Effect of habitat use on PCB body burden in Hudson River striped bass (*Morone saxatilis*)

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Abstract: The Hudson River commercial striped bass (*Morone saxatilis*) fishery has been closed since 1976 due to high polychlorinated biphenyl (PCB) contamination. Accurate forecasting of PCB levels in striped bass has been confounded by high variance in contamination among individuals. We investigated the relationship between habitat use and PCB contamination in Hudson River and Long Island Sound striped bass using electron microanalysis of otolith strontium to generate time series of individual salinity habitation. Males with highly contaminated levels (mean PCB = 8.3 ppm) showed freshwater resident behavior, rarely experiencing salinities >5 ppt. Several individuals showed large habitat shifts. Shifts from brackish or marine habitats to freshwater habitats were often associated with high PCB levels. A third pattern was apparent in large females, where polyhaline/euhaline salinity habitation was associated with lower PCB levels. Total PCB body burden was inversely correlated with mean salinity encountered during the most recent growth season prior to capture. Fish with recent exposure to polyhaline salinities showed high variability in PCB body burdens (0.4–9.0 ppm), suggesting a local source of PCB contamination in the New York Harbor region.

Résumé : La pêche commerciale du bar rayé (*Morone saxatilis*) dans l'Hudson est interdite depuis 1976 en raison d'une forte contamination par les polychlorobiphényles (PCB). La forte variance de la contamination entre individus a rendu difficile l'établissement de prévisions précises des niveaux de PCB chez les bars rayés. Nous avons étudié la relation entre l'utilisation de l'habitat et la contamination par les PCB chez les bars rayés de l'Hudson et de Long Island Sound au moyen de la microanalyse électronique du strontium des otolithes pour générer des séries temporelles de résidence des individus dans des milieux de salanités diverses. Les mâles fortement contaminés (concentration moyenne de PCB = 8.3 ppm) résidaient en eau douce et étaient rarement exposés à des salinités supérieures à 5 parties par millier. Plusieurs individus ont montré d'importants changements d'habitats. Les passages des habitats saumâtres ou marins aux habitats dulcicoles étaient souvent associés à des niveaux élevés de PCB. Une troisième situation a été observée dans le cas des grosses femelles, chez lesquelles le séjour dans les conditions polyhalines ou euhalines était associé avec des niveaux plus bas de PCB. La charge corporelle totale de PCB était corrélée négativement avec la salinité moyenne à laquelle les poissons étaient exposés durant la plus récente saison de croissance avant la capture. Les poissons récemment exposés à des conditions polyhalines ont montré une forte variabilité de leurs charges corporelles de PCB (0,4–9,0 ppm), ce qui laisse penser qu'il existe une source locale de contamination par les PCB dans la région du port de New York.

[Traduit par la Rédaction]

Introduction

The Hudson River commercial striped bass (*Morone saxatilis*) fishery has been closed since 1976 due to high levels of polychlorinated biphenyl (PCB) contamination (Brown et al. 1985; Limburg 1986). The mean PCB body burden in Hudson River striped bass continues to exceed the current U.S. Food and Drug Administration action limit of 2.0 ppm (Bush et al. 1989; Fabrizio et al. 1991). PCB contamination has resulted in an estimated annual loss of US$0.75–3.7 million to New York recreational and commercial striped bass fisheries (Kahn and Buerger 1994). In addition, recreational striped bass fishers have been issued annual fish consumption health advisories since 1976 (Sloan et al. 1986).

A total of 2.7 × 10^5 kg of PCBs was discharged into the Hudson River estuary from about 1947 to 1987 (Thomann et al. 1991). The majority of PCB contamination to the Hudson River estuary resulted from a solvent washing process at the General Electric Corporation capacitor facility above the Troy Dam (river kilometre (Rkm) 246) (Bush et al. 1989). High levels of PCBs (mean 18.1 ppm total PCBs) were found in the edible flesh of the striped bass in 1978 (Horn and Sloan 1985; Bush et al. 1989). As a condition of the 1975 Settlement Agreement signed by General Electric Corporation and the New York State Department of Environmental Conservation, discharge of PCBs from the General Electric Corporation capacitor manufacturing plant was terminated in June 1977 (Hetling et al. 1978; Armstrong and Sloan 1988). PCB concentrations in striped bass initially declined with the significant reduction in upstream loadings. However, concentrations through the 1980s showed little decline and have persisted above levels considered unsafe for human consumption (Sloan et al. 1995).

High-discharge events and dredging projects in the up-estuary region have exacerbated contamination throughout the Hudson River by reintroducing buried contaminants. This has resulted in a PCB gradient within the biota that is

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positively related to river kilometre (Limburg 1986; Bush et al. 1989). For instance, in 1994, total PCB concentrations in striped bass were highest (mean = 6.4 ppm wet weight) in the Albany/Troy region (Rkm 246) and concentrations decreased with distance downstream to about 1.9 ppm in the Tappan Zee region (Rkm 40) (Sloan et al. 1995). In 1994, mean PCB levels in striped bass were <2.0 ppm in Long Island Sound and New York's marine district.

Levels of PCB contamination are expected to be affected by patterns of habitat use by striped bass, which often undertake coastal migrations away from the Hudson River system. The current model of the long-term behavior of PCBs in Hudson River striped bass assumes that striped bass >2 years old occur in coastal habitats during the summer months and use coastal habitats for the majority of the year by age 6 (Thomann et al. 1989). Using otolith microanalysis to investigate migrations, Secor and Piccoli (1996) observed a contingent of resident fish in the upper estuary near the Troy Dam (Rkm 246) that did not participate in coastal migrations. They hypothesized that these fish were most vulnerable to PCB contamination because they fed and grew in close proximity to the most highly contaminated sediments in the Hudson River estuary. Conversely, we expected that fish that participated in regular coastal migrations, or fish that established long-term residence in polyhaline/euhaline habitats, would have lower PCB body burdens due to growth dilution in relatively "clean" habitats.

The objective of this study was to use otolith microanalysis to (*i*) verify the proposed link between habitat use and PCB body burden in Hudson River striped bass (i.e., resident fish should have high PCB body burden) and (*ii*) examine the effects of season, sex, and place of collection on habitat use and PCB body burden.

Methods

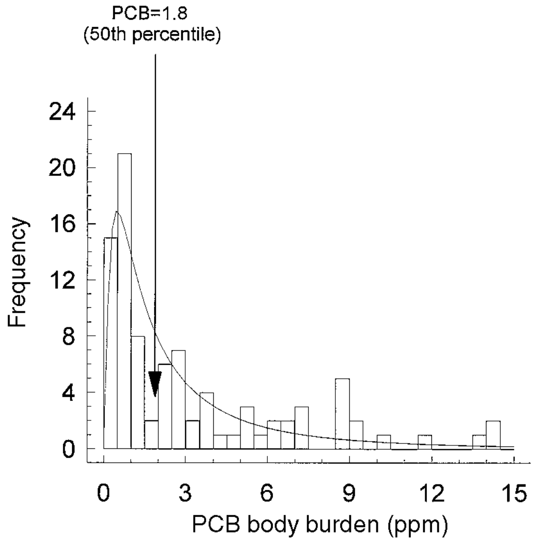
The New York State Department of Environmental Conservation has routinely sampled striped bass in the Hudson River, south shore of Long Island, and Long Island Sound for PCB contamination since 1976. Most fish are collected by beach haul seine (150 m long × 3.7 m deep), although some coastal samples were provided by fishers. Fish selected for PCB analysis were filleted (skin not removed) and then frozen. Muscle tissue from fillets was shipped to Hazleton Laboratories America, Inc., Madison, Wis., for gas chromatography PCB analysis (Aroclor method). We used total PCB values, based on wet weight (measured in parts per million), which is a sum of major Aroclors.

We subsampled 1994 and 1995 samples to represent season, sex, collection site, and PCB level as homogeneously as possible (Table 1). Individuals with PCB burden ≥1.8 ppm were considered "hot" and those with <1.8 ppm were considered "cold." This criterion was close to the U.S. Food and Drug Administration's action limit and represented the 50th percentile in PCB levels in the striped bass analyzed for otolith Sr (Fig. 1). Adult females (*n* = 43) and males (*n* = 45) were sampled from the Troy Dam region (Rkm 246), Catskill (Rkm 179), Poughkeepsie (Rkm 122), Haverstraw Bay (Rkm 64), Tappan Zee bridge (Rkm 43), Manhattan (Rkm 19), New York City Harbor, eastern Long Island Sound, and Long Island's south shore (Fig. 2; Table 1). Females ranged in size from 463 to 1007 mm total length and in age from 3 to 15 years. Males ranged in size from 457 to 858 mm and in age from 3 to 16 years (Table 1).

Table 1. Sample of spring- and fall-collected Hudson River striped bass.

	Females				Males			
	"Hot" (≥1.8 ppm PCBs)		"Cold" (<1.8 ppm PCBs)		"Hot" (≥1.8 ppm PCBs)		"Cold" (<1.8 ppm PCBs)	
	≥ Rkm 90	<Rkm 90	≥ Rkm 90	<Rkm 90	≥ Rkm 90	<Rkm 90	≥ Rkm 90	<Rkm 90
Fall (August–December, *n* = 47)								
Total PCB (ppm)	7.6±0.68	3.54±0.59		0.49±0.08	8.34±1.10	4.64±0.80		0.51±0.04
n	3	9	0	13	8	8	0	6
Total length (cm)	872.67±53.48	711.89±42.78		641.08±47.27	588.25±22.25	700±35.27		561.67±41.23
Weight (g)	7476.67±969.64	4138.89±686.77		3080.77±725.92	2093.75±299.31	4031.25±726.82		2295±616.76
Age (years)	12.33±1.67	8.00±1.03		6.15±1.10	7.63±0.82	9.13±0.93		4.33±0.33
Lipid (%)	4.98±1.01	5.12±0.64		3.77±0.54	3.41±0.76	5.41±1.45		5.82±0.52
Spring (April–June, *n* = 41)								
Total PCB (ppm)	4.88±1.00		1.07±0.09	1.03±0.17	6.78±1.31	2.51±0.01	0.86±0.09	0.7312±0.03
n	3	0	10	5	10	2	6	5
Total length (cm)	664.33±58.67		787.8±26.12	682±75.37	617.7±17.54	583.0±62.0	639.17±35.0	610.0±21.48
Weight (g)	3206.67±719.48		5926.9±701.76	4262.8±1806.09	2740±219.63	2650.0±450.0	3000.0±480.64	2528.0±324.32
Age (years)	6.33±0.88		7.8±0.55	6.6±1.36	8.5±1.14	6.5±1.5	5.67±0.76	5.00±0.32
Lipid (%)	6.34±0.66		4.50±0.37	5.842±1.09	6.33±1.08	7.08±1.42	5.56±0.65	5.49±0.93

Fig. 1. Total wet PCBs in an examined sample of Hudson River striped bass. The modeled lognormal distribution is presented by the curve.



Sagittal otoliths were removed from striped bass carcasses that had been sampled previously for PCB analysis. Otoliths were cleaned with 10% bleach solution and embedded in Spurr low-viscosity resin. Otoliths were sectioned transversely (sections were about 1 mm thick) through the otolith cores using a low-speed diamond metallurgical wafering saw. Sections were mounted on glass slides, polished initially with wet 600-grit sandpaper to remove major marks and scratches, and then polished in a slurry of 0.3-µm alumina until their surfaces were free of pits and abrasions. This polishing method was used to minimize artifacts in microprobe analysis (Kalish 1990). Finally, sections were rinsed with deionized water and placed in an ultrasonic cleaner to remove any residue resulting from the polishing procedure.

Annuli in striped bass otoliths have been verified to form at an annual rate, and precision in age determination was estimated to exceed 95% (Secor et al. 1995*a*). Each annulus comprised a narrow opaque zone and a wide translucent zone when viewed under transmitted light microscopy. Annuli were counted once for each fish under light microscopy (magnification 60 or 150×) along the sulcal ridge in transverse sections by a single reader.

Electron probe otolith microanalysis of Sr and Ca was performed by X-ray wavelength dispersive spectrometry using a JEOL JXA-840A microprobe (Center for Microanalysis, University of Maryland, College Park, Md.). Measurement of atomic weights of Sr and Ca was standardized using strontianite ($SrCO_3$) and calcite ($CaCO_3$) standards (Secor 1992). We routinely used two transects per otolith, spacing each point of measurement 25 µm apart for the initial transect, which ran from the first to fifth annulus. The second transect traversed narrower annuli corresponding to older ages; spacing between points was set at 13 µm. Each point was about 5 µm in diameter. To reduce error between machine runs, Sr was expressed as a ratio, Sr:Ca. Backscatter electron micrographs for each analyzed otolith showed series of low relative atomic mass (dark) zones that corresponded to the optically opaque zones of annuli. Each 5-µm measured "point" was visible in electron micrographs. These points were related to the distance from succeeding opaque zones. Points directly within an opaque zone were considered to represent early spring, prior to spawning (Secor et al. 1995*a*), and were thus the last points associated with a given year of life. Points immediately succeeding the opaque zone were considered to form just after the spawning season and represent the first part of a given year of life (i.e., spring). Points between opaque zones were assumed to sample age in linear proportion. For example, if four points were measured from annulus 7 to 8, then points were assigned ages 7.0, 7.25, 7.50, and 7.75.

Time series data of Sr:Ca were compiled for each striped bass. Based on laboratory and field experiments, Secor et al. (1995*b*) developed a logistic relationship between salinity and otolith Sr:Ca:

$$\text{Salinity habitation (ppt)} = 40.302\,(1 + 56.337\,e^{-1523.310(\mathrm{Sr/Ca})})^{-1};\ r^2 = 0.94,\ n = 54.$$

This model was used to convert Sr:Ca values to salinity chronologies. Salinity habitation estimated the salinity inhabited for the period of time represented by each Sr:Ca datum. Residuals from the logistic model indicated that Sr:Ca typically predicted salinity habitation with a precision error of less than ±6 ppt.

Mean salinities of the most recent growth season, the last two growth seasons, and the last three growth seasons were used as measures of recent habitat use. These variables were regressed against PCB level and contrasted using sequential sums of squares. The most recent growth season's habitat history explained most variance in PCB level, and this response was used to test season, sex, and site effects. To conduct a nested analysis of variance (ANOVA), fish were sampled across seasons (fall–winter versus spring), sexes (males versus females), PCB levels (<1.8 versus ≥1.8 ppm), and zone (<Rkm 90 versus ≥ Rkm 90). Fish analyzed from New York City Harbor, Long Island Sound, and the south shore of Long Island were only collected in fall and thus were excluded from the nested ANOVA. This reduced sample size from 88 to 63. The nested design directed the ANOVA to occur in hierarchal order at four levels:

$$\gamma_{ijklm} = \mu + \gamma_i + \beta_{j(i)} + \gamma_{k(ij)} + O_{\lambda(ijk)} + \xi_{(ijk\lambda)m}$$

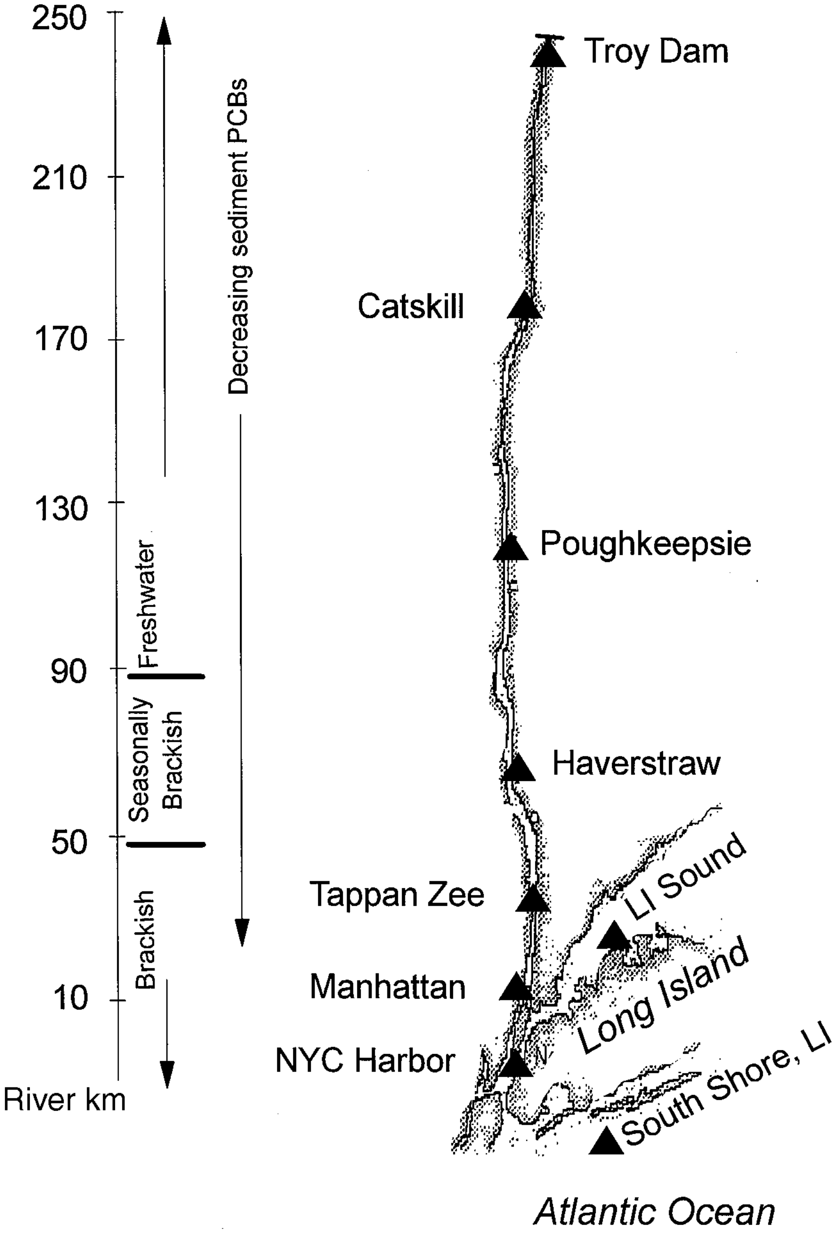
where γ_{ijklm} is the salinity experienced by an individual during its last growth season, μ is the overall mean, γ_i is the effect of the *i*th season, $\beta_{j(i)}$ is the effect of the *j*th sex, $\gamma_{k(ij)}$ is the effect of the *k*th zone, $O_{\lambda(ijk)}$ is the effect of the λth PCB level, and $\xi_{(ijk\lambda)m}$ is the random error component.

Statistical significance for factors was accepted at $\alpha = 0.05$ (type I sum of squares for type I error). Analysis of covariance was also performed to examine the effects of season, sex, and site on the relationship between total PCB body burden and recent salinity history. Site categories were Troy/Catskill/Poughkeepsie (≥ Rkm 90), Haverstraw/Tappanzee (≥ Rkm 20, <Rkm 90), Manhattan/NYC Harbor (<Rkm 20), and Long Island (coastal). The response variable was $\log_{10}$ transformed to normalize residuals.

Results

Salinity chronologies from individual striped bass showed three distinct migratory behaviors. All fish captured during fall and winter in the upper estuary in the vicinity of the Troy Dam had high PCB levels. Fish were predominately resident, inhabiting salinities of 5 ppt or less throughout most of their lives (Fig. 3). A single female (PCB = 7.3 ppm) sampled from this region during fall also exhibited resident behavior. Resident behaviors associated with high PCB contamination also occurred for spring-collected males and females but were less dependent on site of collection. In some individuals, salinity chronologies indicated a habitat shift from either low to high or high to low salinity (Fig. 4). One individual captured in the Troy region (Rkm 246) with a PCB level of 10.5 ppm used mesohaline habitats early in life and then suddenly shifted to freshwater/oligohaline habitats. Alternatively, an individual with low PCB body burden (0.4 ppm) inhabited freshwater for its first two growth sea-

Fig. 2. Collection sites (triangles) in the Hudson River estuary.



sons and then emigrated to marine or polyhaline habitats for the rest of its life. Shifts from low to high salinity were not always associated with low PCB body burdens. A Long Island captured fish with a relatively high PCB body burden (2.7 ppm) inhabited freshwater/oligohaline habitats early in life and then shifted to polyhaline/euhaline regions for most of the remainder of its lifetime (Fig. 4). A third pattern in migration was annual cycles from brackish to marine habitats, indicating possible spawning migrations (Secor and Piccoli 1996). Two such migrating females showed strong cyclic behavior (Fig. 5); the female with higher PCB body burden (7.2 ppm) inhabited lower salinity waters over its lifetime.

Salinity records for each individual were used to compute lifetime means, an overall index of an individual's past habitat use. Frequency distributions of lifetime salinities showed that fish classified as cold (<1.8 ppm) tended to grow in mesohaline/polyhaline environments (Fig. 6). Individuals classified as hot (≥1.8 ppm) and highly contaminated (≥4 ppm) tended to use predominately freshwater and oligohaline environments throughout their lives.

Salinity history over the most recent growth season explained slightly more variance in PCB level than other measures of recent habitat use and was used as an index of recent habitat history (Fig. 7). The PCB classification effect on recent habitat history was highly significant, explaining 22% of model variance. There was a significant, albeit highly variable, effect of total length ($p = 0.03$) on recent salinity history. Therefore, total length was included in the ANOVA as a covariate. ANOVA showed significant effects due to all factors except season (Table 2). Therefore, the nested analysis showed that PCB level was significantly influenced by recent habit history regardless of effects due to

Fig. 3. Representative time series of salinity habitation for resident striped bass. Salinity habitation was determined based on microanalysis of Sr:Ca. Total PCB body burdens (wet weight based) are indicated. Total PCB body burden was determined through the Aroclor method on a single fillet with skin on and scales removed (muscle tissue).

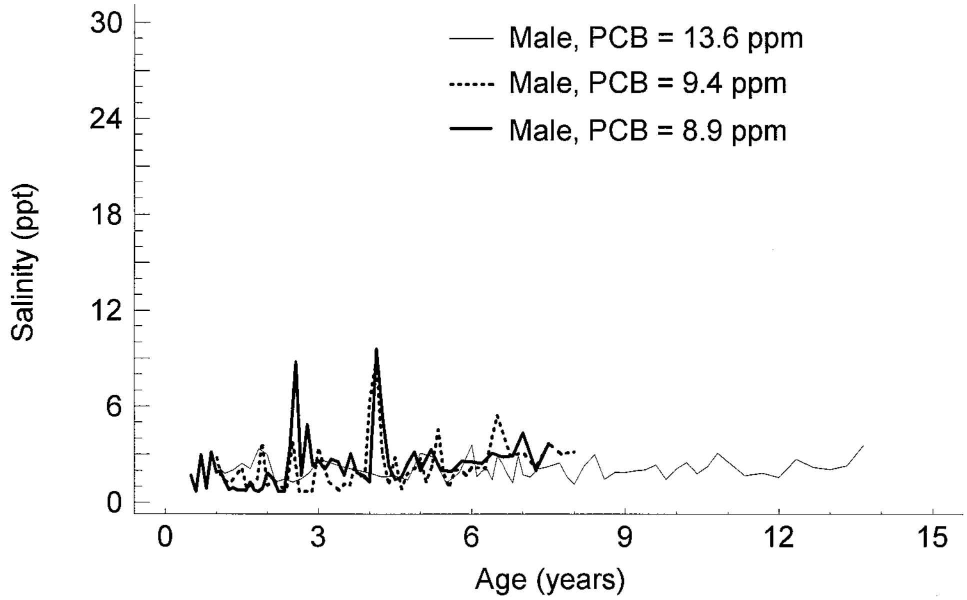
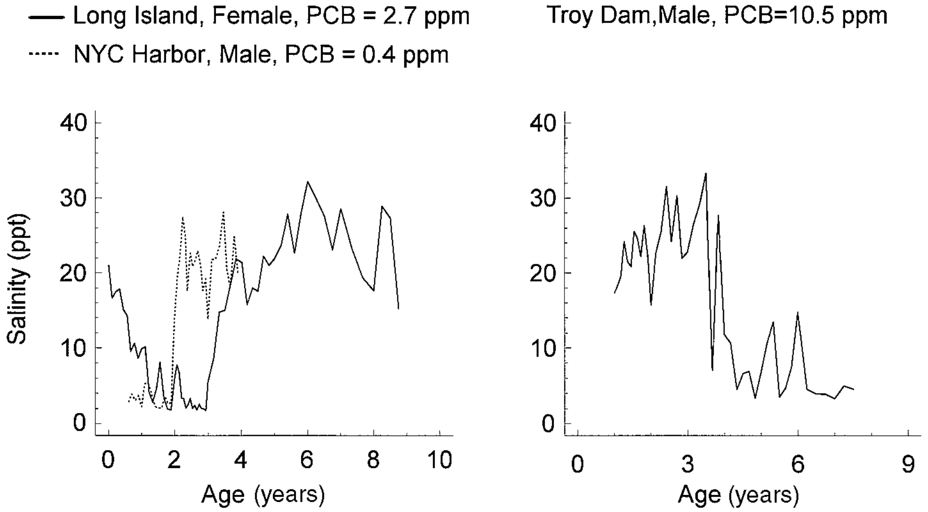


Fig. 4. Representative time series of salinity habitation of striped bass showing habitat shifts. Salinity habitation was determined based on microanalysis of Sr:Ca. Total PCB body burdens (wet weight based) are indicated.



size, sex, or site of collection. Site of collection explained most variance (36%); where fish are collected was largely influenced by where they had recently occurred.

PCB body burden was strongly and inversely related to recent salinity history ($r = -0.71$, $p < 0.001$). There was no significant effect of season on the relationship between recent salinity history and total PCBs (Fig. 7). In an ANOVA using salinity history as a covariate, sex did not significantly affect total PCBs ($p < 0.42$). Similarly, no season effect was observed on the relationship between recent habitat history and total PCBs ($p > 0.32$) (Figs. 7 and 8). Site did significantly influence the relationship between total PCBs and recent habitat history ($p = 0.05$). The site effect was due to fish collected in the upper Hudson River estuary (≥Rkm 90), which showed resident behaviors and high PCB contamination (Fig. 8).

Discussion

A previous model of PCB contamination in Hudson River striped bass (Thomann et al. 1991) assumed that the entire population of striped bass began emigrating into coastal environments following sexual maturity. However, salinity chronologies determined for striped bass collected during 1994–1995 corroborate recent findings (Secor and Piccoli 1996), which indicated that Hudson River striped bass migratory behavior is highly variable. We observed a resident contingent of fish, predominately males, in the upper Hudson

Fig. 5. Representative time series of salinity habitation of female striped bass showing anadromous migratory behavior. Salinity habitation was determined based on microanalysis of Sr:Ca. Total PCB body burdens (wet weight based) are indicated.

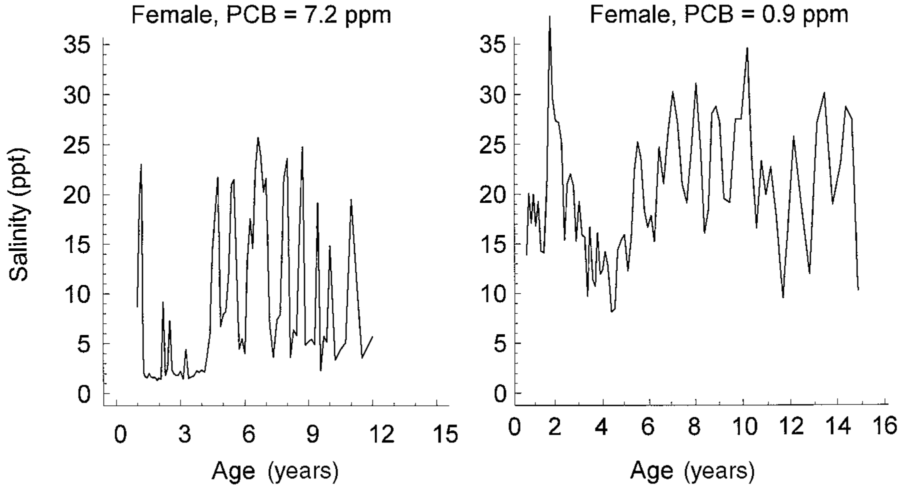


Fig. 6. Frequency histogram of lifetime salinity habitation for "cold" (<1.8 ppm PCBs), "hot" (≥1.8 ppm PCBs), and highly contaminated (≥4 ppm PCBs) Hudson River striped bass.

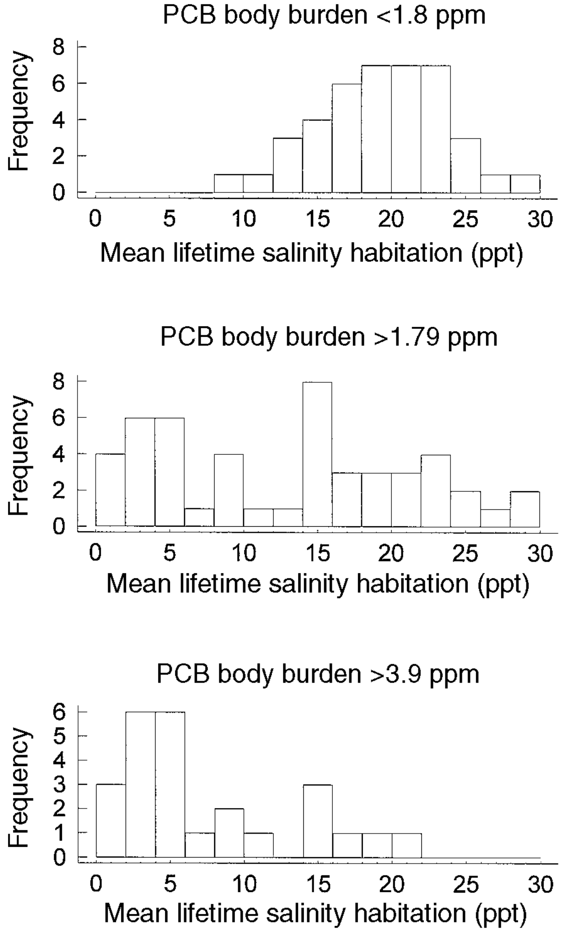
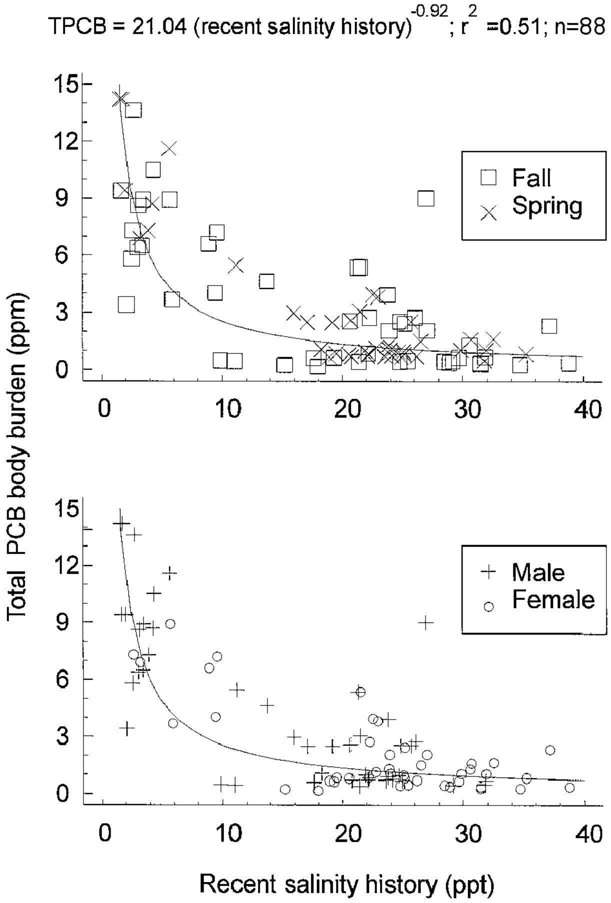


Fig. 7. Mean salinity history of the most recent growth season versus total PCB body burden in striped bass by season and sex. The coefficient of determination for a power function is indicated.



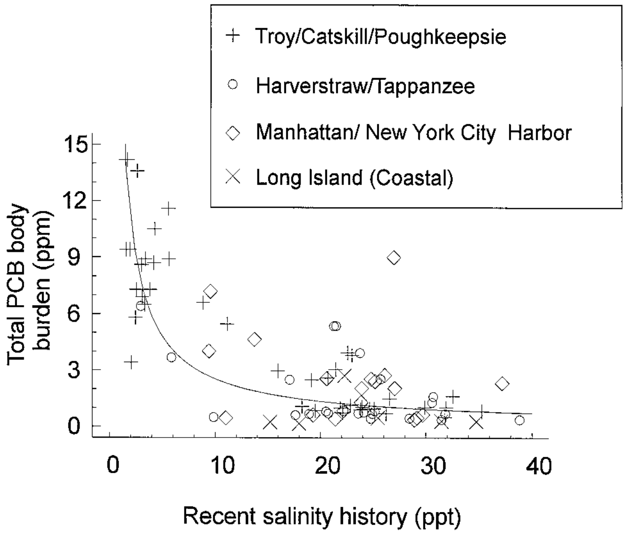
River estuary that were apparently susceptible to high PCB contamination. This trend is supported by the close proximity of this contingent to the most highly contaminated sediments in the Hudson River estuary. Important forage fish for striped bass, blueback herring (*Alosa aestivalis*) and alewife (*Alosa pseudoharengus*) congregate below Troy Dam and

Table 2. Nested ANOVA of season, sex, site of collection, and level of PCB contamination effects on recent salinity history (n = 63).

Variable	df	Sum of squares	Significance level (p)
Covariate			
Total length	1	336.1	0.002
Class variable			
Season	1	394.6	0.001
Sex (season)	2	155.9	0.11
Site (season–sex)	4	790.8	0.001
PCB (season–sex–site)	6	487.7	0.04

Note: Striped bass total length was used as a covariate in the analysis. Season levels were fall and spring, site levels were ≥Rkm 90 and <Rkm 90, and PCB levels were <1.8 and ≥1.8 ppm. Factors in parentheses indicate the nesting procedure. For example, PCB (season–sex–site) refers to variance explained by PCB level nested within combinations of season, sex, and site.

Fig. 8. Mean salinity history of the most recent growth season versus total PCB body burden in striped bass by collection site.



may play a role in the resident behavior of striped bass and their high contaminant levels (K. Hattala, New York State Department of Environmental Conservation, New Paltz, N.Y., personal communication). Sloan and Armstrong (1988) reported total PCB levels of 2–5 ppm for these species from 1980 collections.

In our application of otolith microanalysis, we assumed that Sr in striped bass otoliths was reflective of where the fish lives. This assumption is based on laboratory and field studies (Secor et al. 1995*b*) that showed a strong positive relationship between salinity and Sr:Ca in striped bass otoliths. We have also assumed that otolith microanalysis proportionately sampled all seasons. For instance, otolith growth probably slows or ceases during the midwinter months. Therefore, we are not sampling each season equally. Nevertheless, because PCB uptake is expected to occur primarily in growing fish, we believe that otolith microanalysis serves as a useful measure of habitat history in contaminant studies.

Recent habitat use was a strong determinant of PCB contamination. ANOVA and regression tests showed that recent salinities at which striped bass grew were strongly and negatively related to PCB levels independent of any effects due to season, sex, site of collection, or fish size. Results supported the expectation that fish inhabiting highly contaminated freshwater regions during the growth season before capture will not be able to significantly reduce body burden due to growth dilution. In some cases, otolith microanalysis revealed that fish that shifted from coastal or brackish habitats to up-estuary freshwater habitats were likely to show high PCB levels. However, the converse was not always true: fish that shifted from freshwater to brackish marine habitats did not always reduce their PCB levels, again indicating the possibility of a down-estuary source of PCBs. This result corresponds to recent observations of relatively high mean PCB levels in fish collected in the New York Harbor region (Skinner et al. 1996). For instance, in 1993, mean PCB level for this region was 3.4 ppm (Sloan et al. 1995), a level much higher than adjacent up-estuary regions. This level is in contrast with the overall pattern of down-estuary dilution of PCBs and indicates other sources of PCBs in the Hudson River estuary.

Unlike commercial fishing in the Hudson River, recreational angling for striped bass has become an increasingly important industry over the past decade. At present, the New York State Department of Environmental Conservation allows anglers possession of two fish of at least 71 cm total length. High fishing effort by charter, party, and private vessels as well as shore angling exists in the Hudson River estuary and along both coasts of Long Island (B. Young, New York State Department of Environmental Conservation, East Setauket, personal communication). Striped bass collected in the upper estuary (≥ Rkm 90) during the fall are likely to be resident fish that are highly contaminated. Fishing in the upper estuary should continue to be restricted. In addition, health warnings could be revised to reflect the increased likelihood of contaminated striped bass collected in up-estuary regions during fall. Fishing effort in the lower estuary (Rkm 0–60) and Long Island Sound predominantly targets fish that are part of a more highly migratory contingent. Therefore, fish captured in these regions are less likely to be highly contaminated.

Previous models of the long-term behavior of PCBs in striped bass were biased towards coastal habitat use in adult striped bass and underrepresented PCB burdens in the overall Hudson River population. The fraction of the population that is resident (or spends parts of its life in the New York Harbor region) is unknown and would be expected to vary on an annual and generational time frame based on changes in recruitment and exploitation of the more migratory contingents of the population. The high degree of variability and unpredictability in the spatial dynamics of the Hudson River striped bass prescribes more intensive monitoring of migration patterns and individual-based modeling approaches (Van Winkle et al. 1993) to predict future rates of PCB loss.

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