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Total Mercury Concentrations among Fish and Crayfish Inhabiting Different Trophic Levels in Lake Whatcom, Washington

Karl W. Mueller & David M. Serdar

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Karl W. Mueller
Washington Department of Fish and Wildlife
600 Capitol Way North
Olympia, Washington 98501-1091 USA

and

David M. Serdar
Washington Department of Ecology
Environmental Assessment Program
P.O. Box 47600
Olympia, Washington 98504-7600 USA

ABSTRACT

Tissue samples from six species of fish and one species of crayfish from Lake Whatcom, Washington were analyzed for total mercury content in late spring 2000. Predaceous smallmouth bass (*Micropterus dolomieu*) displayed the highest levels of mercury (mean ± SE, range = 0.49 ± 0.03, 0.10 – 1.84 mg/kg, n = 95), followed by omnivorous yellow perch (*Perca flavescens*; 0.20 ± 0.03, 0.04 – 0.87 mg/kg, n = 30) and brown bullhead (*Ameiurus nebulosus*; 0.16 ± 0.06, 0.03 – 0.79 mg/kg, n = 13), zooplanktivorous kokanee (*Oncorhynchus nerka*; 0.12 ± 0.01, 0.07 – 0.25 mg/kg, n = 30), benthivorous pumpkinseed (*Lepomis gibbosus*; 0.10 ± 0.01, 0.03 – 0.28 mg/kg, n = 30), and herbi-detritivorous signal crayfish (*Pacifasticus leniusculus*; 0.10 ± 0.01, 0.03 – 0.54 mg/kg, n = 45). Predaceous cutthroat trout (*Oncorhynchus clarki*) had the lowest levels (0.07 ± 0.01, 0.03 – 0.20 mg/kg, n = 30), possibly related to the low trophic level of the smaller size classes captured, natal stream residency of wild fish, or hatchery origins of stocked fish. The fastest rates of mercury bioaccumulation were found in brown bullhead, smallmouth bass, signal crayfish, and yellow perch as indicated by the slopes of their log-transformed mercury concentration-age regression lines. The slopes for cutthroat trout, kokanee, and pumpkinseed suggested very slow uptake in these species.

INTRODUCTION

Fish and many other aquatic organisms obtain mercury mostly through feeding, where the toxin is rapidly transferred from the gut to the rest of the body via the bloodstream (Oliveira-Ribeiro et al. 1999). Harris and Snodgrass (1993) demonstrated that food pathways were responsible for 90% or more of mercury uptake in yellow perch (*Perca flavescens*) and walleye (*Stizostedion vitreum*). Not surprisingly, primary producers and primary consumers are critical intermediaries in the movement and biomagnification of mercury from water to upper trophic levels (Hill et al. 1996). Similarly, aquatic insects are part of the food web system that transfers mercury from the physical environment to fish. When exposed to mercury, predaceous aquatic insects accumulate more of the contaminant than herbivorous or detritivorous insects (Hall et al. 1998). A freshwater fish community with large numbers of benthic insectivores, such as yellow perch or pumpkinseed (*Lepomis gibbosus*), can have high rates of mercury cycling from benthos to fishes and ultimately high mercury concentrations in fishes (Wong et al. 1997). The rate of mercury accumulation in piscivorous fishes is typically faster than that of omnivorous, planktivorous, or benthivorous fishes (Phillips et al. 1980, Olivero et al.

1998). However, few studies have examined the relationship of mercury uptake among species inhabiting different trophic levels (Neumann and Ward 1999, Jackson 2001). Therefore, we quantified the differences in total mercury concentrations and uptake in six species of fish and one species of crayfish in Lake Whatcom, Washington. Our goal was to gain a better understanding of the pathway(s) in which mercury might be moving through the food web. To accomplish this, we evaluated the relationship between total mercury concentration and length and age and reviewed the feeding habits of each species studied.

METHODS AND MATERIALS

Study site

Lake Whatcom is a large (surface area = 2,030 ha, volume = 936,651,000 m^3), natural body of water located in Whatcom County, Washington. Total mercury concentrations for the lake and various waters entering the system range from 0.004 to 0.010 µg/l, whereas lake sediment concentrations range from 0.08 to 0.46 mg/kg, dry weight (Serdar et al. 1999, Matthews et al. 2000). Native fish and shellfish species include kokanee (*Oncorhynchus nerka*), cutthroat trout (*O. clarki*), peamouth (*Mylocheilus caurinus*), longnose sucker (*Catostomus catostomus*), three-spine stickleback (*Gasterosteus aculeatus*), sculpin (*Cottus* spp.), signal crayfish, and freshwater mussels. Introduced fish species include smallmouth bass, rainbow trout (*O. mykiss*), yellow perch, pumpkinseed, brown bullhead (*Ameiurus nebulosus*), and largemouth bass (*M. salmoides*) (Mueller et al. 1999).

Fish and crayfish sampling

Fish and crayfish were collected from May 15 to June 2, 2000 with three sampling techniques - electrofishing, gillnetting, and scuba diving. The selective criterion for sample locations was higher catch rates relative to those found in other areas of the lake as determined by Mueller et al. (1999), Mueller (2002), and anecdotal angling reports. All fish and crayfish captured were placed into a live well until they could be processed, usually within 30 min. The target species included smallmouth bass, cutthroat trout, yellow perch, brown bullhead, pumpkinseed, kokanee, and signal crayfish. All specimens were identified to species, measured to the nearest 1 mm, and weighed to the nearest 0.5 g. Several scales were removed from each scale-bearing fish for aging purposes (Devries and Frie 1996). However, a lack of technical resources precluded aging brown bullhead and signal crayfish directly. Instead, their ages were inferred from tables in Wydoski and Whitney (1979) and McGriff (1983), respectively. Fish and signal crayfish were double-wrapped in aluminum foil (dull-side-in), labeled, and placed in large plastic bags. Samples were stored on ice, transported to the laboratory, and stored frozen (-20° C).

Sample preparation

Fish were scaled, the body muscle was filleted, and the skin was removed, all with a stainless steel knife or scalpel. Only the fillet on the right side was used unless both sides were needed to provide adequate material for analysis. Skin was removed from brown bullhead specimens prior to fillet resection. Signal crayfish tail muscle was extracted and processed similarly.

Tissue was homogenized with three passes through a food processor or a hand-held grinder. Ground tissue was thoroughly mixed following each pass through the grinder. All equipment used for tissue preparation was vigorously washed with Liquinox ® detergent and rinsed sequentially in hot tap water, 10% Baker Instra-Analyzed ® nitric acid/deionized water solution, deionized water, and acetone. Fully homogenized tissue from each specimen was placed into a glass jar pre-cleaned for metals as per EPA (1995). Samples were stored at -20° C until analysis, which was within 14 and 82 days.

Analytical methods and data quality

Tissues were analyzed for mercury using cold vapor atomic absorption EPA method 245.5 (EPA 1986), with detection limits of 0.005 – 0.010 mg/kg (wet weight). Precision and bias were assessed through analysis of matrix spikes, matrix spike duplicates, and replicate analyses of 5% of samples. On average, 84% of spiked mercury was recovered from samples. Laboratory precision was very high, with a 9% average relative percent difference between matrix spike duplicates. Laboratory triplicate analyses also showed a high level of precision (average relative standard deviation of 8%) suggesting that sample preparation methods yielded homogenous samples.

Data analysis

To examine bioaccumulation, the total mercury concentration of each specimen was plotted against its total length. Furthermore, the mean (± SE) concentration of total mercury was determined for each year-class by species. Linear regressions were then conducted to determine whether total length and age and $\log_{10}(X+1)$ transformed total mercury concentration (X) were significantly and positively related. However, only the slopes of mercury concentration-age regressions were used to assess differences in mercury uptake among species, since examination of mercury concentration-length regressions can lead to confounding results such as short, old fish having potentially higher body burdens of mercury than longer, young fish (Neumann and Ward 1999).

A relative weight (W_r) index was used to evaluate the condition of all species except signal crayfish. Following Murphy and Willis (1991), the index was calculated as $W_r = W/W_s \times 100$, where W is the weight (g) of an individual fish and W_s is the standard weight of a fish of the same total length (mm). Anderson and Neumann (1996), Bister et al. (2000), and Hyatt and Hubert (2000) have compiled the parameters of the W_s equations for many cold- and warmwater fish species, including the minimum length recommendations for their application. The W_r values from this study were plotted against the total length and national standard for each species. A Fulton condition factor (K) was used to evaluate the condition of signal crayfish. Following Anderson and Neumann (1996), K was calculated as $(W/L^3) \times 10^5$, where W is the weight (g) of an individual signal crayfish and L is its total length in mm (measured from acumen of rostrum to end of telson). As with total length and age, linear regressions were conducted to determine whether relative weights or condition factor and $\log_{10}(X+1)$ transformed total mercury concentrations (X) were significantly and positively related.

To assess the potential risk to humans of consuming mercury-laden fish and crayfish from Lake Whatcom, values from this study were related to a range of values (0.3 – 1.0 mg/kg) representing state, federal, and international screening levels for the contaminant (WHO 1991, Foulke 1994, EPA 2001). These are concentrations that when detected in fish tissues usually result in fish consumption advisories by local health authorities.

RESULTS AND DISCUSSION

Signal crayfish

Signal crayfish (n = 45) ranged in size from 83 to 137 mm TL. Variation in signal crayfish condition, K, increased with length (Figure 1). Estimated ages ranged from two to five years old. Our sample was dominated by the 1998 year-

Table 1. Mean (± SE) and range of total mercury concentration (mg/kg) by year class, species, and number of fish and crayfish sampled from Lake Whatcom, Washington during late spring 2000. CRA = signal crayfish, PS = pumpkinseed, K = kokanee, BBH = brown bullhead, YP = yellow perch, CT = cutthroat trout, and SMB = smallmouth bass. Species are listed in increasing order of trophic level.

Year class	CRA	#	PS	#	K	#	BBH	#	YP	#	CT	#	SMB	#
1999											0.05 ± 0.01 (0.03 - 0.07)	4		
1998	0.08 ± 0.01 (0.03 – 0.21)	28	0.11 ± 0.04 (0.03 - 0.25)	5	0.10 ± 0.01 (0.07 - 0.18)	12	0.05	1	0.10 ± 0.01 (0.07 - 0.15)	10	0.06 ± 0.01 (0.03 - 0.12)	18		
1997	0.11 ± 0.01 (0.05 – 0.19)	13	0.09 ± 0.01 (0.05 - 0.23)	13	0.13 ± 0.01 (0.09 - 0.25)	11	0.08 ± 0.01 (0.07 - 0.09)	2	0.12 ± 0.01 (0.05 - 0.17)	10	0.07 ± 0.01 (0.04 - 0.10)	5	0.19 ± 0.02 (0.11 - 0.29)	12
1996	0.26 ± 0.20 (0.06 – 0.46)	2	0.12 ± 0.04 (0.04 - 0.28)	6	0.13 ± 0.01 (0.09 - 0.17)	7	0.08 ± 0.01 (0.03 - 0.14)	7	0.11	1	0.14 ± 0.05 (0.09 - 0.20)	2	0.28 ± 0.04 (0.10 - 0.45)	12
1995	0.32 ± 0.22 (0.10 – 0.54)	2	0.11 ± 0.02 (0.07 - 0.15)	3			0.09	1	0.22 ± 0.08 (0.12 - 0.39)	3	0.08	1	0.44 ± 0.03 (0.22 - 0.92)	37
1994			0.12 ± 0.02 (0.09-0.14)	3			0.41	1	0.38 ± 0.08 (0.31 - 0.46)	2			0.48 ± 0.04 (0.29 - 0.68)	12
1993							0.79	1	0.69 ± 0.18 (0.51 - 0.87)	2			0.90 ± 0.13 (0.55 - 1.30)	6
1992									0.37	2			0.85 ± 0.06 (0.68 - 1.23)	8
1991													0.98 ± 0.10 (0.88 - 1.08)	2
1990													1.17 ± 0.34 (0.75 - 1.84)	3
Overall mean±SE, range, and total *n*	0.10 ± 0.01 (0.03 – 0.54)	45	0.10 ± 0.01 (0.03 - 0.28)	30	0.12 ± 0.01 (0.07 - 0.25)	30	0.16 ± 0.06 (0.03 - 0.79)	13	0.20 ± 0.03 (0.04 - 0.87)	30	0.07 ± 0.01 (0.03 - 0.20)	30	0.49 ± 0.03 (0.10 - 1.84)	95

class. Total mercury concentration ranged from 0.03 to 0.54 mg/kg, with a mean (± SE) value of 0.10 ± 0.01 (Table 1). Of the 45 signal crayfish sampled, 4% (n = 2) had mercury levels exceeding the proposed EPA screening level of 0.3 mg/kg. These measured > 125 mm TL.

Linear regressions of log-transformed total mercury concentration on total length and age revealed weak, yet significant positive relationships (Table 2). However, regressing log-transformed mercury on K revealed no significant relationship ($r^2 = 0.01$, $P > 0.50$). The slope of the log-transformed mercury concentration-age regression for signal crayfish was greater than the slopes for pumpkinseed, kokanee, cutthroat trout, and yellow perch, but less than those of brown bullhead and smallmouth bass. This suggests that the bioaccumulation rate of mercury in signal crayfish was faster than most of the species studied, probably a reflection of its role as an opportunistic predator capable of structuring food webs through consumption from many trophic levels (Hobbs III 1993, Nyström et al. 1999). For example, signal crayfish eat detritus (both aquatic and terrestrial origins), diatoms, aquatic macrophytes, aufwuchs and periphyton, rotifers, molluscs (especially snails), water mites (Hydracarina), water "bears" (Tardigrada), crustaceans (Copepoda and each other), aquatic insects (Coleoptera, Diptera, Ephemeroptera, Megaloptera, Plecoptera, and Trichoptera), and dead animal remains (Hobbs III 1993, Ackefors and Lindqvist 1994, Nyström et al. 1999).

<u>Pumpkinseed</u>

Pumpkinseed (n = 30) ranged in size from 96 to 185 mm TL. Relative weights, W_r, were consistent with the national 75th percentile, and increased slightly with length (Figure 1). Estimated ages ranged from two to six years old. The 1997 year-class dominated our sample. Total mercury concentration ranged from 0.03 to 0.28 mg/kg, with a mean (± SE) value of 0.10 ± 0.01 (Table 1). None of the fish sampled exceeded the proposed EPA screening level of 0.3 mg/kg mercury in fish tissue.

Linear regressions of log-transformed total mercury concentration on total length and age revealed no significant relationships (Table 2), which indirectly supports Keast's (1978) findings of moderate to high diet overlap between year-classes of pumpkinseed. Furthermore, regressing log-transformed mercury on W_r revealed no significant relationship ($r^2 < 0.01$, $P > 0.50$). The slope of the log-transformed mercury concentration-age regression for pumpkinseed was smallest among all species studied suggesting slow mercury uptake. Pumpkinseed eat molluscs (especially snails), crustaceans (Amphipoda, Cladocera, Decapoda, and Isopoda), and aquatic insects (Anisoptera, Diptera, Ephemeroptera, and Trichoptera). They feed on the most frequent and abundant prey, including crayfish, but become more molluscivorous with size (> 75 mm TL) and age (> 1 year old) (Keast 1978, Mittelbach 1984, Hobbs III 1993).

<u>Kokanee</u>

Kokanee (n = 30) ranged in size from 189 to 240 TL. Relative weights, W_r, were low by national standards, but consistent with length (Figure 1). Estimated ages ranged from two to four years old. The 1998 year-class was dominant. Total mercury concentration ranged from 0.07 to 0.25 mg/kg, with a mean (± SE) value of 0.12 ± 0.01 (Table 1). None of the fish sampled exceeded the proposed EPA screening level of 0.3 mg/kg mercury in fish tissue.

Linear regressions of log-transformed total mercury concentration on total length and age revealed no significant relationships (Table 2), which indirectly supports Beauchamp et al's (1995) findings of considerable diet overlap between year-classes of kokanee. Moreover, regressing log-transformed mercury on W_r

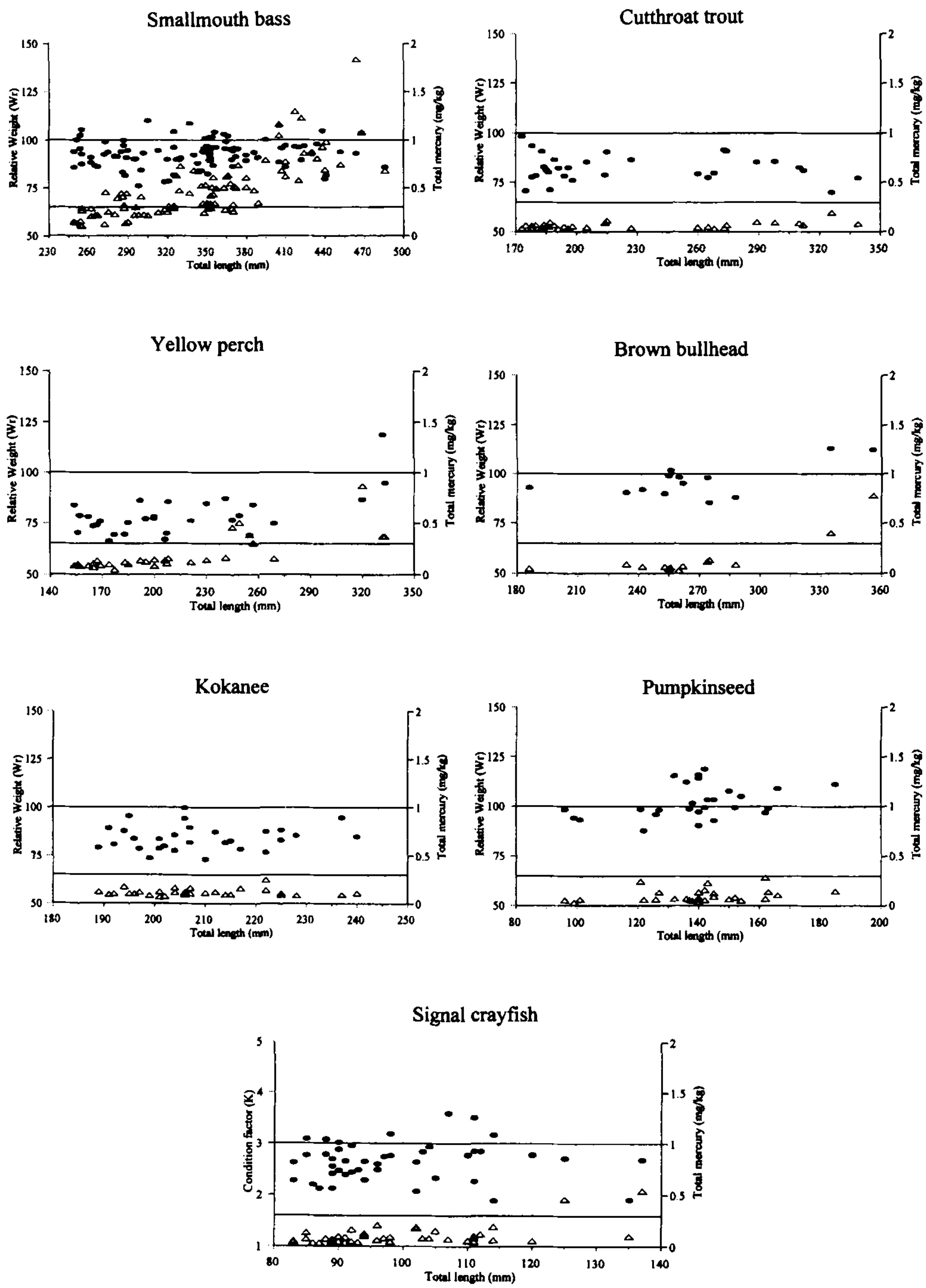

Figure 1. Relationship between total length and condition (relative weight, W_r, or Fulton condition factor, K) of fish and crayfish (black ovals) sampled from Lake Whatcom, Washington during late spring 2000 and relationship between total length and mercury concentration (mg/kg) of fish and crayfish (clear triangles). The range of values for state, federal, and international screening levels of mercury in fish tissues is represented by lines at 0.3 and 1.0 mg/kg.

revealed no significant relationship ($r^2 < 0.01$, $P > 0.50$). The slope of the log-transformed mercury concentration-age regression for kokanee was small compared to those of other species studied suggesting slow mercury uptake similar to pumpkinseed. Kokanee are feeding specialists eating aquatic insects (Diptera), crustaceans (Cladocera and Copepoda), and the occasional benthic invertebrate. The species' preferred diet item is *Daphnia* sp. (Beauchamp et al. 1995).

The kokanee population is supplemented by stocking millions of hatchery-reared fry into Lake Whatcom annually (WDFW 2001), which may partially explain the lower mercury levels. For example, Stafford and Haines (1997) concluded that fish populations maintained by frequent introductions of hatchery-produced fish consisted of younger fish with lower exposure to environmental mercury and thus contained lower concentrations than wild populations. However, the probable reason for low mercury levels in Lake Whatcom kokanee is related to diet; the zooplanktivorous kokanee just cannot bioaccumulate mercury to the same extent as piscivorous fishes.

Brown bullhead

Brown bullhead (n = 13) ranged in size from 186 to 356 mm TL. Relative weights, W_r, were slightly low by national standards, but increased with length (Figure 1). Estimated ages ranged from two to seven years old. Our sample was dominated by the 1996 year-class. Total mercury concentration ranged from 0.03 to 0.79 mg/kg, with a mean (± SE) value of 0.16 ± 0.06 (Table 1). Of the 13 brown bullhead sampled, 15% (n = 2) had mercury levels exceeding the proposed EPA screening level of 0.3 mg/kg. These fish measured > 330 mm TL.

Linear regressions of log-transformed total mercury concentration on total length and age revealed significant positive relationships (Table 2). Likewise, regressing log-transformed mercury on W_r revealed a significant positive relationship ($r^2 = 0.53$, $P < 0.01$). The slope of the log-transformed mercury concentration-age regression for brown bullhead exceeded those of all other species (Table 2) suggesting the fastest mercury uptake, which is unusual given its mid-level position in the food web. Brown bullhead eat molluscs (e.g., snails), crustaceans (Amphipoda and Decapoda), aquatic insects (Diptera) and the occasional fish. Young-of-year brown bullhead feed primarily on aquatic insects, whereas juvenile and adult fish consume prey from a wider variety of trophic levels, including crayfish. When prey fish are superabundant, the normally benthivorous brown bullhead shifts to piscivory (Massengil 1973, Ringler and Johnson 1982, Hobbs III 1993, Kline and Wood 1996).

Yellow perch

Yellow perch (n = 30) ranged in size from 154 to 333 mm TL. Relative weights, W_r, were low by national standards. Only the largest fish, two gravid females, were of good condition (Figure 1). Estimated ages ranged from two to eight years old. The 1997 and 1998 year-classes dominated our sample. Total mercury concentration ranged from 0.04 to 0.87 mg/kg, with a mean (± SE) value of 0.20 ± 0.03 (Table 1). Of the 30 fish sampled, 20% (n = 6) had mercury levels exceeding the proposed EPA screening level of 0.3 mg/kg. These measured > 240 mm TL.

Linear regressions of log-transformed total mercury concentration on total length and age revealed significant positive relationships (Table 2). Furthermore, regressing log-transformed mercury on W_r revealed a weak, yet significant positive relationship ($r^2 = 0.16$, $P = 0.03$). The slope of the log-transformed mercury concentration-age regression for yellow perch was greater than the slopes for pumpkinseed, kokanee, and cutthroat trout, but less than those of signal crayfish, brown bullhead and smallmouth bass. This suggests a moderate mercury uptake in yellow perch, possibly reflecting its dynamic, generalized feeding style. For example, yellow perch eat crustaceans (Amphipoda, Cladocera, Copepoda, Decapoda, Isopoda, and Mycidacea), aquatic insects (Diptera and Hemiptera), and fish. Crayfish and juvenile pumpkinseed both are part of yellow perch diet. Although active piscivory begins at about 130 mm TL (~ age 2), yellow perch ≥ 300 mm TL (~ ≥ age 7) often feed at lower trophic levels, which may partially explain the anomalous mercury levels we observed in the 1992 year-class (Table 1) (Hobbs III 1993, Lott et al. 1996, Pothoven et al. 2000, Fullhart et al. 2002).

<u>Cutthroat trout</u>

Cutthroat trout (n = 30) ranged in size from 173 to 339 mm TL. Relative weights, W_r, were low by national standards, and decreased slightly with length (Figure 1). Estimated ages ranged from one to five years old. The 1998 year-class was dominant. Total mercury concentration ranged from 0.03 to 0.20 mg/kg, with a mean (± SE) value of 0.07 ± 0.01 (Table 1). None of the cutthroat trout sampled exceeded the proposed EPA screening level of 0.3 mg/kg mercury in fish tissue.

Linear regressions of log-transformed total mercury concentration on total length and age revealed weak, yet significant positive relationships (Table 2). However, regressing log-transformed mercury on W_r revealed no significant relationship ($r^2 = 0.11$, $P > 0.05$). Like pumpkinseed and kokanee, the slope of the log-transformed mercury concentration-age regression for cutthroat trout was low compared to those of other species studied suggesting slow mercury uptake. This is unusual given its status as a top-level predator in many lentic systems (Beauchamp et al. 1992). Cutthroat trout primarily eat crustaceans (Amphipoda, Cladocera, Decapoda, and Mycidacea) and aquatic insects (Diptera, Ephemeroptera, and Odonata) until reaching sizes large enough to capture small fishes. This occurs at about age 3 or > 250 mm TL. Large cutthroat trout are known predators of crayfish, kokanee, and yellow perch (Luecke 1986, Beauchamp et al. 1992 and 1995, Hobbs III 1993).

One possible explanation for low mercury levels in cutthroat trout is that we sampled only small, immature fish that fed at lower trophic levels and were potentially isolated from mercury sources before entering the lake (wild cutthroat trout reside in their natal streams up to two years). Alternatively, mercury uptake in cutthroat trout was affected *sensu* Stafford and Haines (1997) since, like kokanee, the population is supplemented by stocking thousands of hatchery-reared fry into the lake annually (WDFW 2001).

<u>Smallmouth bass</u>

Smallmouth bass (n = 95) ranged in size from 249 to 486 mm TL. Relative weights, W_r, were somewhat low by national standards, but consistent with length (Figure 1). Estimated ages ranged from three to ten years old. Our sample was dominated by the 1995 year-class. Total mercury concentration ranged from 0.10 to 1.84 mg/kg, with a mean (± SE) value of 0.49 ± 0.03 (Table 1), which was higher than the national average of weighted means (0.37) reported for the species (EPA 1999). Of the 95 fish sampled, 64% (n = 61) had mercury levels exceeding the proposed EPA screening level of 0.3 mg/kg. These measured > 275 mm TL.

Linear regressions of log-transformed total mercury concentration on total length and age revealed significant positive relationships (Table 2). However, regressing log-transformed mercury on W_r revealed no significant relationship ($r^2 = 0.01$, $P > 0.20$). The slope of the log-transformed mercury concentration-age regression for smallmouth bass exceeded those of all other species except brown bullhead suggesting rapid mercury uptake, which is expected of a top-level fish predator. Juvenile smallmouth bass eat crustaceans (Amphipoda, Copepoda, Decapoda, and Isopoda) and aquatic insects (Diptera, Ephemeroptera, Hemiptera, Plecoptera, and Trichoptera) through age 1 (~ 120 mm TL), while older, larger smallmouth bass eat mostly fish and crayfish (Pflug and Pauley 1984, Livingstone and Rabeni 1991, Easton et al. 1996). In Lake Whatcom, adult smallmouth bass prey on signal crayfish and a variety of finfish, including kokanee and yellow perch (Downen 1999).

Summary

Predaceous smallmouth bass displayed the highest levels of mercury, followed by omnivorous yellow perch and brown bullhead, zooplanktivorous kokanee, benthivorous pumpkinseed, and herbi-detritivorous signal crayfish. The fastest rates of mercury bioaccumulation were found in brown bullhead, smallmouth bass, signal crayfish, and yellow perch as indicated by the slopes of the log-transformed mercury concentration-age regression lines. The slopes for cutthroat trout, kokanee, and pumpkinseed suggest very slow uptake in these species.

The elimination of mercury from aquatic animals is extremely slow (McKim et al. 1976), with reported half-lives ranging from about four months to three years in long-term (> 90 days) experiments on fish (Trudel and Rasmussen 1997). Top-level fish predators may retain up to one-third of the mercury ingested (Phillips and Gregory 1979, McCloskey et al. 1998). This persistence in the food web is cause for concern, especially when aquatic resources are linked through consumption at so many trophic levels. Ostensibly, there is considerable overlap in diet among species for small crustaceans (Amphipoda, Cladocera, Copepoda, and Decapoda) and aquatic insects (Diptera and Ephemeroptera) at Lake Whatcom. Furthermore, except for kokanee, all of the species studied here are known crayfish predators, which is important given the key role of signal crayfish in the lake's food web.

Westcott and Kalff (1996) concluded that zooplankton were good indicators of the relative bioavailability of mercury at the base of the food chain; they found that mercury levels in filter-feeding zooplankton (*Daphnia* spp.) were strongly correlated

Table 2. Regression equations for the relationships between total length (mm), age (year), and Log_{10} (Hg + 1) total mercury concentration (mg/kg, wet weight) in Lake Whatcom, Washington fish and crayfish analyzed during late spring 2000. Species are listed in decreasing order of trophic level.

Species	Number of fish	Regression equation	r^2	*P*
Smallmouth bass	95	$Log_{10}(Hg + 1) = 0.0011 \times (\text{total length}) - 0.2158$	0.6234	< 0.0001
		$Log_{10}(Hg + 1) = 0.0384 \times (\text{age}) - 0.0413$	0.6293	< 0.0001
Cutthroat trout	30	$Log_{10}(Hg + 1) = 0.0001 \times (\text{total length}) + 0.0023$	0.2011	0.0129
		$Log_{10}(Hg + 1) = 0.0078 \times (\text{age}) + 0.0105$	0.2770	0.0028
Yellow perch	30	$Log_{10}(Hg + 1) = 0.0009 \times (\text{total length}) - 0.1113$	0.6319	< 0.0001
		$Log_{10}(Hg + 1) = 0.0240 \times (\text{age}) - 0.0149$	0.6719	< 0.0001
Brown bullhead	13	$Log_{10}(Hg + 1) = 0.0013 \times (\text{total length}) - 0.2948$	0.6980	0.0003
		$Log_{10}(Hg + 1) = 0.0439 \times (\text{age}) - 0.1243$	0.6943	0.0004
Kokanee	30	$Log_{10}(Hg + 1) = 0.00001 \times (\text{total length}) + 0.03574$	0.0033	0.7625
		$Log_{10}(Hg + 1) = 0.0049 \times (\text{age}) + 0.0342$	0.0793	0.1317
Pumpkinseed	30	$Log_{10}(Hg + 1) = 0.0004 \times (\text{total length}) - 0.0134$	0.1057	0.0796
		$Log_{10}(Hg + 1) = 0.0028 \times (\text{age}) + 0.0309$	0.0194	0.4629
Signal crayfish	45	$Log_{10}(Hg + 1) = 0.0015 \times (\text{total length}) - 0.1048$	0.3197	< 0.0001
		$Log_{10}(Hg + 1) = 0.0252 \times (\text{age}) - 0.0215$	0.3302	< 0.0001

with concentrations found in smallmouth bass from 11 of 24 study lakes in south-central Ontario, Canada. Gorski et al. (1999) suggested that planktivorous fish might be useful sentinels for monitoring short-term changes in the availability of mercury in lakes. Hence, future studies may be designed to examine the roles of planktivorous early life stages of fishes and fishes utilizing zooplankton as adults, such as kokanee, in mercury cycling at Lake Whatcom.

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