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Mercury and Selenium in Fish from the Savannah River: Species, Trophic Level, and Locational Differences

Joanna Burger,*,†,[1] Karen F. Gaines,‡ C. Shane Boring,*,† Warren L. Stephens, Jr.,‡ Joel Snodgrass,†,§ and Michael Gochfeld†,‖

*Division of Life Sciences, Nelson Biological Laboratory, Rutgers University, Piscataway, New Jersey 08854-8082; †Environmental and Occupational Health Sciences Institute, and Consortium for Risk Evaluation with Stakeholder Participation (CRESP), Piscataway, New Jersey 08854; ‡Savannah River Ecology Laboratory, University of Georgia, P.O. Drawer E, Aiken, South Carolina, 29802; §Department of Biology, Towson University, Towson, Maryland 21252; and ‖Environmental and Community Medicine, UMDNJ-Robert Wood Johnson Medical School, Piscataway, New Jersey 08854

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Levels of contaminants in fish are of considerable interest because of potential effects on the fish themselves, as well as on other organisms that consume them. In this article we compare the mercury levels in muscle tissue of 11 fish species from the Savannah River, as well as selenium levels because of its known protective effect against mercury toxicity. We sampled fish from three stretches of the river: upstream, along, and downstream the Department of Energy's Savannah River Site, a former nuclear material production facility. We test the null hypothesis that there were no differences in mercury and selenium levels in fish tissue as a function of species, trophic level, and location along the river. There were significant interspecific differences in mercury levels, with bowfin (*Amia calva*) having the highest levels, followed by largemouth bass (*Micropterus salmoides*) and pickerel (*Esox niger*). Sunfish (*Lepomis* spp.) had the lowest levels of mercury. As expected, these differences generally reflected trophic levels. There were few significant locational differences in mercury levels, and existing differences were not great, presumably reflecting local movements of fish between the sites examined. Selenium and mercury concentrations were positively correlated only for bass, perch (*Perca flavescens*), and red-breasted sunfish (*Lepomis auritus*). Mercury levels were positively correlated with body mass of the fish for all species except American eel (*Anguilla rostrata*) and bluegill sunfish (*L. macrochirus*). The mercury and selenium levels in fish tissue from the Savannah River are similar to or lower than those reported in many other studies, and in most cases pose little risk to the fish themselves or to other aquatic consumers, although levels in bowfin and bass are sufficiently high to pose a potential threat to high-level consumers.

Key Words: **fish; mercury; selenium; ecological risk; trophic level; Savannah River; biological amplification.**

INTRODUCTION

The public, governmental agencies, and conservation organizations in the United States are interested in assessing the health of organisms in aquatic systems where transport of contaminants can occur relatively quickly, leading directly to uptake, absorption, and assimilation. Bottom sediments can act as both a sink and a source for contaminants (Barron, 1995), and heavy metal concentrations in sediments can exceed water concentrations by 3 to 5 orders of magnitude (Bryan and Langston, 1992). Heavy metals enter the aquatic food chain through direct consumption of water or biota, and through nondietary routes such as uptake through the absorbing epithelium (i.e., the gills of fish; Brezonik *et al.*, 1991). For small fish, the skin may serve as a particularly important site for uptake because of the high ratio of surface to body (Hayton and Barron, 1990). Contaminant loads in fish are a result of uptake, minus both biotransformation and excretion. Biotransformation through metabolizing a variety of chemicals is an important route of elimination in aquatic organisms (Barron, 1995). For mercury and selenium the interconversion between organic and inorganic forms is important (Brezonik *et al.*, 1991; Spry and Wiener, 1991).

[1]To whom correspondence should be addressed. Fax: 732-445 5870. E-mail: burger@biology.rutgers.edu.

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TABLE 1
Scientific Name, Trophic Levels, and Mobility of Fish Sampled from the Savannah River, as Well as Main Fishing Season (Most Fish Can be Taken All Year)

Common name	Scientific name	Diet/trophic rank	Mobility	Fishing season
Bowfin	*Amia calva*	Top piscivore	Mobile	Year round (not targeted)
Largemouth bass	*Micropterus salmoides*	Piscivore	Mobile	March–May
Channel catfish	*Ictalurus punctatus*	Large invertebrate/piscivore	Highly mobile	Mostly March–June (but all year)
Chain pickerel	*Esox niger*	Large invertebrate/piscivore	Migratory	Year round (opportunistically)
Yellow perch	*Perca flavescens*	Large invertebrate/small fish	Sedentary	Mid March–mid April (opportunistically)
Black crappie	*Pomoxis nigromaculatus*	Large invertebrate/small fish	Highly mobile	Mid March–mid April
American eel	*Anguilla rostrata*	Detritus/invertebrate piscivore	Migratory	March–June (opportunistically)
Shellcracker (redear)	*Lepomis microlophus*	Medium–large invertebrate	Sedentary	March–May
Bluegill sunfish	*Lepomis macrochirus*	Medium–large invertebrate	Sedentary	March–June
Red-breasted sunfish	*Lepomis auritus*	Medium–large invertebrate	Sedentary	March–May
Spotted sucker	*Minytrema melanops*	Plant and invertebrate	Migratory	Year round (opportunistically)

Note. Species are listed in order of decreasing trophic level.

There is great variation in metal bioconcentration between species of animals (Bradley and Sprague, 1985). While zooplankton accumulate certain metals to a high level, fish closely regulate internal concentrations through elimination and sequestration with cellular binding proteins (e.g., metallothioneins; Hodson, 1998). Biomagnification through aquatic food webs has been extensively studied, particularly for persistent, halogenated and hydrophobic chemicals, such as DDT and PCBs (Barron, 1995). Less attention has been devoted to metals, except for methylmercury, and it has been suggested that significant biomagnification in vertebrates occurs only for hydrophobic alkyl metals because other metals are internally highly regulated (Bryan and Langston, 1992). Inorganic mercury in aquatic systems can be converted to methylmercury by microorganisms (Jensen and Jernelow, 1969; Brezonik *et al*., 1991; Spry and Wiener, 1991; Zillious *et al*., 1993).

There are few studies that examine a wide range of fish representing different trophic levels within the same ecosystem (Lacerda *et al*., 1994; Campbell, 1994; Fairey *et al*., 1997). Yet to understand the potential risk to fish assemblages in aquatic systems, and to their consumers, it is useful to examine metal levels in a range of organisms at different trophic levels. The protective effect of selenium on mercury toxicity has been known for about a quarter century (Berlin, 1978; Ganther *et al*., 1972; Satoh *et al*., 1985). Studies in various organisms have found a tendency for the two to be positively correlated in tissues (Eisler, 1985; Caurant *et al*., 1994; Kuehl and Haebler, 1995; Wagemann *et al*., 1996).

In this article we compare the levels of mercury and selenium in 11 species of fish collected in 1997 and 1998 from the Savannah River, adjacent to the Department of Energy's Savannah River Site (SRS). SRS formerly produced material for nuclear weapons, but is currently a research facility with management of its hazardous waste legacy as a high priority (OTA, 1991; DOE, 1995). Additional environmental information on SRS is provided in a series of annual environmental studies (e.g., Westinghouse, 1998). We were particularly interested in verifying the differences among trophic levels in mercury and selenium concentrations. Fish species differed in size, trophic levels, mobility, and location of foraging; thus they might bioaccumulate different amounts of contaminants. Because of concerns that SRS might contribute pollutants to the Savannah River, we investigated whether metal concentrations differed upstream, along, or downstream from the SRS. This study evaluates (1) within-species differences in mercury and selenium levels, (2) differences as a function of life span and size, (3) locational differences (upstream, along SRS, and downstream), and (4) the relationship of mercury and selenium levels.

Fish were selected to represent different trophic levels and to encompass the main species consumed by people fishing along the river (Burger, 1998;

Burger *et al*., 1999). Scientific names are given in Table 1. Further, fish also enter the terrestrial food chain when they are eaten by other vertebrates, such as mink (*Mustela vison*), raccoons (*Procyon lotor*), muskrats (*Ondatra zibethicus*), and opossums (*Didelphis virginiana*) (Baker and Carmichael, 1989; Burger, 1999). These species are themselves eaten by others, contributing to food web distribution of contaminants.

MATERIALS AND METHODS

Study Site

Fish were collected from the Savannah River, which separates South Carolina and Georgia, and bounds the southwestern edge of the Department of Energy's SRS. Our design was to collect fish from upstream, along, and downstream of the SRS (Fig. 1). The SRS (33.1°N, 81.3°W) is a 780-km^2 former nuclear weapons production and current research facility operated by the U.S. government since the early 1950s, which used the river as a source of cooling water for the nuclear reactors when they were functioning. Water was discharged to artificial thermal cooling reservoirs. Prior to the construction of the cooling ponds, there was some ecosystem contamination of streams and the floodplain, and some radionuclides were released subsequently (Ashley and Zeigler, 1980; Whicker *et al*., 1990; Kennamer *et al*., 1998). Streams from the SRS flow directly into the Savannah River, and fish move freely between the on-site tributary streams and the river (Workman and McLeod, 1990).

There is controversy about the relative contribution of different sources of heavy metals in the Savannah River. Some came from industrial activities upstream from SRS, but activities on site resulted in contamination by a wide range of heavy metals and radionuclides (Kvartek *et al*., 1994; Sugg *et al*., 1995). There is some discharge of mercury from the coal burning power plant in D-area of the SRS, which varies depending upon the coal they are burning and the efficiency of combustion. Atmospheric deposition also contributes to the mercury load; the Savannah River is in a zone of high annual atmospheric mercury deposition (>10 μg/m^2, after EPA, 1980; Downs *et al*., 1998). If SRS were the main source of mercury or selenium we would expect to find lower concentrations in fish taken upstream compared with along or downstream of SRS.

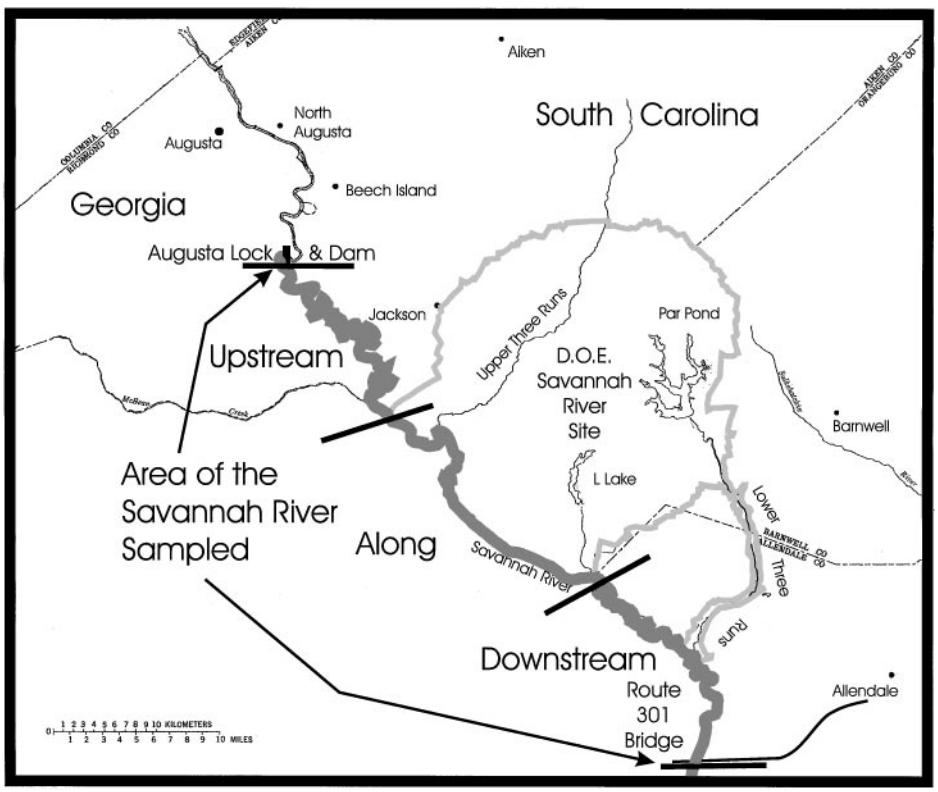

FIG. 1. Map of the Savannah River, showing collection locations upstream, along, and downstream the Department of Energy's Savannah River Site.

Protocol

Under appropriate state permits, and with protocol approvals from the University of Georgia Institutional Animal Care and Use Committee (A960205) and Rutgers University Institutional Review Board (07-017), fish were collected from the Savannah River upstream, along, and downstream SRS (Fig. 1) These represented three contiguous stretches of river. "Upstream" designates the stretch from the Augusta Lock and Dam to the northern edge of SRS. "Along" designates the stretch of river bordering SRS. "Downstream" designates the stretch from the southeastern corner of SRS to the Route 301 bridge across the river. We shocked while boating along the entire length of each segment to ensure that fish were collected throughout the sampling area.

Fish were stunned using a 6-m Smith Root Electrofisher boat and were collected with dipnets, placed on ice, and returned to the Savannah River Ecology Laboratory. Non-target species, or excess of a given species, were not removed from the water. Most species were obtained from all three localities, but because of the nature of fish populations and their distribution, we did not obtain a completely balanced design.

Fish were labeled by date and location and frozen (-4°C) for later dissection. During dissection at the Savannah River Ecology Laboratory (SREL), fish were weighed and their standard and total lengths measured. Edible fillets were removed and subsequently transported to the Environmental and Occupational Health Sciences Institute for metal analysis.

Tissues were washed vigorously in deionized water alternated with acetone to remove external contamination (Walsh, 1990), and then were digested in ultrex ultrapure nitric acid in a microwave oven (MD 2000 CEM), using a digestion protocol of three stages of 10 min each under 50, 100, and 150 (3.5, 7, and 10.6 kg/cm^2) pounds per square inch at 70X power. Digested samples were diluted in 100 ml deionized water. All laboratory equipment and containers were washed in 10% HNO_3 solution prior to each use.

Mercury was analyzed by cold vapor technique (HGS-4), and selenium was analyzed by graphite furnace atomic absorption (Perkin–Elmer graphite furnace PE 5100 PC). All specimens were run in batches that included blanks, a standard calibration curve, and spiked specimens. The accepted recoveries for spikes ranged from 85 to 115%; no batches were outside these limits. The coefficient of variation (CV) on replicate samples ranged from 2 to 9%. Further quality control included periodic blind analysis of an aliquot from a large sample of known concentrations, and blind runs of duplicate samples during the analysis for each metal.

We used ANOVA on log-transformed data with Duncan post hoc test to examine for differences among fish species and locations, followed by parametric correlation (Pearson coefficient) to compare concentrations among mercury, selenium, and fish weight for each fish species (SAS, 1995). The level for significance was designated as <0.05, but values between this level and 0.1 are presented to allow the reader to evaluate whether increased sample sizes would have resulted in significance.

RESULTS

There were significant interspecies differences in both mercury and selenium levels (Table 2). In general, mercury levels were highest in bowfin, and lowest in eel and sunfish. Species with the lowest mercury levels generally had the highest levels of selenium. Mercury and selenium were not significantly correlated for most species, except for bass, perch, and red-breasted sunfish, where the correlation was positive (Table 2). In catfish mercury and selenium were negatively correlated. For most species of fish, mercury levels were positively correlated with body mass. Within a species, larger fish had higher mercury levels than smaller fish (Table 2). Body mass and selenium were significantly correlated only for pickerel, eel, and red-breasted sunfish (Table 2).

There was no consistent pattern across species, and although there were some significant differences, they were not great (Table 3). Mercury was highest upstream from SRS for only one species (bowfin), along SRS for one species (red-breasted sunfish), and downstream from SRS for two species (bass, perch). Selenium was highest upstream for bass and sucker, and along for four species (pickerel, catfish, crappie, bluegill sunfish).

DISCUSSION

Species and Trophic Level Differences

Trophic level correlations have been reported for mercury (Denton and Burdon-Jones, 1986; Lacerda *et al*., 1994; Wiener and Spry, 1996; Watras *et al*., 1998; Snodgrass *et al*., 2000), as well as for other contaminants (Lemly, 1993a; Barron, 1995; Sydeman and Jarman, 1998).

TABLE 2

Overall Arithmetic Means and Standard Error (ppm, Wet Weight) Mercury and Selenium for Fish from the Savannah River

		Total weight (g)	Mercury	Selenium	Hg and Se correlation	Total Weight and Hg correlation	Total weight and Se correlation
Fish	*N*	Mean ± SE	Mean ± SE	Mean ± SE	tau (*P*)	tau (*P*)	tau (*P*)
Bowfin	58	1843.2 ± 86.62	0.94 ± 0.05 A	0.25 ± 0.01 D, E	0.03327 (NS)	0.30309 (0.0008)	0.03327 (NS)
		1736.4	0.84	0.23			
Bass	48	625.47 ± 69.57	0.46 ± 0.04 B	0.33 ± 0.02 B, C, D	0.13475 (NS)	0.42376 (0.0001)	0.11879 (NS)
		497.2	0.38	0.31			
Catfish	45	951.48 ± 131.67	0.2 ± 0.02 E	0.21 ± 0.01 E	− 0.17374 (0.09)	0.26061 (0.01)	− 0.1697 (NS)
		660.25	0.16	0.18			
Pickerel	19	484.9 ± 59.75	0.36 ± 0.03 B, C	0.27 ± 0.03 D, E	0.16959 (NS)	0.36364 (0.03)	0.42229 (0.01)
		424.84	0.33	0.23			
Perch	39	220.24 ± 20.95	0.28 ± 0.02 C, D	0.36 ± 0.04 B, C, D	0.32794 (0.003)	0.29015 (0.009)	0.03914 (NS)
		191.25	0.25	0.3			
Crappie	53	220.77 ± 19.66	0.24 ± 0.02 D, E	0.34 ± 0.03 C, D	0.11321 (NS)	0.24964 (0.008)	− 0.3048 (NS)
		186.46	0.21	0.3			
American eel	24	255.75 ± 20.52	0.15 ± 0.03 F	0.48 ± 0.08 A, B	− 0.2029 (NS)	− 0.34783 (0.02)	0.24638 (0.09)
		232.57	0.11	0.41			
Shellcracker	36	189.26 ± 15.81	0.23 ± 0.03 E	0.43 ± 0.03 A, B, C	0.06984 (NS)	0.20635 (0.08)	0.16508 (NS)
		166.43	0.17	0.37			
Bluegill sunfish	30	161.69 ± 14.69	0.14 ± 0.02 F	0.41 ± 0.03 A, B, C	− 0.17241 (NS)	0.09425 (NS)	0.30115 (0.019)
		143.28	0.11	0.37			
Red-breasted sunfish	35	125.83 ± 7.16	0.13 ± 0.02 F	0.64 ± 0.15 A	0.32437 (0.006)	0.29748 (0.01)	0.30756 (0.009)
		118.21	0.09	0.46			
Spotted sucker	35	520.37 ± 26.01	0.27 ± 0.04 D, E	0.36 + 0.05 D	− 0.12941 (NS)	0.35798 (0.003)	− 0.09916 (NS)
		495.71	0.19	0.27			
F (*P*)		100.16 (0.0001)	39 (0.0001)	8.3 (0.0001)			

Note. Geometric means are given below arithmetic means. Differences in mercury and selenium with ANOVA on log-transformed data with Duncan post hoc test. Correlation of mercury with selenium and weight by Kendall tau. NS not significant.

Carnivorous species generally have higher levels than herbivores, omnivores, or planktivores (Phillips *et al*., 1980), and larger predators have higher levels than smaller ones (Lacerda *et al*., 1994), although such differences are not always noted (Bidone *et al*., 1997). Moreover, some bottom-dwelling fish can have higher levels than some predators, particularly if they ingest sediment. For example, Campbell (1994) found that a bottom-dwelling redear sunfish (*Lepomis microlophus*) had higher mercury levels than bass or bluegill sunfish in Florida. Thus, it is essential to understand the feeding location as well as trophic level to interpret contaminant levels.

We expected that sedentary fishes would spend more time in individual sampling areas (upstream, along SRS, downstream), and the probability of movement among areas would increase through mobile to highly mobile species. If these assumptions are correct, we would expect sedentary species to more closely reflect exposure within individual sampling areas and, therefore, to exhibit larger differences in mercury and selenium levels among areas. In contrast, mobile species are more likely to reflect integrated exposure as they move among areas, resulting in a homogenization of differences in exposure among areas. However, this did not seem to be the case as sedentary, mobile, and highly mobile species exhibited similar differences in mercury and selenium among areas (refer to Table 3).

In this study, mercury levels reflected trophic levels, confirming our initial prediction. The top-level predators, bowfin and bass, had the highest levels, and sunfish had the lowest. Spotted sucker was an exception in that its mercury levels were higher than predicted on the basis of trophic level; suckers eat vegetation as well as some invertebrates, and we expected them to have low mercury levels. This may reflect the fact that they are migratory, and may spend more time in areas where mercury levels are higher. Herbivores sometimes have higher levels than carnivores (Tayel and Shriadah, 1996). The mercury levels in bass were not as high as might be expected, perhaps because the fish collected were not particularly large (and thus might have been younger, with less time for accumulation).

TABLE 3

Concentration (Arithmetic Mean and Standard Error, in ppm Wet Weight) with Maximum Values of Metals in Fish from Above, Along, and Below the SR Site

	N	Above	*N*	Along	*N*	Below	*F* (*P*)
Bowfin							
Mercury	14	1.19 ± 0.10	30	0.81 ± 0.05	14	0.97 ± 0.15	8.67 (0.01)
Max/geo mean		2.22 (1.14)		1.31 (0.75)		1.87 (0.78)	
Selenium	14	0.26 ± 0.02	30	0.24 ± 0.01	14	0.24 ± 0.01	0.53 (NS)
Max/geo mean		0.37 (0.24)		0.38 (0.22)		0.28 (0.24)	
Largemouth bass							
Mercury	15	0.30 ± 0.04	19	0.43 ± 0.06	14	0.68 ± 0.10	12.5 (0.01)
Max/geo mean		0.73 (0.27)		0.96 (0.35)		1.85 (0.61)	
Selenium	15	0.39 ± 0.03	19	0.29 ± 0.03	14	0.31 ± 0.02	9.27 (0.009)
Max/geo mean		0.57 (0.38)		0.67 (0.26)		0.49 (0.30)	
Channel catfish							
Mercury	10	0.19 ± 0.05	20	0.19 ± 0.03	15	0.22 ± 0.03	1.68 (NS)
Max/geo mean		0.59 (0.14)		0.52 (0.16)		0.56 (0.19)	
Selenium	10	0.14 ± 0.02	20	0.25 ± 0.02	15	0.18 ± 0.02	8.95 (0.01)
Max/geo mean		0.28 (0.12)		0.45 (0.23)		0.31 (0.18)	
Chain pickerel							
Mercury	5	0.43 ± 0.08	5	0.34 ± 0.09	9	0.32 ± 0.02	0.88 (NS)
Max/geo mean		0.63 (0.39)		0.64 (0.29)		0.45 (0.32)	
Selenium	5	0.26 ± 0.04	5	0.38 ± 0.05	9	0.21 ± 0.05	5.66 (0.05)
Max/geo mean		0.35 (0.25)		0.54 (0.37)		0.52 (0.18)	
Yellow perch							
Mercury	4	0.20 ± 0.05	21	0.26 ± 0.03	14	0.35 ± 0.03	5.22 (0.07)
Max/geo mean		0.28 (0.17)		0.57 (0.22)		0.67 (0.33)	
Selenium	4	0.33 ± 0.05	21	0.44 ± 0.06	14	0.26 ± 0.03	4.57 (0.101)
Max/geo mean		0.35 (0.32)		0.54 (0.37)		0.52 (0.22)	
Black crappie							
Mercury	14	0.26 ± 0.04	34	0.23 ± 0.02	5	0.27 ± 0.06	1.06 (NS)
Max/geo mean		0.54 (0.22)		0.54 (0.20)		0.47 (0.25)	
Selenium	14	0.24 ± 0.03	34	0.40 ± 0.04	5	0.26 ± 0.03	10.3 (0.006)
Max/geo mean		0.41 (0.21)		1.40 (0.35)		0.35 (0.25)	
American eel							
Mercury	12	0.15 ± 0.04	7	0.09 ± 0.02	5	0.22 ± 0.11	2.99 (NS)
Max/geo mean		0.61 (0.12)		0.15 (0.08)		0.65 (0.15)	
Selenium	12	0.36 ± 0.03	7	0.49 ± 0.06	5	0.77 ± 0.39	4.07 (NS)
Max/geo mean		0.51 (0.34)		0.76 (0.47)		2.32 (0.54)	
Shellcracker (redear)							
Mercury	11	0.22 ± 0.08	12	0.21 ± 0.04	13	0.27 ± 0.05	3.10 (NS)
Max/geo mean		0.82 (0.13)		0.51 (0.17)		0.62 (0.23)	
Selenium	11	0.44 ± 0.04	12	0.42 ± 0.06	13	0.43 ± 0.06	0.17 (NS)
Max/geo mean		0.69 (0.41)		0.90 (0.36)		0.76 (0.36)	
Bluegill sunfish							
Mercury	6	0.13 ± 0.04	16	0.14 ± 0.04	8	0.16 ± 0.03	1.68 (NS)
Max/geo mean		0.27 (0.10)		0.67 (0.10)		0.30 (0.14)	
Selenium	6	0.38 ± 0.08	16	0.48 ± 0.03	8	0.31 ± 0.05	7.99 (0.02)
Max/geo mean		0.75 (0.35)		0.73 (0.47)		0.42 (0.25)	
Red-breasted sunfish							
Mercury	11	0.05 ± 0.01	24	0.16 ± 0.03			13.1 (0.0003)
Max/geo mean		0.15 (0.05)		0.63 (0.12)			
Selenium	11	0.39 ± 0.06	24	0.75 ± 0.22			3.28 (0.07)
Max/geo mean		0.76 (0.33)		5.64 (0.54)			
Spotted sucker							
Mercury	18	0.23 ± (0.06)	17	0.31 ± 0.05			1.92 (NS)
Max/geo mean		1.13 (0.14)		0.73 (0.25)			
Selenium	18	0.50 ± 0.09	17	0.21 ± 0.03			10.2 (0.001)
Max/geo mean		1.68 (0.4)		0.48 (0.17)			

Selenium levels, in contrast, were higher in species that were lowest on the food chain. Further, the selenium levels were highest in the species that are sedentary, implying that the foods they consume locally contain more selenium than those consumed by migratory species when they are away from the

area sampled. The species with highest selenium levels eat mainly invertebrates, which also feed locally, either in the water column or in sediments. This implies that levels of selenium are higher in the water and sediments along SRS than downstream from SRS. Selenium is a contaminant often associated with emissions from coal combustion in power plants (ATSDR. 1995), and there is a coal power plant on site. Rowe *et al*. (1996) showed behavioral deficits for bullfrog (*Rana catesbeiana*) tadpoles on the SRS that were associated with coal ash deposits, which are highly contaminated with selenium and other metals.

Selenium and Mercury

Uptake of metals by fish is affected by both physical properties and the presence of other substances. Selenium has a protective effect on mercury toxicity (Ganther *et al*., 1972: Satoh *et al*., 1985), and the two are often correlated (Eisler, 1985; Caurant *et al*., 1994; Kuehl and Haebler, 1995; Wagemann *et al*., 1996). At high concentrations, selenium has a protective effect on mercury toxicity in salmonid eggs (Klaverkamp *et al*., 1983), but at these high levels, selenium can cause behavioral abnormalities, reproductive deficits, and ultimately mortality (Eisler, 1985; Heinz, 1996). Selenium has an antagonistic effect on mercury metabolism (Fimreite, 1979). The mechanisms of protection are unclear, although it is hypothesized that selenium and mercury form a biologically inactive compound, or that it plays an antioxidative role (Hansen, 1988).

In this study, selenium and mercury levels showed a significant positive correlation only for bass, perch, and red-breasted sunfish; indeed catfish had a negative correlation, suggesting that predators that ate most of the species we studied would have little protective effect conferred by selenium against possible mercury toxicity. Although mercury and selenium were correlated for three fish species, the effects of selenium on mercury levels were not determined. Further, laboratory research is required to determine whether selenium is equally protective for all species of fish.

Species Size Relationships

A positive relationship is often noted in the literature for mercury levels and size and age of fish (Braune, 1987; Lacerda *et al*., 1994; Bidone *et al*., 1997; Park and Curtis, 1997). However, such a relationship may not exist where food is limited and fish stop growing, but continue to accumulate mercury (Downs *et al*., 1998). In this study mercury levels were positively and significantly correlated with body mass for all species, except eel where the relationship was negative, and bluegill sunfish where there was no significant relationship.

The positive relationship between fish mass and mercury suggests that consumers that eat larger fish would have higher exposure to mercury than those that eat smaller fish. Thus, mammals (i.e., raccoon; Burger, 1999) and birds (i.e., osprey *Pandion haliaetus*, or eagles) that eat large fish would be exposed to relatively high mercury loads, allowing for bioaccumulation at still higher trophic levels.

The species selected for this study include species that the local human populations also catch and eat (Burger, 1998; Burger *et al*., 1990). The positive relationship between fish weight and mercury levels suggests that consumers, including people, could reduce their exposure to mercury by eating smaller fish.

Comparisons with Other Geographical Locations

Comparing mercury and selenium levels with fish studies from elsewhere provides a method of assessing relative habitat degradation. Bioaccumulation of metals in fish is a function of metal bioavailability (which can vary by pH), uptake, and toxicokinetics (Spry and Wiener, 1991). Mercury uptake is enhanced by increased water temperatures, reduced salinity, reduced pH, and increased presence of zinc and cadmium (Eisler, 1987).

According to the National Contaminant Biomonitoring Program (NCBP) of fish collected at 109 stations nationwide, concentrations of most heavy metals and selenium declined from 1976 through 1984 (Schmitt and Brumbaugh, 1990). However, the NCBP measured contaminant loads in entire fish, including stomach contents, scales, and bones. Many other studies have done likewise. While this provides a useful method for comparing levels among species, it limits the utility for assessing risks to humans, particularly since stomach contents can bias estimates downward (Burger and Snodgrass, 1998). We measured contaminant levels only in muscle. The use of both dry and wet weights in the literature further complicates comparisons. In general we found that concentrations expressed on a wet weight basis are about 18% of the level expressed as dry weight (with slight differences in moisture content among species).

There are numerous studies of mercury levels in fish, largely because of the potential health hazards from fish consumption (EPA, 1980; Lange *et al*.,

TABLE 4
Comparative Mercury Levels in Fish Tissue

Species	Location	Level (μg/g wet weight)	Reference
Largemouth bass	San Joaquin, California[a]	0.17	Saiki *et al*., 1992a
	Midwestern U.S.	0.09–0.36	Downs *et al*., 1998
	Ontario (14 lakes)	0.46 (0.27–0.87)	Wiener and Spry, 1996
	Oregon lakes	0.3 to > 1.0	Park and Curtis, 1997
	Maryland lakes	0.04–0.43	Pickney *et al*., 1997
	Florida lakes	0.16–1.1	Lange *et al*., 1994
	Lake Tohopekaliga, FL	0.6	Lange *et al*., 1994
	Lake Jacassee, SC	2.9	Wiener and Spry, 1996
	Missouri gulf course[b]	0.43–7.1	Wiener and Spry, 1996
Yellow perch	Idaho	0.23	Kent and Johnson, 1979
	Ontario	0.37	Downs *et al*., 1998
	Finland	Up to 0.6	Verta, 1990
	Russia	0.10–0.78	Haines *et al*., 1994
Bluegill sunfish	San Joaquin, California[a]	0.08	Saiki *et al*., 1992a
	Lake Tohopekaliga	0.09	Lange *et al*., 1994
	Maryland	0.01 to 0.38	Pickney *et al*., 1997
	England	0.1	Downs *et al*., 1998
	England	0.32–1.38	Collings *et al*., 1996

Note: Given are means or range or means for different water bodies.
[a]Whole body analysis (all others are edible muscle).
[b]Treated with mercury fungicide.

1994), or because sources of anthropogenic mercury have raised concerns (Wiener and Spry, 1996). Established background levels for fish are often given as 0.2 to 1.0 μg/g, which exceeds the preindustrial level (0.15 μg/g; Downs *et al*., 1998). The National Contaminant Biomonitoring Program reported mean mercury levels of 0.11 μg/g in freshwater fish collected in the late 1970s (Lowe *et al*., 1985). Whole body burdens of mercury in fish from the United States overall average 0.10 μg/g, with the maximum average being 0.37 μg/g (Schmitt and Brumbaugh, 1990). Wiener and Spry (1996) reported that mean mercury concentrations in muscle from piscivorous fish species ranged from 0.35 to 6.7 μg/g (wet weight).

It is more useful to compare mercury levels in specific fish (Table 4). In general, mercury levels average from 0.09 to 7.1 μg/g for largemouth bass, from 0.23 to 0.78 μg/g for yellow perch, 0.1 to 1.38 μg/g for eel, and 0.01 to 0.38 μg/g for bluegill sunfish. Comparable values for the fish we collected from the Savannah River were 0.46, 0.28, 0.14, and 0.15 μg/g, respectively, falling within the range of those reported generally.

Selenium concentrations from fish in the United States overall range from 0.7 to 0.82 μg/g (whole body, wet weight; Schmitt and Brumbaugh, 1990), although levels in the contaminated San Joaquin River in California ranged as high as 6.4 μg/g (whole body, dry weight = wet weight of approximately 1.1 μg/g) in bluegill and 6.8 μg/g in bass (whole body, dry weight, wet weight of approximately 1.2 μg/g; Saiki *et al*., 1993). Fish from the Savannah River averaged from 0.21 to 0.64 μg/g, within the range reported from elsewhere.

Levels and Effects

Mercury is toxic to all organ systems, particularly the nervous system, and is also a mutagen, a teratogen, and possibly a carcinogen that can also cause growth deficits, locomotory and coordination impairments, loss of appetite, lowered reproductive success, and, ultimately, death (Eisler, 1987; Wiener and Spry, 1996). Mercury levels of 5 μg/g (wet weight) in muscle have been associated with emaciation, decreased locomotion, decreased coordination, loss of appetite, and mortality in some fish, while levels of 15 μg/g are required for these effects in other species (Wiener and Spry, 1996). The mercury levels in fish from the Savannah River average 0.13 to 0.94 μg/g, depending upon species; thus overall they pose no obvious problem for the fish themselves, although some individuals may acquire toxic levels.

For sensitive birds that consume fish, harmful effects can occur at mercury levels of 0.05 to 0.5 μg/g

in the diet; for sensitive mammals, harmful effects can occur at levels of 1.1 μg/g in diet (Eisler, 1987; WHO, 1990, 1991). Thus the mercury levels in the fish from the Savannah River could potentially pose a health hazard for some piscivorous species, particularly if they repeatedly ate the larger individuals of some species, such as bowfin and bass.

Selenium is an essential micronutrient in animals, but above the relatively low normal physiological requirements, it can be toxic, can cause reproductive abnormalities, anemia, and growth retardation (Eisler, 1985), and can reduce the survival of fry of exposed parents, ultimately leading to population declines in fish (Saiki *et al*., 1992a, b; Coyle *et al*., 1993). Sublethal effects include altered locomotory behavior, decreased growth, edema and abnormal development, reproductive failures (Lemly, 1993a, b), and hematological dyscrasia (Sorensen and Bauer, 1983). Selenium effects are more severe at low temperatures, when it causes hematological changes and gill damage that lead to reduced activity and feeding, and ultimately death (Lemly, 1993a). A concentration of 4 μg/g wet weight is the threshold for selenium toxicity involving reproductive failures in some fish (Lemly and Smith, 1987), although more sensitive fish show effects at 1–2 μg/g (Hamilton *et al*., 1990). Muscle levels of 2.6 μg/g wet weight (8 μg/g dry weight) are associated with adverse effects in fish themselves (Lemly, 1993a). Further, selenium levels of 1 μg/g wet weight (5 μg/g dry weight) are toxic to other fish and wildlife that consume them (Lemly, 1993a). Thus, the selenium levels in the fish from the Savannah River (average of up to 0.75 μg/g in red-breasted sunfish) are not likely to produce adverse effects on the fish themselves or on the wildlife organisms that consume them.

CONCLUSIONS

There were species differences in mercury and selenium levels in fish from the Savannah River that reflect trophic level relationships. However, mercury levels increased with trophic level, while selenium decreased with trophic level of the fish. Within a species, mercury and selenium were positively correlated only for bass, perch, and red-breasted sunfish. In general, mercury levels were positively correlated with body mass, indicating that larger and older fish bioaccumulate mercury. These observations suggest that within fish communities, mercury levels reflect trophic level relationships, and increase with the age of the fish, which in turn would lead to further bioaccumulation in mammals or birds consuming large fish. The mercury and selenium levels in fish from the Savannah River are generally similar to or below those reported for the same species from elsewhere and, except for bowfin and bass, are generally below those known to cause ill-effects in consumers.

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REFERENCES

Ashley, C., and Zeigler, C. C. (1980). "Releases of Radioactivity at the Savannah River Plant, 1954 through 1978." E. I. DuPont de Nemours and C. Report, SPU 75-25-1.

ATSDR (1995). "Toxicological Profile for Selenium." Agency for Toxic Substances and Disease Research, Centers for Disease Control and Prevention, Atlanta, GA.

Baker, O. E., III, and Carmichael, D. B. Jr., (1989). "South Carolina's Furbearer's." South Carolina Dept. Natural Res. Columbia, SC.

Barron, M. G. (1995). Bioaccumulation and bioconcentration in aquatic organisms. *In* "Handbook of Ecotoxicology" (D. J. Hoffman, B. A. Rattner, G. A. Burton, Jr., and J. Cairns, Jr., Eds.), pp. 625–666. Lewis, Boca Raton, FL.

Berlin, M. (1978). Interactions between selenium and inorganic mercury. *Environ. Health Perspect.* **25,** 67–69.

Bidone, E. D., Castilhos, Z. C., Santos, T. J. S., Souza, T. M. C., and Lacerda, L. D. (1997). Fish contamination and human exposure to mercury in Tartarugalzinho River, Northern Amazon, Brazil. A screening approach, *Water*, *Air*, *Soil Pollut.* **97,** 9–15.

Bradley, R. W., and Sprague, J. B. (1985). Accumulation of zinc by rainbow trout as influenced by pH, water hardness, and fish size. *Environ. Toxicol. Chem.* **4,** 106–117.

Braune, B. M. (1987). Mercury accumulation in relation to size and age of Atlantic herring (*Clupea harengus harengus*) from the southwestern Bay of Fundy, Canada. *Arch. Environ. Contam. Toxicol.* **16,** 311–320.

Brezonik, P. K., King, S. O., and Mach, C. E. (1991). The influence of water chemistry on trace metal bioavailability and toxicity in aquatic organisms. *In* "Metal Ecotoxicology" (M. D. Newman and A. W. McIntosh, Eds.), Lewis, Boca Raton, FL.

Bryan, G. W., and Langston, W. J. (1992). Bioavailability, accumulation and effects of heavy metals in sediments with special reference to the United Kingdom estuaries: A review. *Environ. Pollut.* **76,** 89–95.

Burger, J. (1998). Fishing and risk along the Savannah River: Possible intervention. *J. Toxicol. Environ. Health* **55,** 405–419.

Burger, J. (1999). "Interactions of Animals in Towns and Cities." Kendall-Hunt, Dubuque, IA.

Burger, J., and Snodgrass, J. (1998). Heavy metals in bullfrog (*Rana catesbeiana*) tadpoles: Effects of depuration before analysis. *Environ. Toxicol. Chem.* **17,** 2203–2209.

Burger, J., Stephens, W. L., Jr., Boring, C. S., Kulkinski, M., Gibbons, J. W., and Gochfeld, M. (1999). Factors in exposure assessment: Ethnic and socioeconomic differences in fishing and consumption of fish caught along the Savannah River. *Risk. Anal.* **19,** 421–431.

Campbell, K. R. (1994). Concentrations of heavy metals associated with urban runoff in fish living in stormwater treatment Ponds. *Arch. Environ. Contam. Toxicol.* **27,** 352–356.

Caurant, F., Amiard, J. C., Amiard-Triquet, C., and Sauriau, P. G. (1994). Ecological and biological factors controlling the concentrations of trace elements (As, Cd, Cu, Hug, Se, Zn) in delphinids *Globicephala melas* from the North Atlantic Ocean. *Mar. Ecol. Prog. Ser.* **103,** 207–219.

Collings, S. E., Johnson, M. S., and Leah, R. T. (1996). Metal contamination of angler-caught fish from the Mersey Estuary. *Mar. Environ. Res.* **41,** 281–297.

Coyle, J. J., Buckler, D. R., Ingersoll, C. G., Fairchild, J. F., and May, T. W. (1993). Effects of dietary selenium on the reproductive success of bluegills (*Lepomis macrochirus*). *Environ. Toxicol. Chem.* **12,** 551–565.

Denton, G. R. W., and Burdon-Jones, C. (1986). Trace metals in fish from the Great Barrier Reef. *Mar. Pollut. Bull.* **17,** 201–209.

DOE (1995). "Closing the Circle on the Splitting of the Atom: The Environmental Legacy of Nuclear Weapons Production in the United States and What the Department of Energy Is Doing About It." Office of Environmental Management, U.S. Department of Energy, Washington, DC.

Downs, S. G., Macleod, C. L., and Lester, J. N. (1998). Mercury precipitation and its relation to bioaccumulation in fish: A literature review. *Water Air Soil Pollut.* **108,** 149–187.

Eisler, R. (1985). "Selenium Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review." U.S. Fish and Wildlife Service Rep. 85(1.5), Washington, DC.

Eisler, R. (1987). "Mercury Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review." U.S. Fish and Wildlife Service Rep. 85(1.10), Washington, DC.

Environmental Protection Agency (EPA) (1980). "Ambient Water Quality Criteria for Mercury." U.S. Environmental Protection Agency Report 440/5-80-058. Natl. Tech. Inform. Serv., 5285, Port Royal Road, Springfield, VA.

Fairey, R., Taberski, K., Lamerdin, S., Johnson, E., Clark, R. P., Downing, J. W., Newman, J., and Petreas, M. (1997). Organochlorines and other environmental contaminants in muscle tissue of sportfish collected from San Francisco Bay. *Mar. Pollut. Bull.* **34,** 1058–1071.

Fimreite, N. (1979). Accumulation and effects of mercury in birds. *In* "The Biogeochemistry of Mercury in the Environment" (J. O. Nriagu, Ed.), pp. 601–627. Elsevier, Amsterdam.

Ganther, H. E., Goudie, C., Sunde, M. L., Kopecky, M. J, Wagner, R., Sang-Hwang, O. H., and Hoekstra, W. G. (1972). Selenium relation to decreased toxicity of methylmercury added to diets containing tuna. *Science* **72,** 1122–1124.

Haines, T. A., Komov, V. T., and Jagoe, C. H. (1994). Mercury concentration in perch (*Perca fluviatilis*) as influenced by lacustrine physical and chemical factors in two regions of Russia. *In* "Mercury in the Environment." (C. J. Waters and J. W. Huckabee, Eds.), pp. 397–407, Lewis, Boca Raton, FL.

Hamilton, S. J., Buhl, K. J., Faerber, N. I., Wiedmeyer, R. H., and Bullard, F. A. (1990). Toxicity of organic selenium in the diet to chinook salmon. *Environ. Toxicol. Chem.* **9**, 347–358.

Hansen, J. C. (1988). Has selenium a beneficial role in human exposure to organic mercury? *Med. Hypoth.* **25,** 45–53.

Hayton, W. L., and Barron, M. G. (1990). Rate limiting barriers to xenobiotic uptake by the gill. *Environ. Toxicol. Chem.* **9,** 151.

Heinz, G. H. (1996). Selenium in birds. *In* "Environmental Contaminants in Wildlife: Interpreting Tissues Concentrations" (W. N. Beyer, G. H. Heinz, and A. W. Redmom-Norwood, Eds.), pp. 447–458. Lewis, Boca Raton, FL.

Hodson, P. V. (1998). The effect of metal metabolism on uptake, disposition and toxicity in fish. *Aquat. Toxicol.* **11,** 3–11.

Jensen, S., and Jernelow, A. (1969). Biological methylation of mercury in aquatic organisms. *Nature* **223,** 753–754.

Kennamer, R. A., Brisbin, I. L., Jr., McCreedy, C. D., and Burger, J. (1998). Radiocesium in mourning doves foraging on the exposed lakebed of a contaminated reactor-cooling reservoir: Risk to human consumers. *J. Wildl. Manage.* **62,** 487–508.

Kent, J. C., and Johnson, D. W. (1974). Mercury, arsenic, and cadmium in fish, water, and sediment of American Falls Reservoir, Idaho, 1974. *Pestic. Monit. J.* **13**, 35–40.

Klaverkamp, J. F., Macdonald, W. A., Lillie, W. R., and Lutz, A. (1983). Joint toxicity of mercury and selenium in salmonid eggs. *Arch. Environ. Contam. Toxicol.* **12,** 415–419.

Kuehl, D. W., and Haebler, R. (1995). Organochlorine, organobromine, metal, and selenium residues in bottlenose dolphin (*Tursiope truncatus*) collected during an unusual mortality event in the Gulf of Mexico, *Arch. Environ. Contam. Toxicol.* **28,** 494–499.

Kvartek, E. J., Carlton, W. H., Denham, M., Eldridge, L., and Newman, M. C. (1994). "Assessment of Mercury in the Savannah River Site Environment." Westinghouse Savannah River Co. (WSRC-TR-94-0218ET), Aiken SC.

Lacerda, L. D., Bidone, E. D., Giumaraes, A. F., and Pfeiffer, W. C. (1994). Mercury concentrations in fish from the Itacaiunas–Parauapebas River System. Carajas region. *Amazon Ann. Acad. Bras. Sci.* **66,** 373–379.

Lange, T. R., Royals, H. E., and Connor, L. L. (1994). Mercury accumulation in largemouth bass (*Micropterus salmoides*) in a Florida Lake. *Arch. Environ. Contam. Toxicol.* **27,** 466–471.

Lemly, D. A. (1993a). Guidelines for evaluating selenium data from aquatic monitoring and assessment studies. *Environ. Monit. Assess.* **28,** 83–100.

Lemly, D. A. (1993b). Metabolic stress during winter increases the toxicity of selenium to fish. *Aquat. Toxicol.* **27,** 133–158.

Lemly, D. A., and Smith, G. J. (1987). Aquatic cycling of selenium: Implications for fish and wildlife. U.S. Fish and Wildlife Service Fish and Wildlife Leaflet, 12.

Lowe, T. P., May, T. W., Brumbaugh, W. G., and Kane, D. A. (1985). National contaminant biomonitoring program: Concentrations of several elements in freshwater fish, 1978–1981. *Arch. Environ. Contam. Toxicol.* **14,** 363–388.

OTA (1991). "Complex Cleanup: The Environmental Legacy of Nuclear Weapons Production." OTA-O484. U.S. Govt. Printing Office, Washington, DC.

Park, J. G., and Curtis, L. R. (1997). Mercury distribution in sediments and bioaccumulation by fish in two Oregon reservoirs: Point-source and nonpoint-source impacted systems. *Arch. Environ. Contam. Toxicol.* **33,** 423–429.

Phillips, G. R., Lenhart, T. E., and Gregory, R. W. (1980). Relations between trophic position and mercury accumulation among fishes from the Tongue River Reservoir, Montana. *Environ. Res.* **22,** 73–80.

Pinkney, A. E., Logan, D. T., and Wilson, H. T. (1997). Mercury concentration in pond fish in relation to a coal-fired power plant. *Arch. Environ. Contam. Toxicol.* **33,** 222–229.

Redmayne, A. C., Kim, J. P, Closs, G. P., and Hunter, K. A. (2000). Methyl mercury bioaccumulation in long-finned eels, *Anguilla dieffenbachii*, from three rivers in Otago, New Zealand, *Sci. Total Environ.* **262,** 37–47.

Rowe, L. C., Kinney, O. M., Flori, A. P., and Congdon, J. D. (1996). Oral deformities in tadpoles (*Rana catesbeiana*) associated with coal ash deposition: Effects on grazing ability and growth. *Freshwater Biol.* **36,** 723–730.

Saiki, M. K., Jennings, M. R., and Ma, T. W. (1992a). Selenium and other elements in freshwater fishes from the irrigated San Joaquin valley, California. *Sci. Total Environ.* **126,** 109–137.

Saiki, M. K., Jennings, M. R., and Wiedmeyer, R. H. (1992b). Toxicity of agricultural subsurface drainwater from the San Joaquin valley, California, to juvenile chinook salmon and striped bass. *Trans. Am. Fish Soc.* **121,** 78–93.

Satoh, H., Yasuda, N., and Shimai, S. (1985). Development of reflexes in neonatal mice prenatally exposed to methylmercury and selenite. *Toxicol. Lett.* **25,** 199–203.

Schmitt, C. J., and Brumbaugh, W. G. (1990). National contaminant biomonitoring program: Concentrations of arsenic, cadmium, copper, lead, mercury, selenium and zinc in U.S. Freshwater fish, 1976–1984. *Arch. Environ. Contam. Toxicol.* **19,** 731–747.

Snodgrass, J. W., Jagoe, C. H., Bryan, A. L., Jr., and Burger, J. (2000). Effects of trophic status, and wetland morphology, hydroperiod and water chemistry on mercury concentrations in fish. *Can. J. Fish Aquat. Sci.* **57,** 171–180.

Sorensen, E. M. B., and Bauer, T. L. (1983). Hematological dysrasia in toleosts chronically exposed to selenium-laden effluent. *Arch. Environ. Contam. Toxicol.* **12,** 135–141.

Spry, D. J., and Wiener, J. G. (1991). Metal bioavailability and toxicity to fish in low-alkalinity lakes: A critical review. *Environ. Pollut.* **71,** 243–304.

Statistical Analysis System (SAS) (1995). "SAS Users' Guide." Statistical Institute, Cary, NC.

Sugg, D. W., Chesser, R. K., Brooks, J. A., and Grasman, B. T. (1995). The association of DNA damage to concentrations of mercury and radiocesium in largemouth bass. *Environ. Toxicol. Chem.* **14,** 661–668.

Sydeman, W. J., and Jarman, W. M. (1998). Trace metals in seabirds, Steller sea lion, and forage fish and zooplankton from central California. *Mar. Pollut. Bull.* **36,** 828–832.

Tayel, F. T. R., and Shriadah, M. M. A. (1996). Fe, Cu, Mn, Pb and Cd in some fish species from Western Harbour of Alexandria, Egypt. *Bull. Natl. Inst. Oceanogr. Fish* **22,** 85–96.

Verta, M. (1990). Changes in fish mercury concentrations in an intensively fished lake. *Can. J. Fish Aquat. Sci.* **47,** 1888–1897.

Wagemann, R., Innes, S., and Richard, P. R. (1996). Overview and regional and temporal differences of heavy metals of whales and ringed seals in the Canadian Arctic. *Sci. Total Environ.* **186,** 41–66.

Walsh, P. M. (1990). The use of seabirds as monitors of heavy metals in the marine environment. *In* "Heavy Metals in the Marine Environment." (R. W. Furness and P. S. Rainbow, Eds.), pp. 183–204. CRC Press, Boca Raton, FL.

Watras, C. J., Back, R. C., Halvorsen, S., Hudson, R. J. M., Morrison, K. A., and Wente, S. P. (1998). Bioaccumulation of mercury in pelagic freshwater food webs. *Sci. Total Environ.* **219,** 183–208.

Westinghouse (1998). "Savannah River Site: Environmental Report for 1998." Westinghouse Savannah River Corp., Aiken, SC.

Whicker, R. W., Pinder, J. E., III, Bowling, J. W., Alberts, J. J., and Brisbin, I. L., Jr. (1990). Distribution of long-lived radionuclides in an abandoned reactor cooling reservoir. *Ecol. Monogr.* **60,** 471–496.

Wiener, J. G., and Spry, D. J. (1996). Toxicological significance of mercury in freshwater fish. *In* "Environmental Contaminants in Wildlife: Interpreting Tissues Concentrations" (W. N. Beyer, G. H. Heinz, and A. W. Redmom-Norwood, Eds.), pp. 297–339. Lewis, Boca Raton, FL.

Workman, S. W., and McLeod, K. W. (1990). "Vegetation of the Savannah River Site: Major Community Types." Publication SRO-NERP-19, Savannah River Ecol. Laboratory, Aiken, SC.

World Health Organization (WHO) (1990). IPCS-methylmercury. *Environ. Health Criteria* **101,** 42–58.

World Health Organization (WHO) (1991). IPCS-inorganicmercury. *Environ. Health Criteria* **101,** 42–58.

Zillioux, E. J., Porcella, D. B., and Benoit, J. M. (1993). Mercury cycling and effects in freshwater ecosystems. *Environ. Toxicol. Chem.* **12,** 2245–2264.