

RELATIONSHIP AMONG MERCURY CONCENTRATION, GROWTH RATE, AND CONDITION OF NORTHERN PIKE: A TAUTOLOGY RESOLVED?

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Abstract: Methylmercury is a bioaccumulative contaminant that biomagnifies in aquatic food webs and adversely affects the health of freshwater fish. Previous studies have documented an inverse relationship between fish condition and concentration of mercury in fish. However, this relationship may be a result of slow-growing fish accumulating large amounts of methylmercury rather than the effects of methylmercury on fish condition and growth. An evaluation was conducted of the relationship among fish condition, growth, and mercury concentration in northern pike *Esox lucius* from 26 lakes in the western region of the Laurentian Great Lakes (USA–Canada). The relative weight (an index of fish condition) of northern pike was inversely related to mercury concentration in the axial muscle. The concentration of mercury in standard-size northern pike increased with fish age and suggested that fast-growing fish accumulated less mercury than slow-growing fish. However, there was no relationship between the mean relative weight of northern pike in each population and mean age or mercury concentration of standard-size northern pike. These results suggest that the relationship between mercury and fish condition is not because of the effects of mercury on rate of growth, but rather because slow-growing fish bioaccumulate greater concentrations of mercury than fast-growing fish of the same length. *Environ Toxicol Chem* 2016;35:2910–2915. © 2016 SETAC

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INTRODUCTION

Atmospheric transport and deposition of mercury, which is mostly from anthropogenic sources, has contaminated aquatic ecosystems globally [1]. Conversion of inorganic mercury to methylmercury by anaerobic bacteria [2] provides a pathway for bioaccumulation and biomagnification of mercury in freshwater aquatic food webs [3]. Concentrations of methylmercury in numerous water bodies in North America exceed concentrations that may cause sublethal effects in fish and also pose a risk to the health of piscivorous wildlife and humans [4,5]. Although effects on biochemistry, organ histology, and reproduction typically occur at mercury concentrations lower than those that affect growth, several field studies have reported an inverse relationship between the condition factor of individual fish (an index based on fish weight relative to length [6]) and mercury concentration in their tissues [7–12]; fish with high concentrations of mercury were in poorer condition than those with low concentrations.

Condition indices have been proposed as an indicator of fish physiological health and the well-being of fish populations [13,14]. Plump fish suggest that individuals have ample energy reserves and that environmental conditions favor good reproductive fitness and growth [14]. For example, positive correlations between fish condition and the relative size of gonads in male and female northern pike *Esox lucius* were observed in Lake Thompson, North Dakota (USA) [15] and between condition and fish growth in 11 populations of northern

pike in the United States and Canada [16]. Consequently, the inverse relationship frequently observed between condition factor and mercury suggests that mercury exposure may deleteriously affect fish growth and reproductive potential. However, it has also been postulated that the growth rate of fish may markedly influence mercury bioaccumulation and tissue concentrations through the process of somatic growth dilution—all other factors being equal, slow-growing fish of a given length have higher tissue mercury concentrations than fish that grow faster to the same length [17,18]. Hence, there appears to be a tautological relationship between fish condition and mercury. Do high concentrations of mercury diminish the condition of fish, or do fish in poor condition grow slowly and accumulate high concentrations of mercury?

Previous studies evaluating the correlation between mercury and fish condition have not considered the rate of fish growth as a factor that may influence this relation. In the present study, we examine fish condition, growth rate, and mercury concentration in northern pike from 26 lakes in the western region of the Laurentian Great Lakes (USA–Canada).

MATERIALS AND METHODS

Sample collection

Northern pike were collected in 4 US National Parks of the western Great Lakes region. These semipristine environments provide a unique opportunity to evaluate the effects of methylmercury on fish. Mercury is the primary contaminant of concern, and concentrations of other contaminants are low to nondetectable [8,19].

Eleven lakes were sampled once in 2002, and 4 lakes were sampled annually from 2009 through 2012 in Voyageurs National Park (MN, USA). In Isle Royale National Park (MI,

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USA), 8 lakes were sampled once during 2004 to 2006, and 4 lakes were sampled annually from 2009 through 2012. Three lakes in Pictured Rocks National Lakeshore (MI, USA) and 2 lakes in Sleeping Bear Dunes National Lakeshore (MI, USA) were also sampled in 2008 and annually from 2010 through 2012. Northern pike were collected by gill net or by hook and line and euthanized on site. Fish were captured and handled in accordance with permits from the US National Park Service and under approval of the Institutional Animal Care and Use Committee at the University of Wisconsin-La Crosse and at Miami University. The sex of each fish was determined, and total length (mm) and wet weight were measured (0.1 kg). A portion of skin-on axial muscle (Isle Royale National Park, 2004–2006) or skin-off axial muscle (Isle Royale National Park, 2009–2012; Voyageurs National Park; Pictured Rocks National Lakeshore; Sleeping Bear Dunes National Lakeshore) was removed from each fish with trace metal clean techniques [20], placed in a food-grade plastic bag, and stored in a conventional freezer until analysis for total mercury.

The age of each fish was estimated from an examination of cleithra (Isle Royale National Park, 2009–2012; Voyageurs National Park; Pictured Rocks National Lakeshore; Sleeping Bear Dunes National Lakeshore) or 2 or more scales (Isle Royale National Park, 2004–2006) [21]. Otoliths are rarely used to estimate the age of esocids [22]. Estimates of age made from cleithra of northern pike are as precise or more precise than those made from sagittal otoliths [23], and scales are also suitable structures for aging this species of fish [24]. The age of northern pike estimated from cleithra was made by 2 persons working independently of each other. If the initial 2 age estimates differed for an individual fish, a third person also independently estimated the age of the fish. Age estimates were retained for fish for which 2 estimates of age were in agreement. In a previous study on northern pike in lakes of Isle Royale [25], the age of the northern pike estimated from scales was used to back-calculate length at age for each individual and compared with estimates obtained in 1995 to 1996 by other investigators. No difference in the estimated size at age for northern pike was detected.

Mercury analysis

Lyophilized samples of axial muscle of northern pike from Voyageurs National Park in 2002 were pulverized into a homogenate with a mortar and pestle. A 50-mg to 250-mg sample of the homogenate from each fish was acid-digested and analyzed for total mercury by flow-injection cold-vapor atomic absorption spectrophotometry with a PerkinElmer FIMS 100, as described by Hammerschmidt et al. [20]. Total mercury in samples of skin-on axial muscle of northern pike from Isle Royale National Park in 2004 to 2006 was also measured with cold-vapor atomic absorption spectroscopy as described by Drevnick et al. [8]. For northern pike collected in 2008 to 2012, total mercury in skin-off axial muscle was measured as described by Wiener et al. [19] with either cold-vapor atomic fluorescence spectroscopy with procedures modified from US Environmental Protection Agency (USEPA) method 1631 [26] or by direct mercury analysis following USEPA method 7473 [27]. For all years and methods of analysis, the precision and accuracy of total mercury were quantified by analyses of 1) analytical and procedural blanks, 2) replicate samples, 3) standard reference materials from the National Research Council of Canada or the National Institute of Standards and Technology, and 4) spiked samples. Quality assurance measures among years and methods of analysis were similar. The relative

percentage difference between sample duplicates (Isle Royale National Park, 2004–2006) was 2.6%; the relative standard deviation of triplicate analyses was less than 10%. The recovery of spiked samples ranged from 90% to 110%, and the concentrations of mercury in standard reference materials were within 10% of the certified ranges.

Fish condition and rate of growth

The condition of each fish was determined by calculating its relative weight (W_r ; [6]) as follows:

$$W_r = (W/W_s) 100 \quad (1)$$

where W is the actual weight of an individual northern pike and W_s is the standard weight for a northern pike of the same total length estimated from a regression equation of weight and length based on a compilation of data for the species. The standard weight equation for northern pike was obtained from Anderson and Neumann [6] and was defined as

$$\log_{10}(W_s) = -5.437 + 3.096 \log_{10}(\text{total length}) \quad (2)$$

The rate of growth was estimated for each sample population of fish. Because male and female northern pike from the same lake may be expected to grow at different rates, a sample population was defined as all male or female fish collected during 1 yr from a specific lake.

Changes in fish length relative to age was modeled with the growth equation of von Bertalanffy [28]:

$$l_t = L_\infty(1 - e^{-K(t-t_0)}) \quad (3)$$

where l_t is the total length of the fish at age t , L_∞ is the asymptotic total length, K is a growth coefficient, and t_0 is a time coefficient at which the total length would hypothetically equal 0. Using SAS Ver 9.3 [29], we fit the von Bertalanffy equation with nonlinear regression [30]. Sample populations for which model parameters were not significant or for which the model failed to converge were not retained for additional analyses.

We modeled the relationship between mercury in the axial muscle and fish total length with an exponential equation,

$$\text{Hg}_{\text{TL}} = \exp^{a+b\text{TL}} \quad (4)$$

where Hg_{TL} is the axial muscle concentration at total length TL, and a and b are constants. The model is made linear by natural log transformation, and the constants were estimated by least-squares linear regression. Previous analyses of northern pike populations in the Great Lakes region had determined that the exponential function was better than other common models for estimating mercury concentration from fish length [31]. Sample populations for which the relationship between total length and axial muscle mercury was nonsignificant were not retained for additional analyses. To avoid bias caused by having more than 1 population of male and female fish from each lake, only replicate populations with the largest number of fish were retained for each lake.

The unweighted grand mean total length of fish in all retained sample populations was calculated and rounded to the nearest 5 mm. This value was selected as the standard size for comparison of condition and mercury concentrations in fish among lakes. The age of the standard-size fish in each population was estimated from the von Bertalanffy equation.

Statistical analysis

Simple linear regression was used to evaluate the relationship between 1) mercury concentrations in the axial muscle of northern pike and relative weight, 2) age of a standard-size fish in each population and the mean mercury concentration in the axial muscle, 3) age of a standard-size fish in each population and relative weight, and 4) mercury concentrations in a standard-size fish in each population and mean relative weight.

RESULTS AND DISCUSSION

During 2002 to 2012, 653 northern pike were obtained from 26 lakes within the 4 national parks (Supplemental Data, Table S1). Of these fish, 300 were female and 353 were male. The total length of the northern pike ranged from 248 mm to 971 mm, and mass ranged from 140 g to 6400 g. There was a strong relationship between weight and total length of the fish ($\log [\text{weight}] = -5.288 + 3.025 \log [\text{total length}]$; $R^2 = 0.94$, $p < 0.0001$).

Mercury concentrations in the axial muscle ranged from 59 ng/g to 3232 ng/g wet weight. The condition (relative weight [Wr]) of the 653 northern pike significantly decreased with increasing concentrations of mercury in the axial muscle (Figure 1). The relationship between fish condition and mercury was greater for male ($n = 353$, $R^2 = 0.18$, $p < 0.0001$) than for female fish ($n = 300$, $R^2 = 0.08$, $p < 0.0001$). Variation in the relationship is likely because of the accuracy of weighing fish in the field and the numerous factors that influence differences in the weight of fish on a daily (e.g., stomach fullness) and seasonal (e.g., reproductive status) basis.

From these 26 lakes, 77 sample populations (combination of lake, year, fish sex) were identified (Supplemental Data, Table S1). The model parameters of the von Bertalanffy equation were significant for 32 of these populations. Sixteen of these sample populations were eliminated from further analysis because they represented replicate populations from the same lake (6 populations) or had a nonsignificant relationship between fish length and axial mercury (6 populations). The

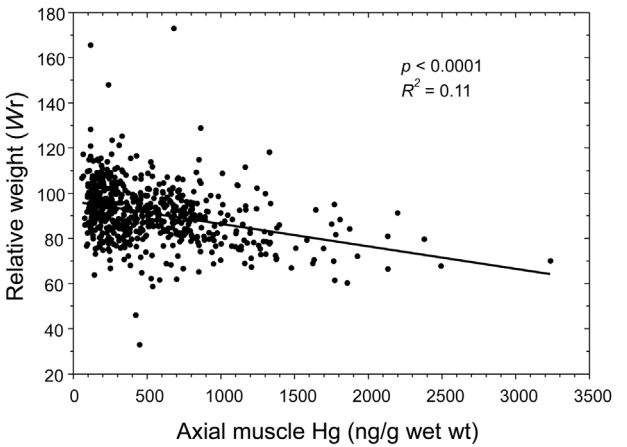


Figure 1. Relationship between fish condition (relative weight [Wr]) and concentration of mercury in axial muscle of 653 male and female northern pike collected in 2002 to 2012 from 26 lakes in the western Great Lakes region.

remaining 16 populations met the previously described criteria and were identified for evaluating the relationship among fish growth rate, relative weight, and mercury (Table 1). The unweighted mean total length of northern pike and, therefore, the standard size used to compare fish among populations was 515 mm. There was good correlation between total length and age for the 16 populations of fish. The mean coefficient of determination for the von Bertalanffy model was 0.82 (range 0.40–0.99). The estimated age at which northern pike from the 16 populations reached 515 mm ranged from 2.2 yr to 6.4 yr. The growth of northern pike in these lakes was similar to that in other lakes within the region. For example, based on the estimated coefficients of the von Bertalanffy growth model, the calculated size of age 4 northern pike ranged from 439 mm to 616 mm total length. This was similar to the mean back-calculated length of age 4 northern pike previously reported from 12 north-central Minnesota (USA) lakes (range

Table 1. Coefficients of the von Bertalanffy growth model, age of standard-size northern pike, coefficients of the exponential model of the relationship between mercury concentration in the axial muscle and fish total length, and estimated mercury concentration of standard-size northern pike

Lake	Yr	Sex	L_{∞}	K	t_0	R^2	Age _{TL515} (yr)	a	b ($\times 10^{-3}$)	R^2	Hg _{TL515} (ng/g wet weight)
Isle Royale National Park	2004	Male	688	0.3037	−0.53	0.99	3.8	1.348	7.35	0.88	169
		Female	1110	0.1378	−0.18	0.85	4.2	1.909	6.08	0.71	155
	2006	Female	666	0.2442	−1.90	0.96	3.9	3.640	2.61	0.45	146
		Male	1283	0.0362	−9.36	0.97	4.5	2.655	4.95	0.74	182
	2005	Female	721	0.1783	−3.19	0.99	3.6	1.099	7.61	0.64	151
	2010	Male	685	0.2608	−2.10	0.76	3.0	3.093	4.66	0.44	243
Wagejo	2005	Female	747	0.2211	−0.87	0.94	4.2	1.893	6.48	0.41	187
Pictured Rocks National Lakeshore	2010	Female	774	0.3031	−1.26	0.67	2.2	2.811	5.46	0.80	277
		Female	2197	0.0365	−3.43	0.98	3.7	4.101	2.84	0.80	261
Sleeping Bear Dunes National Lakeshore	2012	Male	1150	0.1342	−1.72	0.79	2.6	3.614	3.06	0.79	180
Voyageurs National Park	2002	Male	635	0.3913	−0.59	0.78	3.5	3.955	4.89	0.86	647
		Male	704	0.313	0.43	0.73	4.5	4.671	3.84	0.90	772
	2002	Male	536	0.3012	−3.10	0.50	6.4	4.248	4.98	0.81	910
		Male	536	0.6407	0.27	0.40	4.7	5.549	2.52	0.47	941
	2010	Male	1226	0.0957	−1.76	0.87	3.8	4.203	4.70	0.89	754
Tooth	2002	Male	582	0.2814	−0.98	0.92	6.2	5.437	3.12	0.51	1144

L_{∞} = the asymptotic total length; K = growth rate; t_0 = hypothetical fish age, where total length = 0 mm; Age_{TL515} = age of standard-size northern pike; a = intercept; b = slope of linear equation; Hg_{TL515} = estimated mercury concentration.

423–691 mm) [32] and from 19 lakes in northern Wisconsin (USA; mean 490 mm) [33].

Estimated mercury concentrations of standard-size (515-mm) northern pike ranged from 146 ng/g to 1144 ng/g wet weight in the axial muscle of northern pike from the 16 populations (Table 1). Mercury concentrations of these fish were similar to those reported from northern pike in other lakes within the Great Lakes region. For example, estimated concentrations of mercury in 500-mm northern pike collected in 1990 to 2009 from 621 waterbodies in Michigan, Minnesota, and Wisconsin (USA), and Ontario (Canada) exceeded 320 ng/g at 63% of the locations [31]. Total length was a good predictor of mercury concentration in the axial muscle of the northern pike. The mean coefficient of determination for the exponential relationship between mercury concentration and total length was 0.69 (range 0.41–0.90; Table 1).

The concentration of mercury in standard-size northern pike increased with fish age (Figure 2A). This positive correlation suggests that fast-growing fish accumulated less mercury and provides evidence of somatic growth dilution among these populations of northern pike. Similarly, Lavigne et al. [34] found that mercury concentrations in fish from 54 populations of walleye *Sander vitreus* and 52 populations of northern pike in Quebec, Canada were inversely related to rate of growth; fast-growing fish had lower mercury concentrations than slow-growing fish at a standardized length. Experimental evidence has also demonstrated that mercury concentrations in fish are, at least in part, dependent on rate of growth. Mercury concentrations in northern pike decreased as a result of increased growth because of the reduction in population density and

intraspecific competition [35] or as a result of increased individual biomass and growth following stocking of energy-dense, low-mercury prey [36]. Variation in the relationship between mercury and growth in northern pike may also be attributable to differences among lakes in mercury concentrations of their prey. Ward et al. [37] measured the growth and mercury concentrations of Atlantic salmon *Salmo salar* fry 116 d to 143 d after stocking in 18 sites in streams in New Hampshire and Massachusetts (USA). Although rate of salmon growth accounted for 38% of the variation in mercury concentration in salmon fry among the 18 sites, mercury concentration of their prey accounted for 59%.

There was not strong evidence that the condition of northern pike was related to the rate of growth (Figure 2B). Populations in which the mean time to reach 515 mm total length was 2 yr to 3 yr had mean condition factors that were similar to populations that required more than 4 yr to reach that length. Moreover, there was no relationship between the mercury concentration of standard-size northern pike and the mean relative weight of northern pike in each population (Figure 3). These results suggest that the relationship between mercury and fish condition is not the result of the effects of mercury on rate of growth. Instead, slow-growing fish bioaccumulate greater concentrations of mercury than fast-growing fish of the same length. Other studies have reported the relative insensitivity of growth and fish condition to mercury relative to other biologically important endpoints. In a laboratory investigation of the effects of dietary methylmercury on fathead minnows *Pimephales promelas*, Hammerschmidt et al. [38] reported a hormetic effect of mercury with the wet weight of fish positively related to mercury burden. However, although survival and growth were not affected, dietary methylmercury delayed spawning, reduced female gonad size and egg production, limited reproductive success, and was subsequently linked to the suppression of plasma testosterone and estradiol [39] and histological changes in the ovaries [40]. In a review of laboratory studies, Depew et al. [41] noted that effects on growth occurred only at dietary methylmercury concentrations greater than 2500 ng/g wet weight; reproduction and other sublethal effects generally occurred at dietary concentrations less than 200 ng/g wet weight. Moreover, a review of laboratory and field studies of effects of

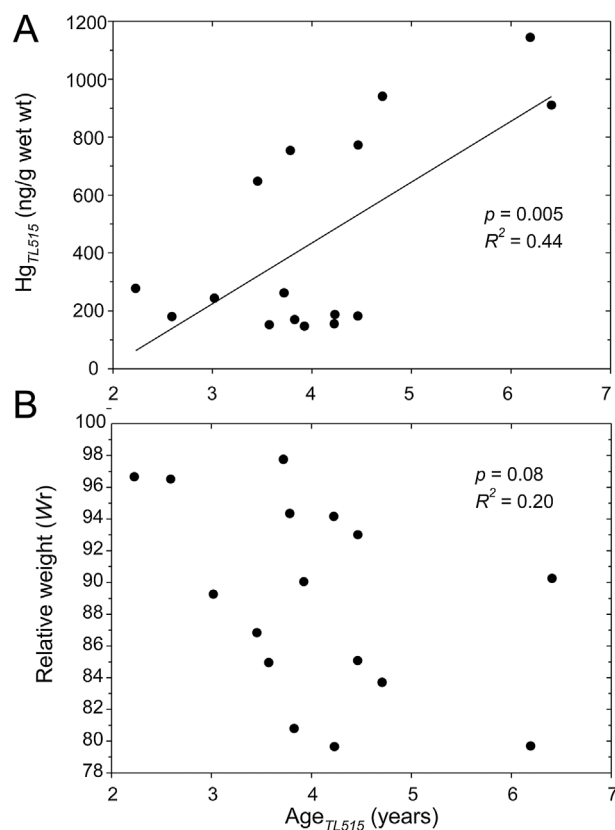


Figure 2. Relationship between age of standard-size (515 mm total length [TL_{515}]) northern pike and (A) mercury concentrations in the axial fillet and (B) mean relative weight for 16 populations in the Great Lakes region.

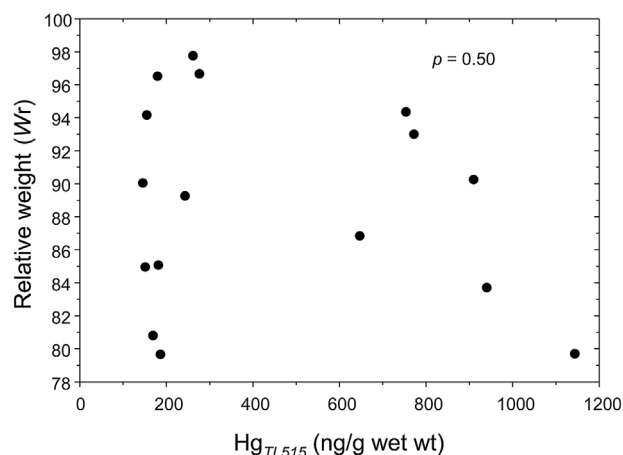


Figure 3. Relationship between mean concentration of mercury in axial muscle of standard-size (515 mm total length [TL_{515}]) northern pike and mean fish condition (relative weight) from 16 populations in the Great Lakes region.

methylmercury bioaccumulation noted that altered biochemical, histological, and reproductive endpoints have been documented at concentrations of approximately 500 ng to 1200 ng Hg/g wet weight in the axial muscle [4]. Based primarily on reproductive endpoints, Beckvar et al. [42] proposed a whole-body threshold tissue concentration of 200 ng Hg/g—equivalent to approximately 320 ng/g wet weight in the axial muscle of northern pike [31]. Of the 653 northern pike in the present study, 57% exceeded 320 ng Hg/g wet weight in the axial muscle, and there is evidence that northern pike in at least some of these lakes are deleteriously affected by mercury contamination. Northern pike from lakes in Isle Royale National Park exhibited liver toxicity as a result of methylmercury exposure. Lipofuscin, a pigment that accumulates as a result of oxidative stress and lipid peroxidation, increased with liver total mercury in northern pike in the 8 inland lakes sampled in 2004 to 2006 [8]. Total mercury concentrations in the skin-on axial muscles of these fish ranged from 69 ng/g to 622 ng/g wet weight. The results of this and other studies [38] suggest that condition factor may not be a sensitive indicator of stress associated with methylmercury exposure and that the inverse relationship between condition indices and mercury concentration in fish likely reflects the influence of growth rate on patterns of mercury bioaccumulation within populations.

Supplemental Data—The Supplemental Data are available on the Wiley Online Library at DOI: 10.1002/etc.3521.

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Conflict of Interest—The authors declare they have no conflicts of interest.

Data availability—Data are available on request from M. Sandheinrich (msandheinrich@uwla.edu).

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