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Mercury Accumulation in Relation to Size and Age of Atlantic Herring (*Clupea harengus harengus*) from the Southwestern Bay of Fundy, Canada

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Abstract. Measured muscle and whole fish total mercury concentrations showed significant positive correlations with age, weight and length, in order of decreasing correlation. Within herring age classes, however, muscle and whole fish mercury concentrations showed significant negative correlations with weight and length due to a 'growth dilution' effect in 1- and 2-year-old herring, but demonstrated positive correlations with weight and length in 3- to 5-year-old fish. A bioenergetics-based pollutant accumulation model was used to describe total mercury accumulation for the commercially valuable Atlantic herring aged 3 to 5 years with the predicted values falling within one standard deviation of the measured annual body burdens.

The Atlantic herring (*Clupea harengus harengus*) is a migratory, pelagic species of great ecological and commercial importance in the Bay of Fundy (Iles 1979). The Quoddy region in the southwestern Bay of Fundy supports one of the largest inshore herring fisheries in eastern Canada (Iles 1975). Also, herring constitute a large part of the food base for resident and migratory seabirds and marine mammals in the region (Gaskin and Smith 1979). High levels of mercury have been recorded in some marine mammals (Gaskin *et al.* 1973, 1979) which feed extensively on Atlantic herring; yet, little is known of the mechanisms of transport of heavy metal pollutants in the Fundy ecosystem or of the relationship of environmental levels of pollutants with those accumulated in herring tissues.

Positive correlations have been found between mercury concentration in marine fish in relation to body weight (Fimreite *et al.* 1971; Cocoros *et al.* 1973; Cross *et al.* 1973; Suzuki *et al.* 1973), length (Barber and Cross 1972; De Clerck *et al.* 1974; Cutshall *et al.* 1978; Barber and Whaling 1983), and age (Cocoros *et al.* 1973; Westöö 1973; De Clerck *et al.* 1974; Perttilä *et al.* 1982). Other studies, however, have found no significant relationship between mercury concentration and fish body weight (Freeman *et al.* 1974), length (Scott 1977), or age (Pentreath 1976). The primary objectives of this study are to establish whether or not relationships exist between weight, length or age, and total mercury concentration in Atlantic herring, and to determine whether or not a model for total mercury accumulation developed for freshwater fish is applicable to a sampled population of marine fish, specifically Atlantic herring.

Several approaches to the modelling of uptake and clearance of pollutants by fish have been presented in the literature (Fagerström and Asell 1973; Norstrom *et al.* 1976; Aoyama *et al.* 1978; Thomann 1981). Although these models vary in complexity, all incorporate both a food and water component, and a pollutant clearance component for pollutant accumulation. The major difficulty with most lies in the assignment of values to parameters and constants. Norstrom *et al.* (1976) discussed, in detail, the derivation of their values, facilitating tests with field data from other fish species to determine the general applicability of this form of bioenergetics-based model. It was their model, therefore, which was used to establish the value of this type of model using data from Atlantic herring.

Materials and Methods

Sampling Procedures

Zooplankton—During the period of June–September 1981, 55 zooplankton samples were collected from five surface stations in

the Quoddy region. At the sampling site, a subsurface, horizontal tow was made, using a 0.5 m diameter plankton net with 0.4 mm mesh. Copepods were sorted from the plankton samples, double-bagged in polyethylene bags, and frozen to −20°C.

Herring—Samples of herring caught in weirs off the east coast of Campobello Island (44°54′ N, 66°53′ W) and near Fish Island (45°00′ N, 66°56′ W) on 14 and 23 July 1981, respectively, were randomly selected from fresh landings at the Connors Bros. Fairhaven processing plant on Deer Island, New Brunswick. Young herring (spawned the previous autumn), obtained by the Biological Station in St. Andrew's, New Brunswick, were collected 6 July 1981 by trawl off Negro Head (45°11′ N, 66°09′ W) south of Saint John, New Brunswick. Additional samples of young herring were collected 14 August 1981 by dip net in Letete Passage (45°03′ N, 66°55′ W).

Herring taken from the processing plant were rinsed with fresh water to remove any packing salt. Wet weight and standard length were measured, and otoliths removed for age determination. Stomachs from 40 young herring collected in Letete Passage were removed and the contents preserved in 70% alcohol for subsequent identification. Stomachs were not removed from weir-caught herring as it is common practice among fishermen to leave fish in weirs for several days to allow clearance of the digestive tract to simplify processing. After measurements and removal of stomachs and otoliths were completed, all fish were individually stored in polyethylene bags and frozen to −20°C.

Because of sample size variation between age classes, subsamples of 1- and 2-year-old herring, and all 3–5-year-old herring were filleted prior to mercury analysis. Muscle and whole fish mercury concentrations, therefore, could be analyzed for different individuals of 1- and 2-year-old herring, whereas muscle and body with muscle removed were analyzed for the same individuals of 3–5-year-old herring. Fillets were weighed so that muscle weight fraction of the whole fish could be calculated for 3–5-year-old herring.

Mercury Analysis

Total mercury concentrations for the collected copepod and herring samples were analyzed by cold vapor atomic absorption spectrophotometry after the method of Hatch and Ott (1968). A 3–5 g sample (wet weight) was digested in a 4:1 mixture of concentrated sulphuric:nitric acid agitated in a shaker bath at 63–65°C for one hour. The organo-mercury bonds were oxidized with potassium permanganate in order to convert all mercury present to Hg^{2+}. The sample solutions were further agitated for another two hours. Excess oxidizer was reduced with hydroxylamine sulphate to reduce adsorption of mercury on the glass walls of the apparatus. Metallic mercury was released with stannous sulphate. The elemental mercury was driven from solution by a stream of nitrogen and carried through an absorption cell where the cold vapor was measured at 253.7 nm using a flameless atomic absorption spectrophotometer (Pharmacia UV optical unit) attached to a recorder. Mercury recovery was 98–105%.

Data Analysis

Since collections of 1-year-old herring were made before and after collections of 2–5-year-olds, the two collections of 1-year-old herring were pooled to generate average values comparable in time with the 2–5-year-olds. Mercury concentrations of whole fish were calculated for 3–5-year-old herring by normalizing the concentration of mercury in muscle and in whole body minus muscle to that in the whole body (see Sampling Procedures—Herring). Muscle and whole fish mercury concentrations within each age class were compared, using t-tests (Bailey 1959). Length, weight, age, muscle weight fraction, muscle mercury concentration, and whole fish mercury concentration within and across all age classes were analyzed, using simple linear regressions.

Mercury Accumulation Model

The bioenergetics-based model for pollutant accumulation by fish developed by Norstrom *et al.* (1976) was the model for mercury accumulation applied to Atlantic herring in this paper. The complete model equation used by those authors was:

$$(dP/dt) = \frac{e_{pw}C_{pw}}{e_{ox}C_{ox}q_{ox}}(\alpha W^{\gamma} + \beta\,(dW/dt)) + \left[\frac{e_{pf}C_{pf}}{e_f} \times (\alpha W^{\gamma} + (\beta + 1)\,(dW/dt))\right] - k_{el}PW^{\zeta} \quad (1)$$

which, simplified, reads:

rate of change of pollutant body burden = uptake rate from water + uptake rate from food − clearance rate

Parameters of Growth and Metabolism

Most herring growth is assumed to occur during only approximately one half of the year, May–October (Sinclair *et al.* 1982). To account for the variation over annual energy requirements, the year has been divided into three time periods where T_1 = 13 weeks (August–October), T_2 = 26 weeks (November–April), and T_3 = 13 weeks (May–July). T_0 is the time of sampling (mid-July). Larval herring in the Bay of Fundy are spawned from late August to late October (Das 1972). The model therefore assumes only six weeks of growth during T_1 for 0–1-year-old herring. T_2 is assumed to be a period of no growth for all age classes. It follows, then, that the average weekly growth increment, (dW/dt), may be calculated by dividing the annual weight change by 26 weeks of growth or, in the case of 0–1-year-old herring, 19 weeks of growth (Table 1).

Conversion efficiency is defined as the percentage of the ingested food material that is converted into fish flesh (De Silva and Balbontin 1974). Interpolation of data given by those authors results in a conversion efficiency of 9% for young herring at 10°C. This value was used for 0–2-year-old herring. Mathematically, net conversion efficiency, E_n, is defined as:

$$E_n = \frac{(dW/dt)}{R - R_{maint}} \quad (2)$$

where (dW/dt) is the growth rate, R is the total ration, and R_{maint} is the maintenance ration (Norstrom *et al.* 1976). Using this relationship and energy requirement data given for 2–8-year-old Baltic herring (*Clupea harengus membras*) at 10°C (Chekunova 1980), net conversion efficiency was calculated as 8% for 2–3-year-olds, 6% for 3–4-year-olds, and 5% for 4–5-year-olds.

Table 1. Weight and growth parameters of Atlantic herring from the southwestern Bay of Fundy

Age (yrs)	Mean wt[a] ($\overline{W}$) (g)			Actual wt[b] (g)	Growth rate	
	T_1	T_2	T_3	T_0	(dW/dt)[c] (g/wk)	% Body wt
0–1[d]	0.5	0.9	1.9	2.8[e]	0.15	100
1–2	14.0	25.2	36.3	47.4	1.72	94
2–3	64.8	82.2	99.7	117.2	2.68	60
3–4	126.0	134.9	143.7	152.6	1.36	23
4–5	158.8	165.1	171.3	177.6	0.96	14

[a] Mean weight calculated from actual weights and weight change over time for two growth periods (T_1, T_3) and one non-growth period (T_2) where T_1 = 0–13 wks, T_2 = 14–39 wks, T_3 = 40–52 wks
[b] Actual weight taken at end of year; T_0 = July
[c] Weight change over time is based on 26 weeks of growth during the year
[d] Autumn spawning occurs during late August-late October; therefore, assume only six weeks growth during T_1
[e] Average of weight means from two sampling periods for young herring

The proportionality constant, β, which relates growth rate to energy associated with growth, may be expressed by:

$$\beta = \frac{e_f}{E_n} - 1 \tag{3}$$

where e_f is the efficiency of assimilation of metabolizable energy from food (Norstrom *et al.* 1976). The value of 0.82 is used for energy uptake from food (Beamish *et al.* 1975). The calculated values of β are as follows: 8.1 = 8.0 for 0–2-year-old herring, 9.4 = 9.0 for 2–3-year-olds, 12.7 = 13.0 for 3–4-year-olds, and 15.4 = 15.0 for 4–5-year-olds. If both food and deposited tissue are assumed to have a caloric equivalent of 1 kcal/g wet weight (1 kcal = 4.186 kJ), then [(β + 1) (dW/dt)] is the sum of the caloric content of the deposited tissue and the energy required to deposit the tissue (Norstrom *et al.* 1976).

The metabolic component, Q, in the water and food vectors is described by the generally accepted empirical expression:

$$Q = \alpha W^{\gamma} \tag{4}$$

where α is the level of metabolism and γ is the exponent of body weight, W. Norstrom *et al.* (1976) use γ = 0.81 as giving a reasonable approximation of body weight dependence of total energy metabolism for most fish. Chekunova (1980), however, showed that the body weight exponent comes close to unity (γ = 0.978) in the 2–8-year-old Baltic herring. Although De Silva and Balbontin (1974) determined γ = 0.773 for young herring (0–1-year-old), their calculations were based on a relatively limited weight range of fish. Therefore, based on Chekunova's (1980) work, γ = 0.98 is used in the model.

The value of α varies with temperature. Chekunova (1980) gave an average value of α = 0.306 for Baltic herring at 10°C. The mean offshore water temperatures (average of bottom and surface temperatures) in the Quoddy region during the three time periods considered are as follows: T_1 = 11.0°C, T_2 = 5.0°C, and T_3 = 6.0°C (Trites and Garrett 1983). Adjustment of α to these temperatures using Winberg's (1956) table of temperature coefficients gives α_{T1} = 0.334, α_{T2} = 0.134, and α_{T3} = 0.167.

The mean weights calculated for use in each of the three time periods are given in Table 1. The units of Q (ml O_2/hr) may be converted to energy units, assuming that the consumption of 1 ml O_2 is equivalent to the release of 5 calories (Winberg 1956).

Accumulation of Mercury from Water

Volume of water flow past the gills per unit time, V, is calculated by:

$$V = \frac{1}{e_{ox}C_{ox}q_{ox}} (\alpha W^{\gamma} + \beta (dW/dt)) \tag{5}$$

where e_{ox} is the efficiency of assimilation of oxygen from the water by the gills, C_{ox} is the concentration of oxygen in the water, and q_{ox} is the caloric equivalent of oxygen. The metabolic function, αW^{γ}, and the growth function, β (dW/dt), have already been described. The estimated efficiency of oxygen clearance from the water is e_{ox} = 0.75 (Lloyd 1961), and the caloric equivalent of oxygen was assumed to be q_{ox} = 3.42 kcal/g (Winberg 1956). The average oxygen concentration in the well-mixed upper 100 m of sea water is C_{ox} = 9.6 μg/ml (Broecker 1974). Therefore, mercury utpake from the water per unit time, $(dP/dt)_w$, may be described by:

$$(dP/dt)_w = e_{pw}C_{pw}V \tag{6}$$

where e_{pw} is the efficiency of pollutant transfer across the gills and C_{pw} is the concentration of pollutant in the water. Methylmercury is the form most readily accumulated in tissues of fish (Olson *et al.* 1973; Pentreath 1976). Norstrom *et al.* (1976) used e_{pw} = 0.12 for methylmercury and Phillips *et al.* (1980) support the use of this value.

In nearshore coastal waters of the southeastern United States, total mercury concentrations are generally uniformly low, varying from 10 to 100 ng/L (Windom 1973). The minimum end of this range agrees favorably with Fitzgerald and Lyons' (1975) value of 8 ng/L total mercury in northwest Atlantic waters. Due to the large tidal incursions in the Bay of Fundy, there is substantial mixing with Atlantic Ocean waters. Therefore, the waters of the Quoddy region are assumed to contain a total mercury concentration of 10 ng/L. Only methylmercury, however, is taken up from the water to any extent. The total methylmercury concentration in ocean waters is 0.88% or approximately 1% of the total mercury concentration (Topping and Davies 1981). Therefore, 1% of 10 ng/L was used to give a methylmercury concentration in sea water of 0.1 ng/L.

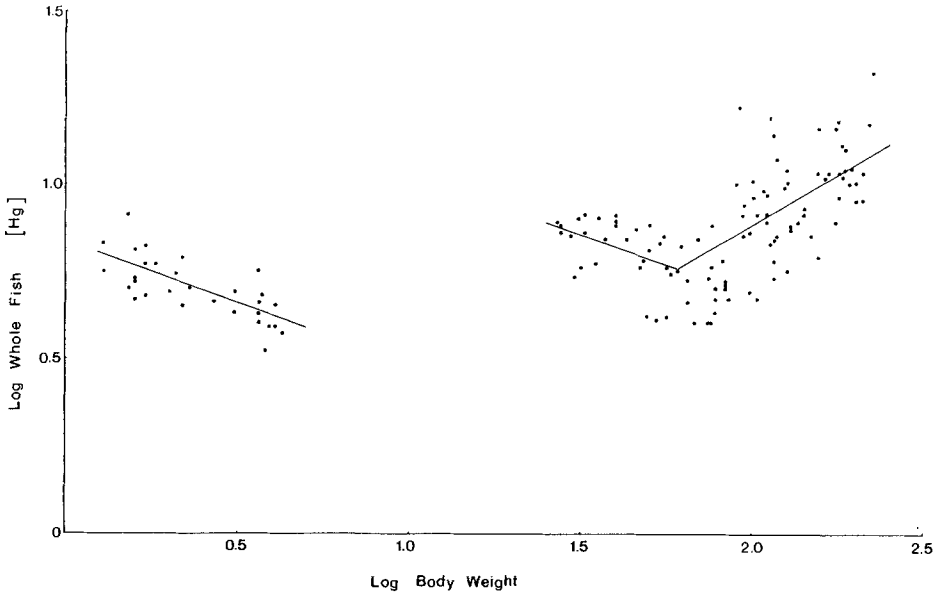

Fig. 1. Log/log transformation of mercury concentration [Hg] (ng/g) in herring vs body weight (g) of Atlantic herring from the southwestern Bay of Fundy. Slopes of lines shown are those used in calculation of the exponents of body weight ($\zeta_{1-5\ g}$, $\zeta_{25-60\ g}$, $\zeta_{60+\ g}$) used in the clearance expression

Accumulation of Mercury from Food

The ingested ration per unit time, R, is described by:

$$R = \frac{1}{e_f}[\alpha W^{\gamma} + (\beta + 1)(dW/dt)] \quad (7)$$

Mercury uptake from food per unit time, $(dP/dt)_f$, may be described by:

$$(dP/dt)_f = e_{pf}C_{pf}R \quad (8)$$

where e_{pf} is the efficiency of assimilation of methylmercury from food, and C_{pf} is the concentration of methylmercury in the food. Based on an assessment of literature values ranging from 0.67 to 0.94 for e_{pf}, Norstrom *et al.* (1976) assigned e_{pf} a value of 0.80. Pentreath (1976), however, found $e_{pf} = 0.10$ or less for plaice (*Pleuronectes platessa*), and Fagerström and Asell (1973) used $e_{pf} = 0.15$ for pike (*Esox lucius*). Phillips *et al.* (1980) concurred with this latter value which is used in the present model.

Stomach contents of 40 1-year-old herring collected from Letete Passage during 1981 consisted mainly of copepods, which are the dominant food item of Atlantic herring in the Quoddy region (Battle *et al.* 1936; Legare and Maclellan 1960). The diet was, therefore, assumed to consist entirely of copepods for all herring from 1 to 5 years. Using a caloric value of 0.90 kcal/g wet weight for copepods (Cummins and Wuycheck 1971), the ration, R (see Table 5), may be converted from kilocalories per unit time to grams of copepods per unit time. The mean total mercury concentration in copepod samples (N = 26) collected from the Quoddy region is 4.3 ± 2.21 ng/g. Limited sample quantities and technical difficulties hindered analysis of methylmercury content of copepod samples from the Quoddy region. Hirota *et al.* (1979), however, found that total mercury content of mixed zooplankton samples containing only crustaceans including copepods averaged 46% methylmercury content. This agrees well with Kikuchi's (1979) finding that the total mercury content of euphausiids consisted of 40–50% methylmercury. It is, therefore, assumed that 46% of the total mercury in copepods is available for uptake by the fish (see Table 6 for calculation).

Clearance of Mercury

The clearance rate of mercury, $(dP/dt)_{cl}$, can be written as:

$$(dP/dt)_{cl} = -k_{cl}PW^{\zeta} \quad (9)$$

where k_{cl} is the clearance coefficient, P is the body burden of mercury in the fish, and ζ is an exponent of body weight, W. The value of $k_{cl} = 0.202\ g^{-\zeta}/wk$ given by Norstrom *et al.* (1976) is also used for herring. The body burden of mercury, P, in fish at any given point in time may be calculated from the uptake of mercury from water and food (see Table 7 for calculation) since mercury concurrently accumulated from water and food is quantitatively additive (Phillips and Buhler 1978). The slope of the curve of log mercury concentration in herring vs log body weight is used to establish the exponent of body weight for clearance (Norstrom *et al.* 1976). Since this relationship was not linear over the entire weight range of herring collected (Figure 1), $\zeta_{1-5g} = +0.06$, $\zeta_{25-60g} = +0.04$, and $\zeta_{60+g} = -0.87$.

Results

Total Mercury Accumulation

The mean values for length, weight, muscle weight fraction, muscle mercury concentration, and whole fish mercury concentration over five age classes are presented in Table 2. Muscle and whole fish mercury concentrations are positively correlated with herring age class, weight and length ($P < 0.001$ in each set) over five age classes, with the highest correlation occurring with age and the lowest, with length (Table 3, Figure 2). Within the age class, muscle and whole fish mercury concentrations are negatively correlated with length and weight in 1-year-old herring (Table 4, Figure 2). Correlations of

Table 2. Mean values for standard length, weight, muscle fraction, muscle and whole fish total mercury concentrations [Hg] in Atlantic herring from the southwestern Bay of Fundy

		Age (yrs)				
		1	2	3	4	5
Length	N	245	91	28	22	4
(cm)	$\bar{x}$	5.8	14.5	19.4	21.5	22.7
	s	0.83	1.84	1.55	1.64	2.71
Weight	N	245	91	28	22	4
(g)	$\bar{x}$	2.3	47.4	117.2	152.6	177.6
	s	1.30	20.64	28.22	33.01	61.26
Muscle	N	92	46	28	22	4
fraction	$\bar{x}$	.6	.7	.7	.7	.7
	s	.05	.03	.02	.03	.03
Muscle [Hg]	N	15	46	28	22	4
(ng/g)	$\bar{x}$	5.1	5.2	7.6	12.1	14.6
	s	1.06	1.03	2.38	3.10	5.91
Whole [Hg]	N	31	45	28	22	4
(ng/g)	$\bar{x}$	5.1	6.2	7.4	11.1	14.9
	s	1.03	1.36	1.87	2.32	4.78

Table 3. Correlation coefficients and linear regression equations for age (yrs), length (cm), weight (g), muscle fraction, and muscle and whole fish total mercury concentrations [Hg] (ng/g) in Atlantic herring from the southwestern Bay of Fundy

N	r	Equation
191	.90**[a]	Length = 4.971 (Age) + 3.237
191	.91**	Weight = 50.724 (Age) − 49.842
192	.67**	Log (Muscle Fraction) = 0.035 (Age) − 0.283
192	.61**	Log (Muscle Fraction) = 0.001 (Weight) − 0.243
191	.98**	Log (Weight) = 0.119 (Length) − 0.217
115	.78**	Log (Muscle [Hg]) = 0.138 (Age) − 2.532
130	.78**	Log (Whole [Hg]) = 0.110 (Age) − 2.434
115	.71**	Log (Muscle [Hg]) = 0.002 (Weight) − 2.348
130	.68**	Log (Whole Hg]) = 0.002 (Weight) − 2.303
115	.64**	Log (Muscle [Hg]) = 0.023 (Length) − 2.534
130	.63**	Log (Whole [Hg]) = 0.017 (Length) − 2.427

[a] Significance levels are as follows: *$0.05 > P > 0.02$; **$P < 0.001$

mercury concentrations with length and weight continue to be negative with the 2-year-olds but become positive with the 3–5-year-old herring (Table 4, Figure 2). Whole fish mercury concentration is generally more strongly correlated, either negatively or positively, with herring length and weight than is muscle mercury concentration. Herring of age class five are the exception, but this may be the result of small sample size.

Simulated Accumulation of Mercury

The energy requirements and volume of water flow past the gills of Atlantic herring over the year are summarized in Table 5. Based on the calculated values of mercury uptake from water and food (Table 6), the model predicts that total mercury body burden in Atlantic herring increases with age (Table 7). The period of no growth, T_2, is very important for mercury depuration within all age classes since the total mercury uptake rate from both water and food is lowest during this part of the year. The annual cumulative mercury body burdens predicted by the model fall within one standard deviation of the measured annual mercury body burdens of 3–5-year-old herring (Figure 3). The model predicted no net mercury body burden for 1–2-year-old herring.

Discussion

Mercury concentration increases with size and age of a fish due to the inability of a fish to eliminate mercury at a rate at which it is assimilated (Cutshall

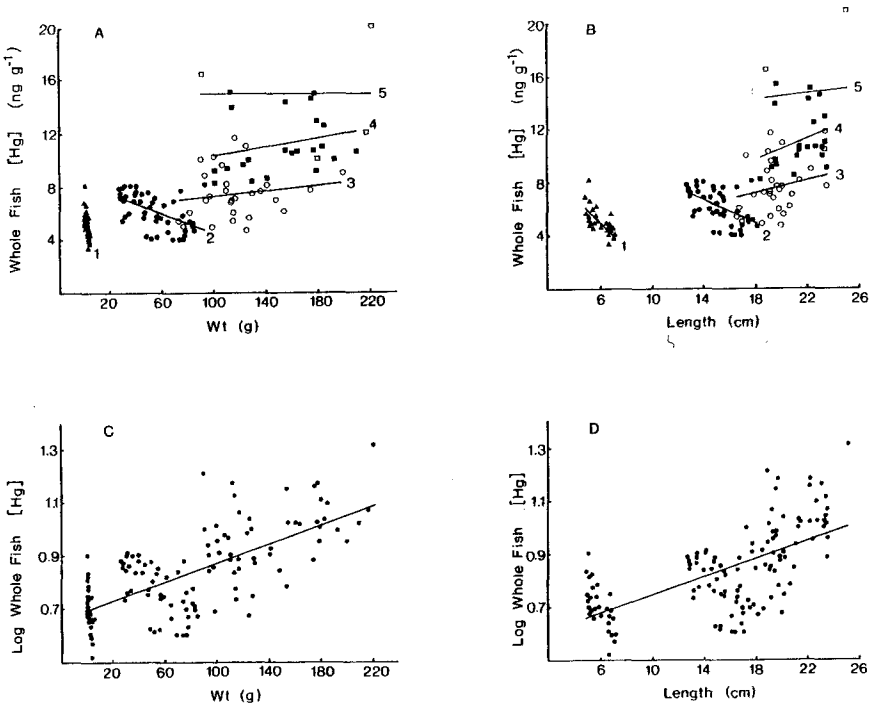

Fig. 2. Relationship between weight, length and whole fish total mercury concentration [Hg] (ng/g) in Atlantic herring from the southwestern Bay of Fundy within (A, B) and across (C, D) age classes. In Figures 2A and 2B, age classes 1 to 5 are shown by: 1:▲, 2:●, 3:○, 4:■, 5:□. Relationships with total mercury concentration in muscle are of similar configuration

Table 4. Correlation coefficients for muscle and whole fish total mercury concentrations [Hg] by weight and length within age classes of Atlantic herring from the southwestern Bay of Fundy

	Age (yrs)									
	1		2		3		4		5	
	N	r	N	r	N	r	N	r	N	r
Length vs Muscle [Hg]	15	−.58*[a]	46	−.08	28	.01	22	.23	4	.12
Length vs Whole [Hg]	31	−.69**	45	−.53**	28	.19	22	.26	4	.07
Weight vs Muscle [Hg]	15	−.58*	46	−.11	28	.00	22	.22	4	.01
Weight vs Whole [Hg]	31	−.69**	45	−.52**	28	.15	22	.23	4	−.01

[a] See Table 3 for significance levels

et al. 1978). Most of the mercury in fish (approximately 82% in marine fish) exists as methylmercury (Zitko *et al.* 1971). Methylmercury is cleared from the tissues of small fish at a faster rate per unit body tissue than from larger fish (Sharpe *et al.* 1977). The high mercury clearance rate in combination with rapid increases in length and weight therefore appear to effectively decrease whole fish mercury concentration through a 'growth dilution' effect and yields the negative correlations between mercury concentrations vs length, and weight in 1- and 2-year-old herring. Slowed growth rate, in combination with a reduced metabolic rate in larger fish, may cause the apparent plateau of mercury concentrations in larger, older herring (Figure 2A).

There is an increase in muscle weight fraction in 1- to 2-year-old herring (Table 2). This may account for the significant difference ($P < 0.001$) between muscle and whole fish mercury concentration in 2-year-old herring. Once the muscle mass to whole fish ratio has stabilized, muscle and whole fish mercury concentrations are no longer significantly different within an age class (3–5-year-olds).

In defining values for parameters and constants used in the mercury accumulation model, it is important to assign values as specifically as possible within the scope of data or literature available. Norstrom *et al.* (1976) applied a single value for β to all of their age classes of fish. The relationship of growth rate to energy associated with growth, however, should change with fish size and age within a given species. The trend is for conversion effi-

Table 5. Metabolic rate, Q, volume of water flow past the gills, V, and ingested ration, R, required by Atlantic herring during the year

	Q^a (ml O_2/hr)			V^b (g H_2O/wk) × 10^6			R^c (kcal/wk)		
Age (yrs)	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3
0–1	0.17	0.12	0.31	0.055	0.004	0.059	1.82	0.12	1.96
1–2	4.44	3.17	5.64	0.71	0.11	0.75	23.43	3.25	24.66
2–3	19.91	10.09	15.19	1.66	0.34	1.50	53.08	10.34	48.24
3–4	38.20	16.39	21.73	2.02	0.56	1.46	62.35	16.79	45.48
4–5	47.93	19.98	25.81	2.22	0.68	1.47	67.83	20.47	45.17

[a] $Q = \alpha \overline{W}_{Tx}^{\gamma}$ where $\alpha_{T1} = 0.334$, $\alpha_{T2} = 0.134$, $\alpha_{T3} = 0.167$, $\gamma = 0.98$

[b] $V = \frac{1}{e_{ox}C_{ox}q_{ox}} (\alpha \overline{W}_{Tx}^{\gamma} + \beta (dW/dt))$ where $\beta_{0-2} = 8.0$, $\beta_{2-3} = 9.0$, $\beta_{3-4} = 13.0$, $\beta_{4-5} = 15.0$

[c] $R = \frac{1}{e_f} [\alpha \overline{W}_{Tx}^{\gamma} + (\beta + 1)(dW/dt)]$

Table 6. Mercury uptake from water and food in Atlantic herring

	$(dP/dt)_w^a$ (ng Hg/wk)			$(dP/dt)_f^b$ (ng Hg/wk)		
Age (yrs)	T_1	T_2	T_3	T_1	T_2	T_3
0–1	0.66	0.05	0.71	0.55	0.04	0.59
1–2	8.5	1.3	9.0	7.0	1.0	7.4
2–3	19.9	4.1	18.0	15.9	3.1	14.5
3–4	24.2	6.7	17.5	18.7	5.0	13.6
4–5	26.6	8.2	17.6	20.3	6.1	13.6

[a] $(dP/dt)_w = e_{pw}C_{pw}V$ where $e_{pw} = 0.12$, $C_{pw} = 10.0$ ng/L × 0.01 = 0.1 ng/L

[b] $(dP/dt)_f = e_{pf}C_{pf}R$ where $e_{pf} = 0.15$, $C_{pf} = 4.3$ ng/g × 0.46 = 2.0 ng/g

ciency to decrease with increasing body weight (De Silva and Balbontin 1974). The conversion efficiency of herring is lower than most fish species studied, probably as a reflection of their active schooling mode of life, which demands a large amount of energy and thus a higher food intake, of which only a small proportion is converted into fish flesh (De Silva and Balbontin 1974). Since the value of β has considerable impact on the calculated food ration and water volume requirements per unit time (see equations 5 and 7), each size/age class should be treated separately as was done for the herring.

Similar caution should be taken when calculating the body weight exponent, ζ, in the clearance equation. The slope of the log/log transformation of the measured mercury concentration vs body weight data may be successfully used in the calculation of ζ only if the relationship is linear. In order to overcome the problem of non-linearity over the whole weight range, the slope may be calculated over portions of the weight range where the relationship is more or less linear, thereby increasing the accuracy of the value assigned to ζ. As a result, different values of ζ may be applied over the weight range as they best represent the relationship. If a single value for ζ were to be applied to the whole weight range ($\zeta = -0.42$ for 1–5-year-old herring), the accuracy of the model would be compromised (Figure 3).

The model demonstrates good predictive capability of whole fish mercury concentrations for herring greater than 60 g in weight (Figure 3), that is, herring of 2+ years of age (Table 1). Since the inshore fishery catches few herring younger than 2 years of age, the model may be used in predicting whole fish mercury concentrations in commercially valuable herring.

The model, however, predicted that there was no net mercury accumulation in 1–2-year-old herring. Norstrom *et al.* (1976) showed that the body weight exponent, ζ, in the clearance equation has a marked effect on pollutant accumulation, and that the curves for all values of ζ intersect at a very small weight. Since weights of 0–1-year-old herring are

Table 7. Total mercury uptake, clearance and accumulation in Atlantic herring

Age (yrs)	$(dP/dt)^{a}_{w+f}$ (ng Hg/wk)			$(dP/dt)^{b}_{cl}$ (ng Hg/wk)			P^{c} (ng Hg)		
	T_1	T_2	T_3	T_1	T_2	T_3	T_1	T_2	T_3
0–1[d]	1.2	0.1	1.3	0.7	0.9	1.8	3.0	0.0	0.0
1–2	15.5	2.3	16.4	22.6	6.9	24.9	0.0	0.0	0.0
2–3	35.8	7.2	32.5	1.2	2.4	2.9	449.8	574.6	959.4
3–4	42.9	11.7	31.1	3.7	4.6	5.0	1469.0	1653.6	1992.9
4–5	46.9	14.3	31.2	5.6	6.4	6.8	2529.8	2735.2	3052.4

[a] $(dP/dt)_{w+f} = (dP/dt)_w + (dP/dt)_f$

[b] $(dP/dt)_{cl} = k_{cl}\overline{P}_{Tx}\overline{W}^{\zeta}_{Tx}$ where $k_{cl} = 0.202\ g^{-\zeta}/wk$, $\overline{P}_{Tx} = P_{T(x-1)} + 0.5T_x(dP/dT_x)_{w+f}$, $\zeta_{1-5g} = +0.06$, $\zeta_{25-60g} = +0.04$, $\zeta_{60+g} = -0.87$

[c] Cumulative body burden of mercury at the end of time period T_x where $P_{Tx} = P_{T(x-1)} + T_x[(dP/dt)_{w+f} - (dP/dt)_{cl}]$

[d] Assume only six weeks growth during T_1

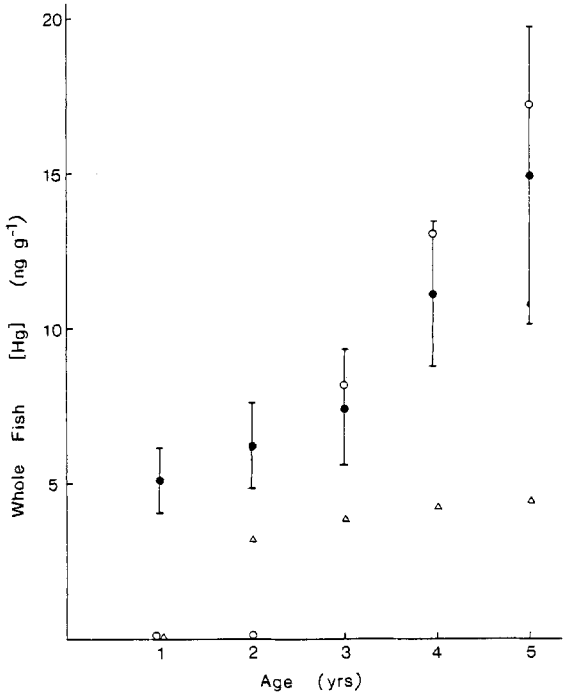

Fig. 3. Measured (●) and model-generated (○) values of whole fish total mercury concentration using 3 different values of ζ ($\zeta_{1-5\ g} = +0.06$, $\zeta_{25-60\ g} = +0.04$, $\zeta_{60+\ g} = -0.87$) over the weight range, and one average value ($\zeta = -0.42$) for ζ (△) for 1–5-year-old herring from the southwestern Bay of Fundy. Standard deviations are indicated for measured values

small (Table 1), the value of ζ may be an inadequate representation of the clearance rate parameter for 1-year-old herring. Also, since the slopes for log mercury concentration vs log body weight were negative due to growth dilution effects for 1–5 g and 25–60 g herring (Figure 1), ζ was positive for these weight ranges which approximately coincide with 0–2-year-old fish. The positive values for ζ resulted in high calculated clearance rates which prevented net accumulation of mercury.

The success of the pollutant accumulation model in predicting total mercury body burdens for Atlantic herring of the commercially valuable age classes demonstrates the general applicability of physiologically dynamic contaminant models. The successful use of such models depends upon the use of realistic values for parameters and constants appropriate to the fish size, age and species in question as well as the environmental conditions to which the species is exposed.

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