



Patterns of migration in Hudson River striped bass as determined by otolith microchemistry

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Abstract

Ontogenetic patterns of migration in Hudson River striped bass were measured using microprobe analysis of strontium (Sr) in otoliths. Otoliths of 88 adult striped bass collected in 1994 and 1995 were analyzed for Sr content, from which past histories of habitat use—as measured by salinity—were constructed. Marginal increment analysis of otoliths was conducted to correctly assign microprobe measurements to time of year (season). We classified striped bass into distinct, cohesive migratory “contingents”. Contingents exhibited four dominant spatial behaviors: (1) long-term residence in the upper Hudson Estuary; (2) long-term residence in the lower Hudson Estuary and western Long Island Sound; (3) coastal habitat use; (4) abrupt mid-life habitat shifts between freshwater and saltwater environments. A freshwater-oligohaline resident behavior was observed for 94% of individuals collected near Troy Dam, located at the uppermost tidal extent of the Hudson River. As further evidence of their residency, these individuals were also highly contaminated by polychlorinated biphenyls (PCBs) due to a local point source. Striped bass may establish residence in the upper estuary because of enhanced foraging opportunities below the Troy Dam. Our study supported Clark’s contingent hypothesis, demonstrating that divergent habitat use patterns occur throughout the life-spans of Hudson River striped bass.

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1. Introduction

The striped bass (*Morone saxatilis*) is an important recreational and commercial temperate sea bass (family Moronidae) in the Hudson River and coastal marine waters of New York, US. Historically, gillnet and haul-seine commercial fisheries were important in the

Hudson River and the eastern south shore of Long Island (Fig. 1; Cole, 1978; McLaren et al., 1988). The Hudson River commercial striped bass fishery was closed in 1976 due to polychlorinated biphenyl (PCB) contamination, which exceeded the US Food and Drug Administration action level of 2 ppm. High levels of PCBs have persisted through the 1980s and 1990s, and the fishery remains closed (Sloan et al., 1995). Recreational angling is permitted, and while no prescription against consumption of angled striped bass exists, warnings against consuming striped bass and other fishes taken from the Hudson River are well advertised to the public.

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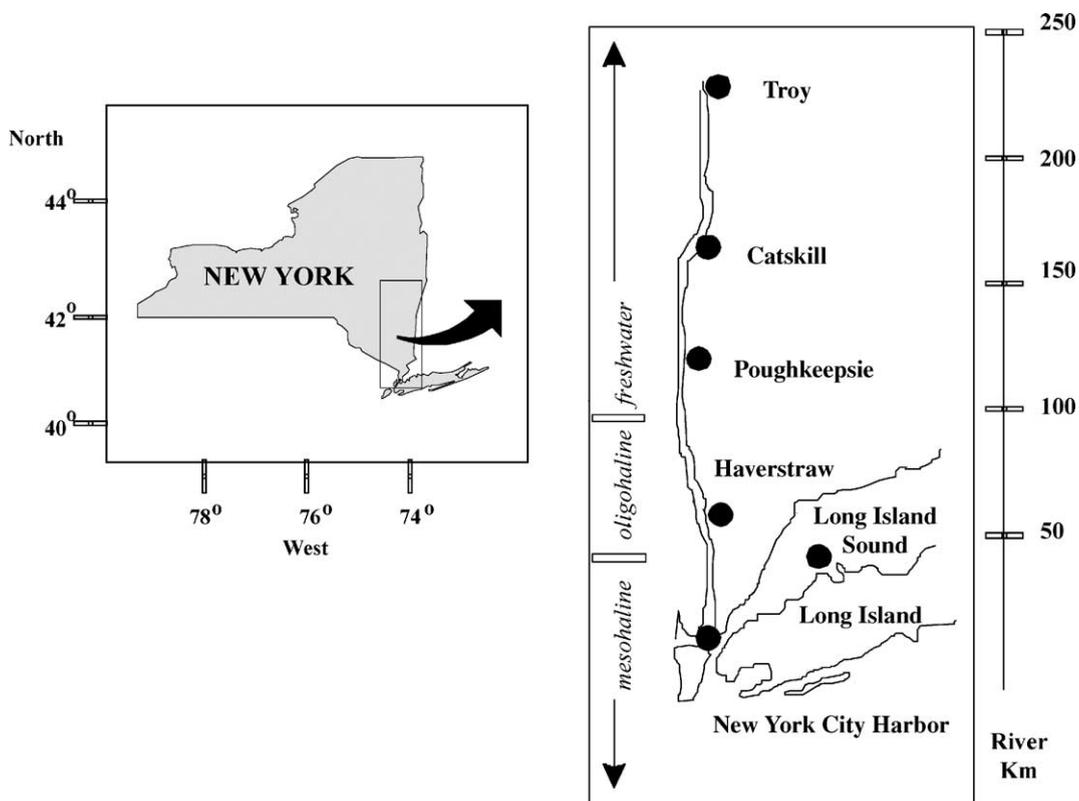


Fig. 1. Map of Hudson River estuary, showing Troy Dam at extreme northern limit of estuary. Salinity zones, striped bass collection sites, and river kilometers are shown.

While it is generally concluded that striped bass contamination by PCBs arises from substantial point sources in the upper Hudson River (Baker et al., 2001), forecast models have been hampered by an oversimplified concept of striped bass migration. Early meristic (Raney et al., 1954) and tagging work (Clark, 1968), and recent otolith composition studies (Secor and Piccoli, 1996; Zlokovitz and Secor, 1999) provide evidence that individual migration patterns within the HR population are highly variable. In simulations, migration has been stereotyped as an anadromous circuit, whereby all striped bass leave the system, migrating into coastal habitats at a certain age (Thomann et al., 1991). Variable migration behaviors can result in differential vulnerabilities to harvest and pollution (Secor, 1999). For example, a limited commercial fishery in adjacent regions off the eastern south coast of Long Island is allowed under the assumption that fish captured there primarily

utilize coastal habitats and have limited exposure to PCB sources in the Hudson River. The aim of this paper is to describe and classify individual migratory behaviors of Hudson River striped bass.

Past tagging studies have yielded conflicting views on patterns of migration and habitat use by Hudson River striped bass. Most notably, Clark (1968) proposed a “contingent” behavior within stocks of striped bass (the term “contingent” was originally used to describe a discrete sub-population of juvenile Atlantic herring that undertook a specific pattern of habitat use (Hjort, 1914)). Based upon ca. 500 mostly immature striped bass tagged and recaptured throughout the New York Bight, Clark proposed three major contingents of Hudson River origin fish: those principally utilizing “Hudson Estuary”, “Hudson–Atlantic” or “Hudson–West Sound”. This hypothesis was later questioned by Waldman et al. (1990), who conducted the most intensive tagging study to date: 28 667 striped

bass were tagged between 1984 and 1986 in the lower Hudson River and New York City Harbor. The fish ranged 20–72 cm TL and larger fish (50–72 cm) were found to disperse greater distances. Waldman et al. (1990) argued that Clark's contingents were the likely result of size-dependent migrations rather than conservative lifetime migration behaviors.

The two major opposing views on migration can be summarized as follows: (1) continuous variation around a single ontogenetic trajectory (Waldman et al., 1990); (2) discrete migratory groups, where patterns of migration and habitat use persist throughout ontogeny (Clark, 1968). Here, we seek to evaluate Clark's contingent hypothesis of lifetime differences in habitat use based upon a retrospective analysis of habitat use. Habitat use is measured as salinity and estimated by otolith Sr chronologies (Secor and Piccoli, 1996). We test Clark's hypothesis by classifying past ontogenetic migrations for a sample of 88 males and females collected during the 1994/1995 fall foraging seasons and 1995 spring spawning season from the Hudson River and Long Island waters. Further, we evaluate the consequences of these migratory classifications on PCB contamination in Hudson River striped bass.

2. Methods

Using otolith microprobe analysis of Sr, we generated life-history chronologies for 47 fall-collected and 41 spring-collected Hudson River striped bass (Table 1). Fall-collected fish were collected during the months of August, October, November, and De-

cember in 1994 and 1995. Spring-collected fish were collected during the months of April, May, June, and July 1995. Most fish were collected as part of New York State Department of Environmental Conservation monitoring surveys by beach haul seine (150 m long \times 3.7 m deep). PCB analysis was performed on fillets (skin not removed) by the Aroclor method (Sloan et al., 1995). PCB values reported here are for summed Aroclors, presented on a wet weight specific basis.

Otoliths (sagittae) were extracted, soaked in 10% sodium hypochlorite solution to remove organic tissue, rinsed with deionized water, and embedded within a Spurr epoxy (Secor, 1992). Transverse sections, approximately 1 mm thick, were cut through the otolith cores using a metallurgical wafering saw. The sections were mounted on glass slides, polished on wetted 600 grain sandpaper, and polished again on a slurry of 0.3 μ m alumina until their surfaces were free of pits and abrasions, which can cause artifacts in microprobe analysis. After polishing, sections were ultrasonically cleaned in deionized water to remove residual polishing compounds, and coated with a thin conductive layer of carbon to prevent charge build-up (Gunn et al., 1992).

Electron microprobe analysis of otolith 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 molar proportions of strontium and calcium was standardized using strontianite (SrCO₃) and calcite (CaCO₃) standards (Secor, 1992). Spacing among points ranged 13–25 μ m to

Table 1
Samples of Hudson River striped bass taken for otolith microprobe analysis of Sr:Ca^a

Site	River (km)	Fall 1994			Spring 1995		
		Male	Female	PCB \pm S.D.	Male	Female	PCB \pm S.D.
Troy Dam	246	9	2	8.1 \pm 2.6	5	2	8.8 \pm 3.1
Catskill–Kingston	151–200	–	–	–	2	9	1.3 \pm 0.9
Poughkeepsie	123	–	–	–	7	2	1.9 \pm 1.4
Haverstraw Bay	60	5	6	2.6 \pm 2.3	3	3	1.1 \pm 0.7
Tappan Zee	38	1	–	0.6	4	2	1.2 \pm 0.7
New York City Harbor	0	7	9	2.7 \pm 2.4	–	1	1.3
Long Island	Marine	1	7	0.9 \pm 0.9	–	–	–

^aFall samples include August–December and Spring samples include April–July. See Fig. 1 for site locations. River (km) is distance upstream from the mouth of the Hudson River. Samples sizes are given by season and gender. Mean PCB levels \pm 1 S.D. are also presented. One individual from spring 1995, not included in Table 1, was from Poughkeepsie and had an undetermined gender.

allow ≥ 5 points per annulus. Each point is $5 \mu\text{m}$ in diameter and ca. $1 \mu\text{m}$ deep. Because Sr incorporation in otoliths is a competitive process with Ca uptake (Chowdhury and Blust, 2001), Sr was expressed as a ratio, Sr:Ca. Backscatter electron micrographs for each analyzed otolith showed series of low electron density (dark) zones that corresponded to the optically opaque zones of annuli. Point measurements were related to the annulus or interannular material they sampled. Points directly within an opaque zone were considered to represent early spring, prior to spawning (Secor et al., 1995a), 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 represented the first part of a given year of life (i.e., spring).

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

$$\text{Salinity habitation (ppt)} = \frac{40.3}{1 + 56.3 e^{-1523(\text{Sr}/\text{Ca})}},$$

$$r^2 = 0.94, n = 54 \quad (1)$$

This model was used to convert Sr:Ca values to salinity habitation. Salinity habitation estimated the salinity inhabited for the period of time represented for each Sr:Ca datum. Residuals from the logistic model indicated that Sr:Ca typically predicted salinity habitation with a precision error less than 7 ppt.

In previous applications of otolith microchemistry, it was necessary to assume that otolith growth was constant throughout the year. Points between annuli were assumed to sample age in linear proportion. For example, if 10 points were sampled between annuli 5 and 6, then points would be assigned ages 5.0, 5.1, 5.2, . . . , 6.0 (Secor, 1992). This assumption remains largely untested and depends upon the seasonal rate of otolith growth. Declining otolith growth during winter months would result in a temporal sequence in salinity habitation that under represented months of slow, zero, or negative growth and over represented months of faster growth. To estimate seasonal otolith growth, striped bass were collected monthly and marginal increment analysis was conducted. Otoliths were sampled from 129 adult striped bass captured during four distinct seasons: mid-winter (January–February,

$N = 43$), spring (April–June, $N = 45$), summer (July–August, $N = 9$), and fall (October–December, $N = 32$). Age ranged from 3 to 16 years; TL ranged from 500 to 1000 mm. We were unable to obtain adult striped bass from the Hudson River in mid-winter during January–March, and used winter-captured individuals from the Chesapeake Bay ($N = 17$) and mid-Atlantic ($N = 26$) coastal waters. Water temperatures in the mid-Chesapeake Bay during winter are $< 10^\circ\text{C}$ (Hartman and Brandt, 1995) and similar to temperatures in the Hudson River (Cooper et al., 1988) during winter.

Annular increments between successive opaque zones were measured along a transect parallel to the ventral sulcal ridge. The marginal increment was measured as the distance between the last opaque zone and the outer edge of the otolith. A marginal increment ratio (MIR) was calculated:

$$\text{MIR} = \frac{\text{width of marginal increment}}{\text{width of penultimate annular increment}} \quad (2)$$

where the penultimate annular increment was defined as the last full translucent inter-annular zone deposited previous to the marginal increment. The MIR reduced biases associated with ontogenetic variation in widths of annuli and inconsistencies in the location where the otolith was sectioned. Such inconsistencies were also reduced by sectioning directly through the core.

Probed points were related to seasonal increments (SIs) by first considering inter-annular distance (IAD) as the distance of each probed point from the previous opaque zones. SI, the fraction of the year represented by each transect point, was calculated based upon the month of capture. Here we assumed that the peripheral marginal increment measures were equivalent to IAD increments. Theoretically, these IADs cannot represent more than 1 year (12 months). But in fact, due to the manner in which MIR were measured, IAD values did occasionally exceed 1.0 especially for fall and winter months. Therefore, we constrained the relationship to $\text{MIR} = 1$ for $\text{SI} > 0.8$. At $\text{SI} > 0.8$ (fish collected after October), $\sim 30\%$ IAD values exceeded unity.

MIRs were used to model seasonal otolith growth. Modes in IAD were estimated for each seasonal sample and fit with a multiplicative model (Fig. 2):

$$\text{SI} = 0.784(\text{mode IAD})^{0.451} \quad (3)$$

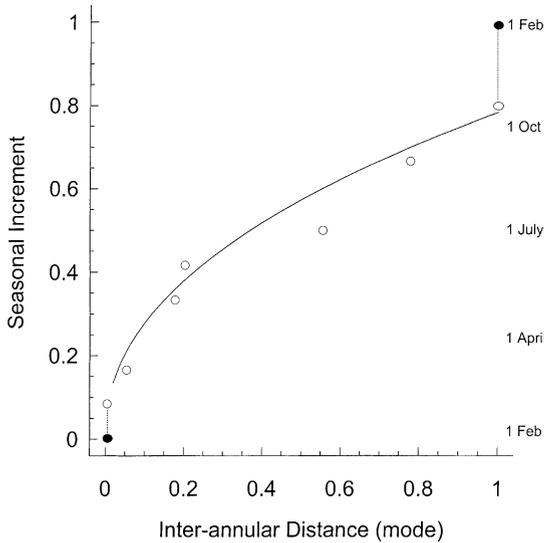


Fig. 2. Seasonal otolith growth model constructed from marginal increment analysis of adult Hudson River striped bass otoliths. It shows SIs (open circles) fit to modes in IAD. Months corresponding to SIs are shown on right. Filled circles represent opaque zones.

Overall age was assigned to each transect point as

$$\text{Age} + \text{SI} \tag{4}$$

where age is the number of annuli (years), and SI is predicted from IAD (Table 2). The exponent in Eq. (3) indicates a lower rate of increase in SI at

Table 2
Example of conversion of IAD to SI and overall age^a

Age (years)	IAD (chronology)	SI (Eq. (3))	Overall age (years)
3	0	0	3
3	0.1	0.28	3.3
3	0.2	0.38	3.4
3	0.3	0.46	3.45
3	0.4	0.52	3.5
3	0.5	0.57	3.55
3	0.6	0.62	3.6
3	0.7	0.67	3.65
3	0.8	0.71	3.7
3	0.9	0.75	3.75

^aIn this example, 10 transect points were evenly spaced between the third and fourth opaque zones. Note that conversion of these points to SIs results in more points representative of summer and fall seasons and fewer points representative of winter and early spring.

high IADs. Otolith growth slows down in late fall as the marginal increment (IAD) reaches a maximum. Large changes in IAD during summer and early fall indicated that habitat use as a function of time (SI) was being recorded at a disproportionately higher rate.

Striped bass were placed into salinity classifications based upon the range and central tendency of life history chronologies. Salinity classifications were based on the following major salinity zones: Freshwater-Oligohaline = 0–8 ppt, Mesohaline = 9–18 ppt, Polyhaline = 19–29 ppt, and Euhaline (marine) >30 ppt. An additional category was considered, those transects that showed abrupt mid-life change, termed habitat shift. Mean lifetime salinity was estimated as the mean of all salinity points derived from a Sr:Ca chronology. Distributions of lifetime salinity records were analyzed for modal separation. We specified that modal means should be separated by more than 2 standard deviations (S.D.) (separation index = 2.0; Gulland and Roseberg, 1992). Distributions were analyzed using ENORMSEP (Gayanilo et al., 1996), which is a maximum likelihood method for identifying modes.

3. Results

3.1. General migration patterns

Among fall-collected striped bass, the greatest fraction (32%) of sampled individuals utilized marine and polyhaline habitats (Table 3; Fig. 3). Some fish (23%) showed habitat shifts, shifting from freshwater to saltwater, or saltwater to freshwater, mid-way through life (Fig. 4). Habitat shifts from polyhaline to oligohaline habitats were exhibited by 9% of sampled fish (Fig. 4, ID = 69, 66); shifts from oligohaline to polyhaline or oligohaline to mesohaline habitats occurred for 15% of the sample (Fig. 4, ID = 71, 72). Note that highly contaminated individuals tended to show a past habitat shift from polyhaline to oligohaline habitats (Fig. 4, ID = 69, 66, 67). Although striped bass are typically considered anadromous teleosts, a significant number of individuals ($n = 9$; 19% of fall fish) exhibited resident behavior, using freshwater-oligohaline habitats for the majority of their life-span (Fig. 5). All of these individuals were highly contaminated with PCBs

Table 3

Assignment of sampled Hudson River striped bass to contingents (salinity zones), by season and sex^a

Contingent	Female (N)	Male (N)	Unknown (N)	Total (%)
Fall (1994, 1995)				
Marine-polyhaline	11	4	0	15 (32)
Meso-polyhaline	3	3	0	6 (13)
Mesohaline	5	1	0	6 (13)
Freshwater-oligohaline	2	7	0	9 (19)
Habitat shift 1-poly-oligo	2	2	0	4 (8)
Habitat shift 2-oligo-poly	5	2	0	7 (15)
Fall subtotal	28	19	0	47
Spring (1995)				
Marine-polyhaline	12	2	1	15 (37)
Meso-polyhaline	3	11	0	14 (34)
Mesohaline	1	1	0	2 (5)
Freshwater-oligohaline	1	4	0	5 (12)
Habitat shift 1-poly-oligo	0	1	0	1 (2)
Habitat shift 2-oligo-poly	1	2	0	3 (7)
Habitat shift 1 and 2	0	1	0	1 (2)
Spring subtotal	18	22	1	41
Total (fall/spring)	46	41	1	88

^aPercent of striped bass in each salinity zone is shown in parentheses. Marine-polyhaline = salinities all >19 ppt, meso-polyhaline = 9–29 ppt, mesohaline = 9–18 ppt, fresh-oligohaline = 0–8 ppt.

(mean = 8.1 ppm). Only 17% of individuals used marine habitats for the majority of their life-span.

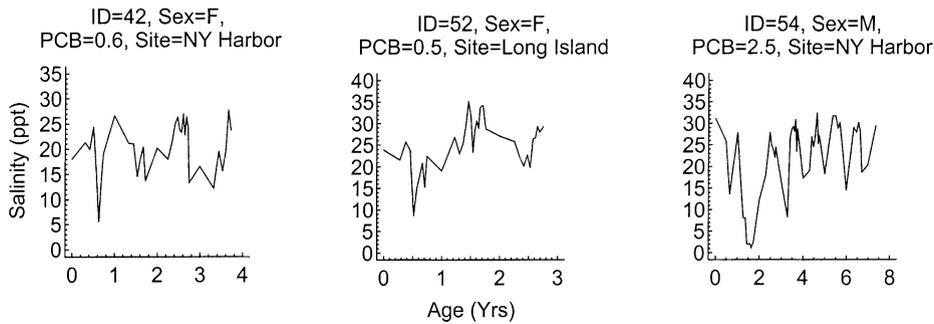
Among spring-collected striped bass, the greatest fraction of individuals (37%) showed marine-polyhaline habitat use (Table 3; Fig. 3). As with fall-collected fish, several (12%) exhibited habitat shift behavior (Fig. 4). About 7% of the sample shifted from oligohaline to polyhaline habitats (Fig. 4, ID = 84); one highly contaminated individual (ID = 30; PCB = 11.6 ppm) shifted from polyhaline to oligohaline habitats. Another contaminated individual (ID = 33; PCB = 5.5 ppm) exhibited two distinct habitat shifts, first moving from polyhaline to oligohaline habitats, residing in oligohaline waters, and then abruptly shifting back to polyhaline habitats (Fig. 4). Five striped bass, 12% of the spring sample, showed resident behavior (Fig. 5). Like the fall sample, all of these individuals were highly contaminated by PCBs (mean = 8.8 ppm). Nearly 15% of spring-collected individuals spent the majority of their lifetimes in marine habitats (Fig. 3).

In both spring and fall samples, there were often annual nadirs in salinity in the early portion of each year. These abrupt seasonal nadirs were consistent with the

expected timing of spawning runs to the upper Hudson estuary, followed by rapid down-estuary movement to higher salinity waters. Note, however, that these low points often did not reach levels indicative of the freshwater-oligohaline spawning reaches (e.g. Fig. 3, ID = 54, 28; Fig. 6, ID = 39, 41, 79), probably due to the fact that these individuals did not spend enough time in the upper estuary to show a clear freshwater signal.

Between seasons, resident behavior was observed for the majority (94%) of fish collected in the Troy Dam region (river, 246 km). Many of these individuals spent their entire lifetimes in freshwater-oligohaline zones (Fig. 5) and all showed high contamination by PCBs. Others used mesohaline-marine habitats early in life, and then shifted to freshwater-oligohaline residence for the 2–4 years before capture (Fig. 4, ID = 69, 66, 67, 30). A single striped bass captured at Troy did not exhibit significant up-estuary residence (Fig. 3, ID = 17). The majority of fish in the Troy region were male; however, several females showed the same pattern of lifetime residence (e.g. Fig. 5, ID = 57, 58, 4). In the middle and lower estuary (Catskill-Haverstraw), we observed a mix of oligohaline, mesohaline (Fig. 7,

Polyhaline-Marine Contingent - Fall



Polyhaline-Marine Contingent - Spring

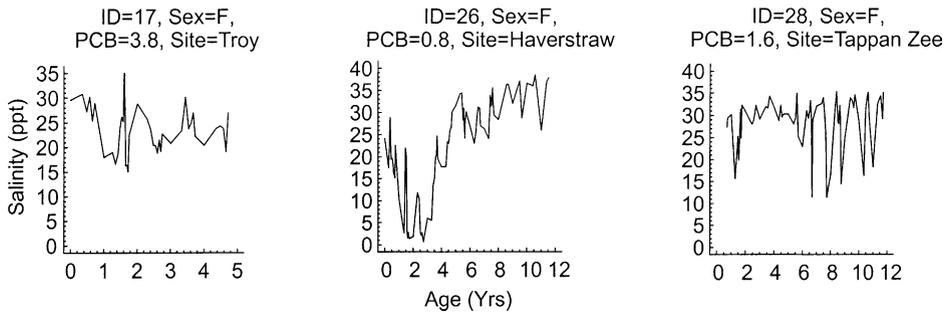


Fig. 3. Representative salinity chronologies for adult Hudson River striped bass classified as polyhaline-marine contingent. All chronologies were determined by electron microprobe analysis of otolith strontium. Note for some marine contingent individuals, the y-axis is scaled from 0 to 40 ppt. M: male; F: female; PCB: polychlorinated biphenyls (ppm).

ID = 81, 16), polyhaline, and marine habitat use patterns. Fish captured near the mouth of the estuary, New York City Harbor, and Long Island waters exhibited mainly polyhaline-marine habitat use (Fig. 3).

For most individuals (70%), mesohaline and polyhaline habitats were used during the first and second year of life, generally followed by up-estuary movement and freshwater-oligohaline residence (e.g. Fig. 3, ID = 54, 26; Fig. 4, ID = 72, 66, 67; Fig. 5, ID = 58; Fig. 6, ID = 85, 41). Because not all individuals were sampled during their first year of life, the fraction of fish showing this behavior may have been under represented.

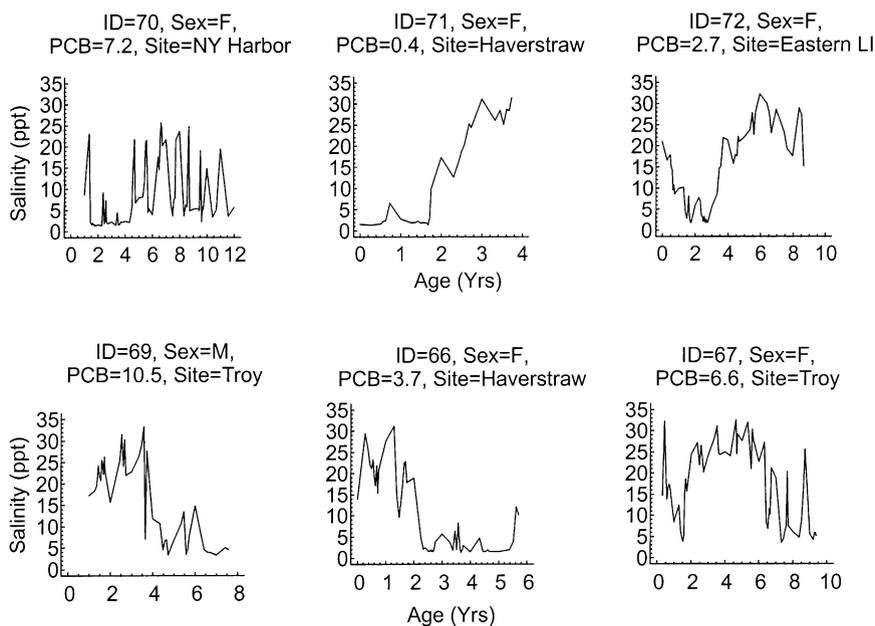
Other behaviors shown by the salinity chronologies were more erratic. Most striking were those individuals with large habitat shifts, from low to high, and high to low salinities (Fig. 4). These habitat shifts were

not related to any particular age or site of collection. Some individuals exhibited brief seasonal excursions between zones, while others showed longer term use of differing salinity zones in the same year or over a number of years.

3.2. Mean lifetime salinity

Males showed a discontinuous distribution of mean lifetime salinities (Fig. 8a; separation index = 5.5 S.D.), with two discrete modes centered at 3.9 ppt (± 2.3 S.D.) and 17.0 ppt (± 2.8). More resident males were included in the fall than the spring sample. Females showed a more continuous distribution of mean lifetime salinities (Fig. 8b), but for combined data, two modes were distinguishable with a separation index of 2.0. Modes were centered at 13.7 ppt (± 6.3) and

Habitat Shift - Fall



Habitat Shift - Spring

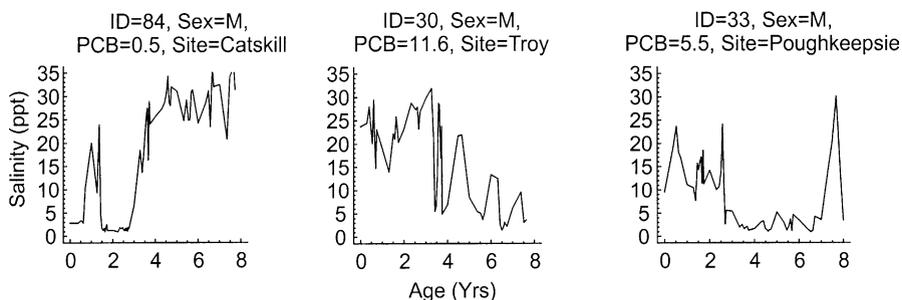


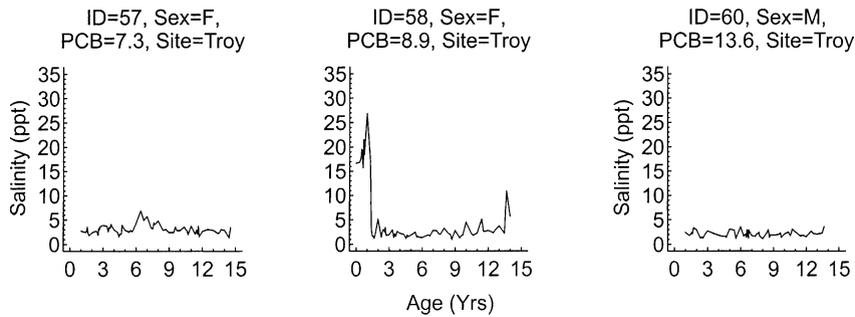
Fig. 4. Representative salinity chronologies for adult Hudson River striped bass classified as habitat shift contingents. All chronologies were determined by electron microprobe analysis of otolith strontium. M: male; F: female; PCB: polychlorinated biphenyls (ppm).

22.9 ppt (± 2.9). The majority of life time salinities fell between 13 and 30 ppt. Several females ($n = 3$) showed oligohaline resident behaviors (< 6 ppt). Overall, oligohaline resident behaviors (< 5 ppt) were more common in males; females showed more pronounced use of polyhaline and marine habitats.

Lifetime salinities were significantly ($P < 0.001$) and inversely correlated (males: $r = -0.63$; females;

$r = -0.64$) with total PCB levels (\log_e -transformed to meet variance assumptions; Fig. 9). For males, the discontinuous pattern of habitat use corresponded to a discontinuous pattern of PCB levels, principally due to the group of resident males showing consistently high contamination levels. More continuous patterns in both lifetime salinity and PCB levels were observed for females.

Resident Contingent - Fall



Resident Contingent-Spring

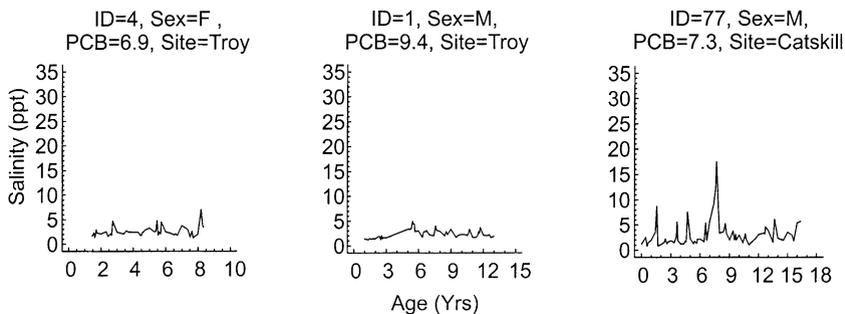


Fig. 5. Representative salinity chronologies for adult Hudson River striped bass classified as resident contingent. All chronologies were determined by electron microprobe analysis of otolith strontium. M: male; F: female; PCB: polychlorinated biphenyls (ppm).

4. Discussion

4.1. Accuracy, precision, and limiting assumptions

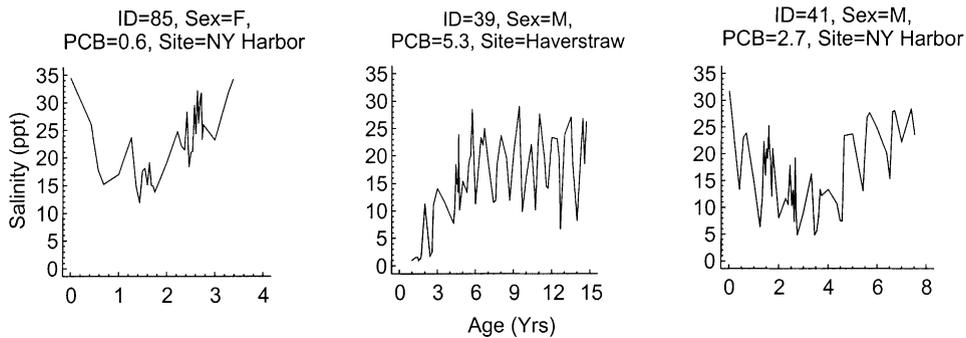
Precision error and spatial resolution of the electron microprobe analysis is critical to the charting of individual migratory histories (Secor, 1992) and the accurate classification of striped bass into migratory contingents. Several recent otolith microchemistry studies have addressed issues of accuracy and precision (Gunn et al., 1992; Secor, 1992; Secor et al., 1995b). Striped bass otoliths have been found to be resilient to electron beam power densities (Secor, 1992), compared with work on salmonid otoliths (Kalish, 1990). This resiliency permitted analysis of small points ($5 \mu\text{m} \times 5 \mu\text{m}$) at high accelerating voltage (25 kV) and probe current (20 nA). In previous

work using the same instrument and procedures as in this study, Secor (1992) calculated a detection limit of 580 ppm for Sr. Instrument error was calculated at <1% for Ca counts and 8.2% for Sr counts (95% confidence intervals for Sr:Ca are ± 0.003 ; Goldstein et al., 1981; Secor, 1992). Repeated measures of the same point ($n = 9$) showed 98% precision in Sr:Ca.

The logistic regression relating environmental salinity to otolith Sr:Ca (formula 1) yielded an accuracy of approximately 6 ppt in Sr:Ca-based prediction of salinity. This error indicates that the otolith microchemistry method can be used to distinguish among conventional salinity-habitat designations. Secor et al. (1995b) demonstrated that temperature was a minor determinant of Sr:Ca ratios in striped bass.

Correction for otolith growth in assignment of Sr:Ca ratios indicated highest temporal resolution

Meso-Polyhaline Contingent - Fall



Meso-Polyhaline Contingent - Spring

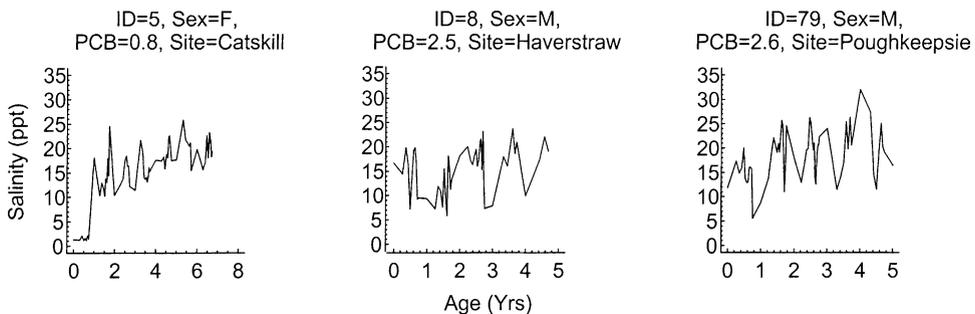


Fig. 6. Representative salinity chronologies for adult Hudson River striped bass classified as mesohaline–polyhaline contingent. All chronologies were determined by electron microprobe analysis of otolith strontium. M: male; F: female; PCB: polychlorinated biphenyls (ppm).

of habitat use was recorded in the otolith from late spring to early fall, coincident to the growth season of Hudson River striped bass, because this is when most otolith growth occurs. Most studies of seasonal otolith growth have been done in subtemperate systems (Beaumariage, 1973; Powell, 1982; Thorogood, 1986). In those studies, otolith growth declined during winter months, but remained positive.

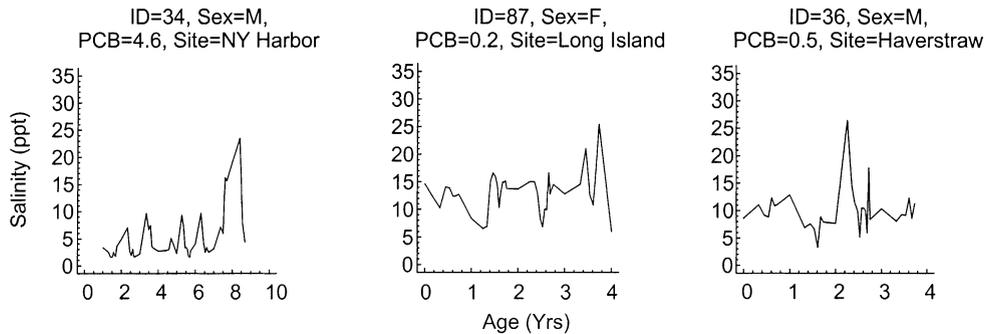
4.2. Contingent behavior

Migratory behavior in Hudson River striped bass varied substantially among individuals, but can be classified into three major categories: (1) resident individuals that primarily utilized the upper, freshwater portions of the Hudson Estuary, just below the

Troy Dam; (2) coastal migrants that exhibited marine habitat use interspersed with freshwater migrations associated with spring spawning runs; (3) individuals that undertake habitat shifts at some mid-point in their lives. There was also some evidence for a group of fish that principally utilized polyhaline to mesohaline habitats. These salinities are commonly encountered in New York City Harbor and western Long Island Sound. Zlokovitz and Secor (1999) and Ashley et al. (2000) suggested that these individuals are exposed to “secondary” PCB sources from the harbor region (historically, the primary source of PCBs was from electrical capacitor facilities upstream of Troy Dam).

Clark (1968) defined a contingent as “a group of fish that engage in a common pattern of seasonal migration between feeding areas, wintering areas, and

Mesohaline Contingent - Fall



Mesohaline Contingent - Spring

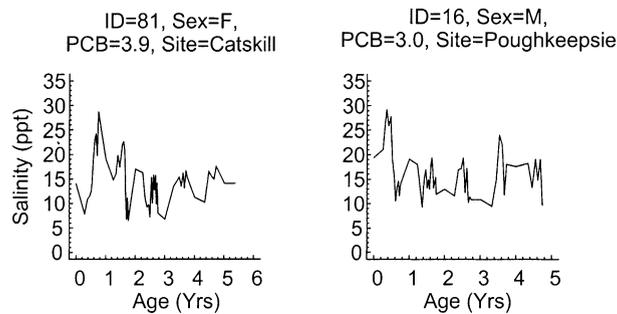


Fig. 7. Representative salinity chronologies for adult Hudson River striped bass classified as mesohaline contingent. All chronologies were determined by electron microprobe analysis of otolith strontium. M: male; F: female; PCB: polychlorinated biphenyls (ppm).

spawning areas". He proposed that the Hudson River striped bass population is subdivided into three discrete contingents that have characteristic patterns of seasonal movement. Waldman et al. (1990) argued that the groups which Clark (1968) described as distinct contingents were actually different size-groups each of which displayed unique behaviors. Overall, the latter tagging study did not show distinct distribution patterns in recapture records, but indicated that fish size affected distribution patterns. Smaller fish were recaptured for the most part near the estuary and larger fish were caught in coastal habitats farther from the estuary. Waldman et al. (1990) argued that maintenance of distinct patterns of seasonal habitat use among years would require that striped bass of all sizes would show unique migration behaviors. Salinity chronologies of resident fish and polyhaline fish support Clark's con-

tingent hypothesis that seasonal patterns of habitat use do in fact occur across size classes as well as across life-spans.

The most convincing evidence for contingent behaviors is that for resident individuals (Fig. 5) that used the upper and middle estuary as habitat throughout their lives. Some individuals maintained a resident behavior with few or no excursions to higher salinity waters for periods of more than 10 years. Presumably, during periods of extreme cold, fish should move into deep channel areas from Catskill-Saugerties, as far south as the embayment at Haverstraw, where salinity and marine influences would moderate temperature stress (Hurst and Conover, 2002). Alternatively, striped bass could seek winter refuges in polyhaline and marine environments, which we were unable to detect due to cessation of otolith growth.

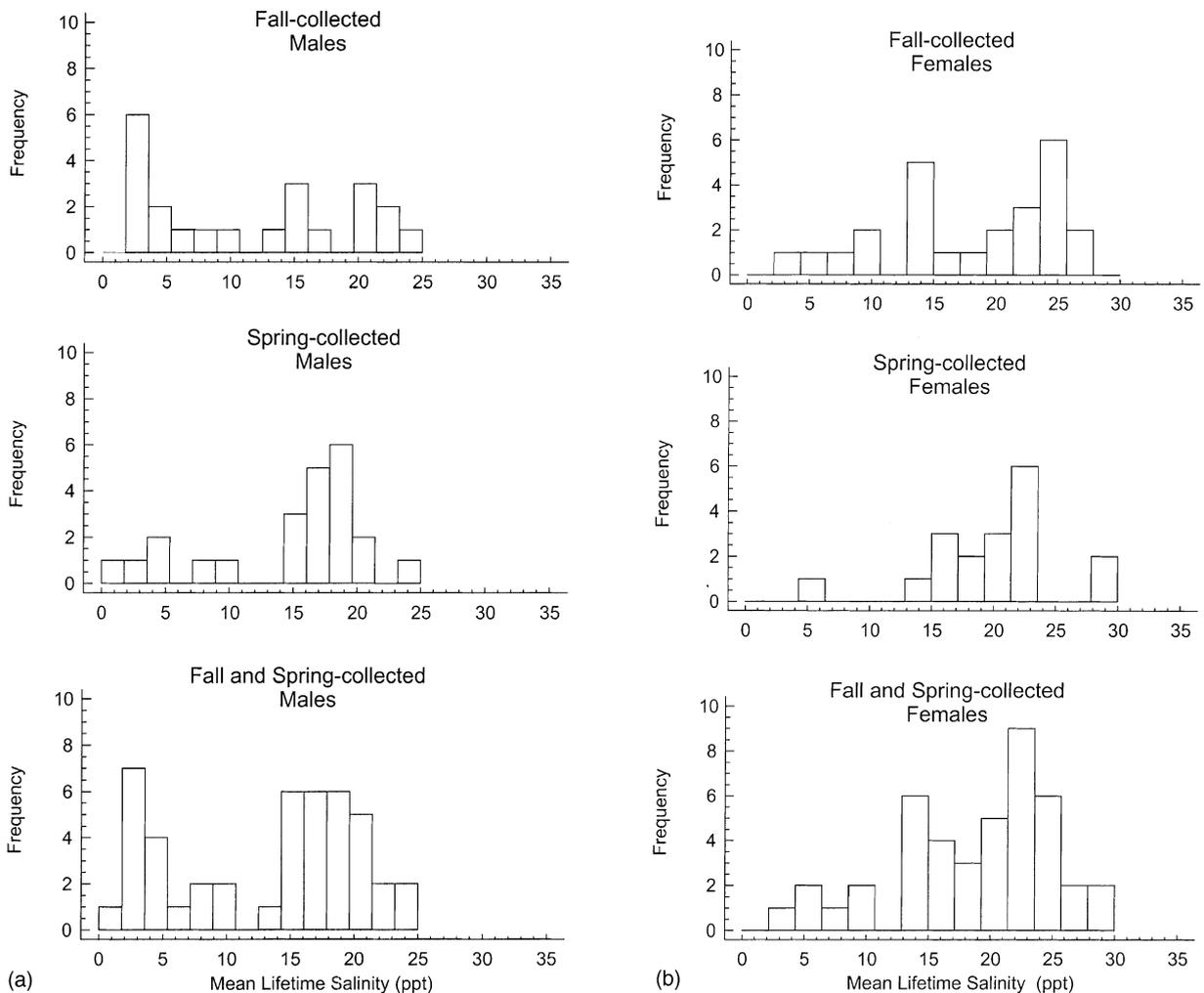


Fig. 8. Frequency histograms showing distribution of mean lifetime salinity histories for (a) male, and (b) female Hudson River striped bass.

Circumstantial evidence for resident behavior is provided by an important fishery that historically occurred in the lower Hudson River estuary during winter months. The winter striped bass fishery dates back to the 1800s, although accurate record-keeping started at about 1931 (McLaren et al., 1988). In the 1930s and 1940s, striped bass were harvested during an open season December–March.

The fall sample provided some evidence for a polyhaline contingent that utilizes the New York City Harbor region (Fig. 3, ID = 42, 52, 54; Fig. 6, ID = 41). The majority (75%) of these fish had PCB levels be-

tween 2.0 and 2.5 ppm. Life history transect points indicated polyhaline (19–29 ppt) habitat use but they fluctuate widely (e.g. Fig. 6, ID = 41). An individual which limits itself to a small geographical area within the New York City Harbor region might be expected to exhibit a variable salinity chronology due to the alternating effects of spring freshets and dry summers.

Further evidence for contingent behavior is revealed by the distribution of mean lifetime salinity histories. In males, three modes were apparent: a resident group (Troy Dam, 2–5 ppt), a mesohaline group (15 ppt, New York City Harbor), and a polyhaline group (20–25 ppt,

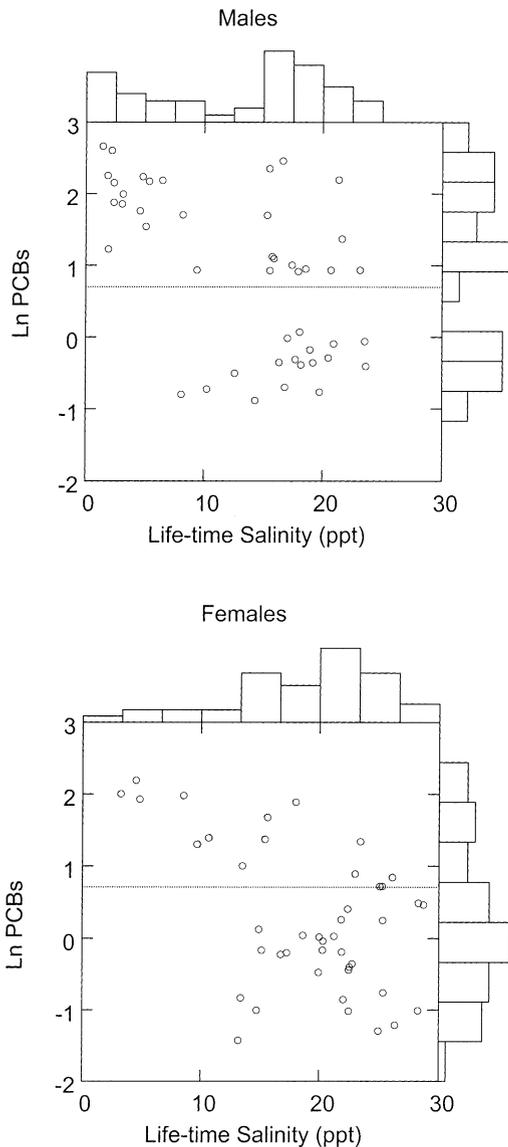


Fig. 9. Scatter plots total PCBs (ppm) versus mean lifetime salinity histories for male and female Hudson River striped bass. Total PCBs were \log_e transformed. Dashed line indicates total PCBs = 2 ppm. Frequency histograms are graphed on the peripheral axes of each plot.

Long Island Sound). In females, distributions were bi-modal, with the dominant mode at higher salinities. In general, resident behavior was associated with males and the fall sample, and mesohaline-marine contingents were associated with females and the spring sample.

4.3. Habitat shifts

Why do individual striped bass engage in habitat shift behavior? In general, we observed shifts after 2 years in age were from freshwater to mesohaline, polyhaline or marine habitats. These shifts were more common than shifts from higher salinities to freshwater. After striped bass acclimate to higher salinity waters, it may be physiologically stressful for them to return to freshwater habitats for long periods of time. There may also be a high-temperature/low dissolved oxygen barrier, which prevents some individuals from entering the upper Hudson Estuary during the summer months (Coutant, 1985).

We observed a consistent trend by juveniles to utilize polyhaline habitats sometime during their first year of life. According to Dovel (1992), in late October, young-of-the-year juvenile striped bass begin moving from the Hudson River into the New York City Harbor area, which is a known area of wintering aggregation. This is supported by recent findings (Hurst and Conover, 2002) that young striped bass may reduce over-wintering mortality by seeking higher salinities. Subsequent to the over-wintering period, young striped bass may again utilize oligohaline environments, which continue to provide suitable habitat for juveniles.

4.4. Resident behavior

Temperature and dissolved oxygen levels may be unfavorable during mid-summer and mid-winter periods in the Hudson River (Coutant, 1985). In addition, the Troy dam area is the most highly contaminated (based on sediment PCB levels) portion of the Hudson Estuary (Brown et al., 1985; Bush et al., 1987). Why then do some striped bass establish resident behaviors in the upper estuary and not engage in coastal migrations? Two possible explanations for this behavior are: (1) enhanced foraging conditions due to concentrations of prey in the dam tailrace, and (2) reproductive advantage.

Anecdotal evidence from observations of stomach contents during spring haul-seine collections indicates that soft-rayed *Alosa* spp. are a major prey item for Hudson River striped bass. Concentrations of these prey and possible resident contingents of *Alosa* spp. (Limburg, 1998) and other small fishes below the

dam may attract and retain large numbers of striped bass in the upper estuary. In addition, there is a run of blueback herring in late spring that spawn above the dam in the upper Hudson and Mohawk Rivers. After their progeny reach a size of 50–60 mm as juveniles in fall, they begin moving downriver in response to cooling water temperatures (Schmidt et al., 1988). As a result of this mass emigration, favorable foraging conditions for piscivores may occur below the Troy Dam during fall months. Alternatively, it may be bioenergetically advantageous for some individuals to remain in the upper estuary, utilizing their energy for reproduction rather than long-distance migrations. This behavior is analogous to the “sneaking” behavior of resident male jack salmon (Gross, 1987). Striped bass that leave the Hudson River are subjected to greater recreational and commercial fishing pressure and a greater diversity of natural predators. Therefore, the presence of a resident contingent may help in maintaining the overall reproductive potential of the Hudson River population.

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