[a]	*P. clarkii*	Egypt	125.8	–
Bruno et al. (2006)[a]	*C. destructor* (adults)	Italy	18.0	179.29
Hothem et al. (2007)	*P. clarkii*	USA	76.90	–
	P. leniusculus		100.35	–

[a] Results originally given as the concentration in a wet weight were recalculated to dry weight with the water content set at 80% for abdominal muscle and 72% for hepatopancreas (Jorhem et al. 1994)

[b] Concentration from an unpolluted (or reference) locality

[c] Specimens heavier than 120 g

until copper bioavailability exceeds a high threshold and net accumulation begins (White and Rainbow 1982; Rainbow and White 1989). For example, following exposure of *P. clarkii* to varying concentrations of copper (0.125–0.500 mg l^{-1}) for 96 h, no significant differences were found in tissue copper content (Maranhão et al. 1995). However, after exposure for 8 weeks to a copper concentration of 5 mg l^{-1}, a time-dependent accumulation of copper was observed in tissues in the order: gills>exoskeleton>abdominal muscle. When placed in clean water, the level of copper in the exoskeleton, gills, and abdominal muscle reduced by 73%, 72%, and 65%, respectively, within 2 weeks (Naqvi et al. 1998). A similar pattern of copper accumulation and depuration was observed in *A. leptodactylus,* (Guner 2007). No changes in tissue concentrations of copper were observed in *C. destructor* fed the floating aquatic macrophyte *Lemna minor* which had been previously treated with a copper solution (Allinson et al. 2000). Crayfish can, thus, be useful for assessing bioavailability of copper in aquatic ecosystems, but not in a long-term monitoring program, due to their capacity for rapid depuration (Naqvi et al. 1998; Guner 2007).

Reports of mean copper concentrations in abdominal muscle and hepatopancreas of crayfish are presented in Table 4.

2.5 Lead

Lead is introduced from many sources into aquatic environments, where it is rapidly incorporated into suspended and bottom sediments. This element is neither essential nor beneficial to living organisms and is responsible for a large number of adverse effects on biota (Eisler 1988; Allert et al. 2009).

Mackevičienė (2002) found that lead accumulated in tissues of crayfish under aquaculture conditions in the order: hepatopancreas>digestive tract>muscle>exoskeleton. During exposure of *A. astacus* to low concentrations of lead (0.02 mg l^{-1}) for a maximum of 10 weeks, the metal was accumulated primarily in the hepatopancreas, carapace, and gills and reached only low concentrations in the hindgut and muscle

Table 4 Mean copper concentrations in abdominal muscle and hepatopancreas of crayfish expressed as mg kg^{-1} dry tissue weight

Reference	Species	Country	Abdominal muscle	Hepatopancreas
Dickson et al. (1979)	*O. australis australis*	USA	71.9[b]	584.9[b]
	C. tenebrosus		37.3[b]	188.4[b]
Stinson and Eaton (1983)[a]	*P. leniusculus*	USA	21.32[b]	–
Bagatto and Alikhan (1987a)	*C. bartoni*	Canada	50.0[b]	111.0[b]
Bagatto and Alikhan (1987b)	*C. bartoni*	Canada	147.0 and 114.0	1510.0 and 996.0
France (1987)	*O. virilis*	Canada	69.0[b]	–
Finerty et al. (1990)[a]	*P. clarkii and P. a. acutus*	USA	16.77[b]	58.49[b]
Madden et al. (1991)	*P. clarkii*	USA	3.12[b] and 2.97[b]	14.65[b] and 10.33[b]
Jorhem et al. (1994)[a]	*A. astacus*	Sweden	28.50[b]	185.71[b]
	P. leniusculus		25.50[b]	157.14[b]
Schilderman et al. (1999)[a]	*O. limosus*	The Netherlands	–	1537.41
Gherardi et al. (2002)	*A. pallipes*	Italy	–	780.0
	P. clarkii		–	353.0
Mackevičienė (2002)[a]	*A. astacus*	Lithuania	6.10	4.93
Abd-Allah and Abdallah (2006)[a]	*P. clarkii*	Egypt	32.72	–
Bruno et al. (2006)[a]	*C. destructor* (adults)	Italy	39.10	64.07
Hothem et al. (2007)	*P. clarkii*	USA	44.60	–
	P. leniusculus		36.30	–

[a] Results originally given as the concentration in a wet weight were recalculated to dry weight with the water content set at 80% for abdominal muscle and 72% for hepatopancreas (Jorhem et al. 1994)

[b] Concentration from an unpolluted (or reference) locality

Table 5 Mean lead concentrations in abdominal muscle and hepatopancreas of crayfish expressed as mg kg^{-1} dry tissue weight

Reference	Species	Country	Abdominal muscle	Hepatopancreas
Dickson et al. (1979)	*O. australis australis*	USA	1.2[b]	8.3[b]
	C. tenebrosus		0.5[b]	0.1[b]
Stinson and Eaton (1983)[a]	*P. leniusculus*	USA	<2.25[b]	–
France (1987)	*O. virilis*	Canada	1.97[b]	–
Finerty et al. (1990)[a]	*P. clarkii and P. australis acutus*	USA	10.69[b]	6.40[b]
Madden et al. (1991)	*P. clarkii*	USA	<5.0[b]	<5.0[b]
Madigosky et al. (1991)	*P. clarkii*	USA	0.06[b]	0.04[b]
Jorhem et al. (1994)[a]	*A. astacus*	Sweden	0.11[b]	0.18[b]
	P. leniusculus		0.12[b]	0.11[b]
Gherardi et al. (2002)	*A. pallipes*	Italy	–	0.1
	P. clarkii		–	0.1
Mackevičienė (2002)[a]	*A. astacus*	Lithuania	0.25	0.29
Abd-Allah and Abdallah (2006)[a]	*P. clarkii*	Egypt	15.93	–
Bruno et al. (2006)[a]	*C. destructor* (adults)	Italy	1.90	7.54
Hothem et al. (2007)	*P. clarkii*	USA	< 0.19	–
	P. leniusculus		<0.19	–

[a] Results originally given as the concentration in a wet weight were recalculated to dry weight with the water content set at 80% for abdominal muscle and 72% for hepatopancreas (Jorhem et al. 1994)

[b] Concentration from an unpolluted (or reference) locality

Table 6 Mean nickel concentrations in abdominal muscle and hepatopancreas of crayfish expressed as mg kg^{-1} dry tissue weight

Reference	Species	Country	Abdominal muscle	Hepatopancreas
Bagatto and Alikhan (1987a)	*C. bartoni*	Canada	1.0[b]	0.3[b]
Bagatto and Alikhan (1987b)	*C. bartoni*	Canada	5.09 and <0.15	7.5 and 0.8
Finerty et al. (1990)[a]	*P. clarkii and P. a. acutus*	USA	4.84[b]	4.64[b]
Madden et al. (1991)	*P. clarkii*	USA	1.13[b,c] and 1.08[b,c]	1.25[b,c] and 1.23[b]
Jorhem et al. (1994)[a]	*A. astacus*	Sweden	<0.50[b]	3.54[b]
	P. leniusculus		<0.38[b]	4.29[b]
Gherardi et al. (2002)	*A. pallipes*	Italy	–	10.0
	P. clarkii		–	44.0
Mackevičienė (2002)[a]	*A. astacus*	Lithuania	0.85	1.54
Hothem et al. (2007)	*P. clarkii*	USA	1.81	–
	P. leniusculus		1.11	–

[a] Results originally given as the concentration in a wet weight were recalculated to dry weight with the water content set a 80% for abdominal muscle and 72% for hepatopancreas (Jorhem et al. 1994)

[b] Concentration from an unpolluted (or reference) locality

[c] Values less than the detection limit were replaced with the detection limit in calculation

(Meyer et al. 1991). *P. clarkii* showed marked accumulation of lead in the hepatopancreas and gills after 7 days exposure at a contaminated location (Anderson et al. 1997). The hepatopancreas was observed to be the main storage organ of lead in *C. destructor* (Bruno et al. 2006). It has been reported by Roldan and Shivers (1987) that lead is stored in metal-containing vacuoles of hepatopancreatic cells and in vacuoles, cytoplasmic bodies, and vesicles in cells of the antennal (green) gland of *O. propinquus*. In contrast, the freshwater crab, *Potamonautes perlatus*, showed the lowest concentration of lead in the digestive system (especially in the hepatopancreas) while the highest concentration was in the gonads (Reinecke et al. 2003). Following experimental exposure to lead concentrations of 0.15 mg l^{-1} for 7 weeks, 3 weeks clearance was sufficient to decrease lead concentrations in the exoskeleton (87% depuration), abdominal muscle (79%), gills (50%), and hepatopancreas (22%) in *P. clarkii*, and to affect a

Table 7 Mean chromium concentrations in abdominal muscle and hepatopancreas of crayfish expressed as mg kg^{-1} dry tissue weight

Reference	Species	Country	Abdominal muscle	Hepatopancreas
Dickson et al. (1979)	*O. australi australis*	USA	2.7[b]	0.9[b]
	C. tenebrosus		3.1[b]	0.5[b]
Madden et al. (1991)	*P. clarkii*	USA	0.51[b,c] and 0.46[b,c]	<0.4[b] and 0.46[b,c]
Jorhem et al. (1994)[a]	*A. astacus*	Sweden	<0.13[b]	0.15[b]
	P. leniusculus		<0.10[b]	0.18[b]
Mackevičienė (2002)[a]	*A. astacus*	Lithuania	0.30	0.25
Abd-Allah and Abdallah (2006)[a]	*P. clarkii*	Egypt	5.03	–
Bruno et al. (2006)[a]	*C. destructor* (adults)	Italy	21.75	214.64
Hothem et al. (2007)	*P. clarkii*	USA	0.43	–
	P. leniusculus		0.60	–

[a] Results originally given as the concentration in a wet weight were recalculated to dry weight with the water content set at 80% for abdominal muscle and 72% for hepatopancreas (Jorhem et al. 1994)

[b] Concentration from an unpolluted (or reference) locality

[c] Values less than the detection limit were replaced with the detection limit in calculation

return of hemolymph concentration of lead to pre-exposure levels (Anderson et al. 1997).

Reported mean lead concentrations in abdominal muscle and hepatopancreas of crayfish are presented in Table 5.

2.6 Nickel

Nickel is a ubiquitous element known for its toxicity, persistence, and affinity for bioaccumulation (Eisler 1998) but is considered to be essential to various biological functions, often at very low concentrations (Alikhan and Zia 1989; Muyssen et al. 2004). It has been shown to accumulate in tissues of crayfish in relation to its availability in the environment. The presence of a substantial concentration of nickel in the exoskeleton might indicate that this tissue is involved in the excretion of this metal (Bagato and Alikhan 1987a). Mackevičienė (2002) reported nickel accumulation in *A. astacus* to be: exoskeleton (0.82 mg kg^{-1} wet weight)>hepatopancreas (0.43 mg)>muscle (0.17 mg)>digestive tract (0.16 mg). A similar pattern was found in the tissues of *C. bartoni* (Bagatto and Alikhan 1987b). When this crayfish was exposed for 4 weeks to a nickel solution at a concentration of 0.2–0.8 mg l^{-1}, accumulation occurred primarily in the gills and alimentary tract (Alikhan and Zia 1989).

Reports of mean nickel concentrations in abdominal muscle and hepatopancreas of crayfish are presented in Table 6.

2.7 Chromium

Chromium is an essential element, although harmful at high levels (Eisler 1986). Mackevičienė (2002) found chromium accumulation in tissues of *A. astacus* in the following order: exoskeleton>digestive tract>hepatopancreas>muscle. Jorhem et al. (1994), studying *A. astacus* and *Pacifastacus leniusculus*, also observed higher concentrations in the hepatopancreas than in muscle. Adult *C. destructor* shows levels of chromium nearly twice that of juveniles and at much higher concentrations in hepatopancreas than in exoskeleton and muscle (Bruno et al. 2006). Following 7-day exposure in a location with high environmental chromium levels, *P. clarkii* accumulated chromium primarily in the gills and hemolymph (Anderson et al. 1997).

Reports of mean chromium concentrations in abdominal muscle and hepatopancreas of crayfish are presented in Table 7.

3 Conclusions

Due to rapid bioaccumulation and long retention times, crayfish of both sexes are suitable bioindicators of heavy metal contamination of freshwater ecosystems. Hepatopancreas was found as a specific tissue for accumulation of cadmium, zinc, copper, lead, and chromium. Mercury and nickel accumulated largely in muscles and exoskeleton, respectively. By analyzing these specific tissues, it is possible to deduce the bioavailability and, by presumption, the level of environmental pollution by specific metals. However, in the case of zinc and copper, their utility is limited to assessing bioavailability, since rapid depuration of these metals renders them less useful for long-term environmental monitoring programs. Mainly summarized published data from unpolluted or control sites could be beneficial as referential values, which can help in evaluation of monitored localities.

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