Does otolith composition reflect early life history? A prospective analysis in Atlantic tomcod *Microgadus tomcod* and weakfish *Cynoscion regalis* from the Hudson River estuary.

A Final Report of the Tibor T. Polgar Fellowship Program

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Martin, J.M. and E.T. Schultz. 2000. Does otolith composition reflect early life history? A prospective analysis in Atlantic tomcod *Microgadus tomcod* and weakfish *Cynoscion regalis* from the Hudson River estuary. Section V: 17pp. *In* W.C. Nieder & J.R. Waldman (eds.), Final Reports of the Tibor T. Polgar Fellowship Program, 1999. Hudson River Foundation.

ABSTRACT

Sagittal otoliths from juvenile Atlantic tomcod *Microgadus tomcod* and weakfish *Cynoscion regalis* from the Hudson River estuary were examined with a wavelength dispersive microprobe to describe patterns in otolith microchemistry. Otolith edges (most recently accreted portion) were assayed from juvenile fish collected across the estuarine salinity gradient. Sr:Ca values of otoliths from tomcod collected in the lowest region of the Hudson were high (river mile (RM) 14 and 16; mean Sr:Ca = $2.92 \times 10^{-3} \pm 1.13$ SD) compared to those individuals collected further upriver (RM 71 and 72; mean Sr:Ca = $1.72 \times 10^{-3} \pm 0.35$ SD). Sr:Ca values for weakfish peaked at intermediate salinities (RM 24, 15.8 psu; mean Sr:Ca = $2.29 \times 10^{-3} \pm 0.28$ SD), with lower values obtained from fish collected in both the polyhaline and oligohaline regions of the river, but no significant difference existed ($p > 0.05$). Temporal patterns in Sr:Ca ratios in transects across tomcod otoliths were examined to trace the environmental history of individuals collected throughout the Hudson. The mean whole-transect value from an individual collected at RM 71 was low ($1.4 \times 10^{-3} \pm 0.14$). The trend of low values near the core (younger age), to higher values towards the edge of the otolith (reflecting downstream movement) was demonstrated within an individual collected downriver (RM 16; mean Sr:Ca = 2.02×10^{-3} ± 0.20). Otolith microchemistry has the potential to determine movement and habitat utilization of juvenile tomcod and weakfish in the Hudson River. More rigorous verification studies are needed to better establish the relationship of Sr:Ca and salinity in these species and the influence of other environmental factors on the chemistry of otoliths.

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INTRODUCTION

Fish otoliths are an important research tool, providing insight into life histories, population dynamics, and ecological parameters of fish populations. Otoliths are acellular and are composed primarily of calcium carbonate in the aragonite crystal form (Radtke et al.1990) which is deposited rhythmically throughout the life of a fish. Historically, researchers have focused on the utility of otoliths for aging. Microstructural analysis of otoliths, examining the daily accretion of increments (Campana and Nielson 1985), provide precise estimates of age, as well as daily and seasonal growth rates.

It has recently been shown that the chemical composition of otoliths can record information of environmental conditions (Kalish 1989; Radtke et al.1990; Secor 1992; Limburg 1995, 1998). Microchemical constituents incorporated into otoliths provide some indication of an individual's transport history and habitat utilization. Many microchemical studies have focused on the uptake of strontium (Sr) into the lattice of aragonite. Not only does strontium have the same valence (+2) as calcium (Ca), the two elements have a similar ionic radius, which allows strontium to substitute into the otolith aragonite (Radtke et al. 1990). Strontium concentrations in seawater exceed those in freshwater by more than an order of magnitude (Secor et al.1995). Ingram and Sloan (1992) have also shown that the strontium concentration in estuarine environments is in direct proportion to salinity. The deposition rate of Sr into otoliths is also proportional to the ambient concentration of Sr in the environment (Kalish 1989).

Coupled with the age information provided by otoliths, Sr:Ca ratios can be used to track individual migrations through a salinity gradient, such as those found in estuaries

(Secor 1992, Limburg 1995,1998). Because of its potentially widespread application, there is considerable interest in testing its feasibility in a range of species.

We report here on the potential use of Sr:Ca ratios as indicators of past environmental conditions for the Atlantic tomcod *Microgadus tomcod* and the weakfish *Cynoscion regalis*. Extensive weakfish spawning occurs in coastal and marine waters throughout the spring and summer in the New York Bight (Consolidated Edison 1995). The extent to which juvenile weakfish utilize the Hudson River estuary as a nursery area is not well documented. However, juveniles are fairly common throughout the lower Hudson River (Consolidated Edison 1995). Recently, the juvenile range of weakfish has extended further upriver (Kingston region) than has been seen in the long-term record (Consolidated Edison 1995). The analysis of Sr:Ca ratios in otoliths may allow the range of the Hudson River being used by weakfish juveniles to be assessed.

The Hudson River marks the current southern limit to the Atlantic tomcod spawning range (Grabe 1978), and has been noted as one system in which this species is strictly riverine (Dew and Hecht 1994), with individuals spending their entire life history in the estuary. Juveniles are thought to remain in the Hudson over the summer, however a portion of the population may inhabit nearby New York and Raritan Bays when temperatures rise (Consolidated Edison 1995). The analysis of the Sr:Ca ratios in juvenile Atlantic tomcod collected in the Hudson River should reflect patterns of migration throughout the estuary as well as marine migrations if they are occurring.

Our approach was twofold. First, measurements obtained from otolith edges for both species tested the hypothesis that the Sr:Ca ratio in the outer-most portion of an otolith reflects the salinity in which the individual was captured. Secondly, Sr:Ca measurements were taken along a complete growth axis (different ages) in tomcod otoliths to explore individual transport history as a result of different chemical concentrations (Sr:Ca ratios) experienced throughout estuarine movement.

METHODS

Sample collection

Weakfish were collected during the 1999 Fall Shoals Survey, part of the Hudson River Estuary Monitoring Program, which is jointly funded by five Utilities. Fish were collected from RM 8 to RM 35 using a 3.0-m beam trawl (3.8 cm stretch mesh for the trawl body). Salinity at time of capture was also measured with calibrated YSI meters. Individuals were preserved in 95% EtOH until otolith removal. The relative concentrations of Sr and Ca are not detectably altered by preservation (Proctor and Thresher 1998). Individuals for analysis were selected from across a range of salinities at capture (range 2.5 psu to 36 psu; n = 8). Due to the Utilities' sampling design, collection locations were random and sample availability was limited.

Juvenile tomcod were obtained from the Utilities' Longitudinal River Ichthyoplankton Survey (LRS). Samples were collected in June and July of 1998 with either a Tucker trawl or a Tucker trawl mounted on an epibenthic sled (505 μm mesh size) from RM 16 to RM 72 (n = 12). Individuals were preserved in 95%EtOH until otolith removal. An adult tomcod (20.32 cm SL) collected from RM14 in July 1999 was also included in this study. Salinity at time of capture is not yet available. Tomcod will instead be referenced to river mile (RM) at capture.

Otolith preparation

Sagittal otoliths were extracted, cleaned in deionized water, air-dried, and embedded in standard lab epoxy-resin. Transverse sections were cut through the otolith core with a diamond-wafering saw and mounted on glass slides. Otoliths were then ground with 1000 grit silicon carbide powder and polished on 1µm alpha alumina slurry until surfaces were smooth (Kalish 1989). All samples were ultrasonically cleaned between polishes. Prior to final analysis, samples were recleaned, dried, and carbon coated (250 Å thickness) for surface conductivity.

Otolith microanalysis

Elemental concentrations were quantified using a JEOL JXA-8600 wavelength dispersive electron microprobe at the Department of Geology and Geophysics, Yale University. The standards used for Sr and Ca were celestine ($SrSO_4$) and calcite ($CaCO_3$). For all analyses, accelerating voltage was 15kv and the probe current was 10 nA. Elemental weight percents were computed and ZAF matrix corrections applied. Weight percents were then converted to atom percents.

Weakfish otoliths: Sr was counted on peak for 100 s and Ca for 10 s. Background was measured for 50 s on each side of the peak and subtracted. Beam diameter was 20µm. Measurements were taken in the outer-most portion of the otolith and assumed to reflect the salinity at the time of capture (Secor and Piccoli 1996). Individual Sr-Ca ratios are the mean of 4 random points measured along the edge. The left and right sagittae from one individual (collected in 26 psu) were assayed to test for significant differences between otoliths of the same fish. This resulted in a nonsignificant difference ($p = 0.4613$), allowing either the right or left sagitta to be analyzed.

Tomcod otoliths: Individual edge Sr:Ca for tomcod are the mean of 3 random points measured along the edge. Sr and Ca in each otolith were measured for a total of 30 s on peak and 30 s background. Tomcod otoliths were less susceptible to beam damage therefore a smaller beam diameter of 15 µm was used. Multiple point transects were conducted from the otolith core to the edge (longest radius in the transverse plane) on individuals collected from across the salinity gradient. An otolith from one individual (RM 57) was cut in the sagittal plane and measurements taken across the longest axis. These life-history scans were used to assess temporal changes in exposures to differing Sr concentrations (salinities). For transect measurements, Sr peak and background were counted for 100s and Ca for 10s.

Statistical analysis

Two approaches to assessing the effect of salinity (or RM) on elemental composition were taken. The first approach treated levels of the independent variable as unordered categories; differences in Sr:Ca were tested in a nested analysis of variance (ANOVA), with salinity and individual nested within salinity as treatments. Individual readings (3 or 4 per individual) constituted the observation in this model. The F-test for the fixed salinity treatment used the mean squares for individual nested within salinity as a denominator. The second approach treated the independent variable as ordered and continuous; the relationship between Sr:Ca and salinity was tested in a simple linear regression. Individual fish, represented as the means of multiple readings, constituted the observation in this model. In both the ANOVA and regression models, the Sr:Ca was arcsine transformed, as is appropriate for proportions (Sokal and Rohlf 1981).

RESULTS

Weakfish edge analysis

Mean Sr:Ca ratios (± SD) per individual plotted against salinity are shown in Figure 1. Mean values ranged from 1.71 x 10^{-3} to 2.41 x 10^{-3}, with the highest values obtained at the intermediate salinity (15.8 psu), and the lowest ratios from individuals furthest upriver (2.5 psu). However, the salinity effect in the ANOVA model was not quite significant ($r^2 = -0.05$, $p = 0.0881$). There is also a nonsignificant difference between means of individuals nested within a salinity ($p > 0.05$).

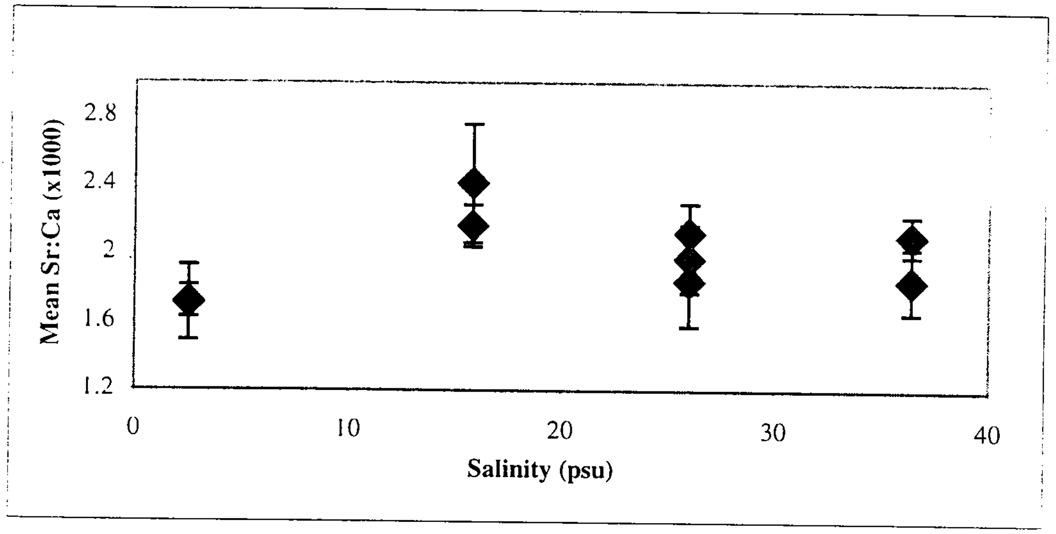

Figure 1. *Cynoscion regalis*. Otolith edge mean Sr:Ca (x1000) plotted against salinity at time of capture (± SD). Two individuals sampled at 2.5 psu had the same mean.

Tomcod edge analysis

Figure 2 plots the mean Sr:Ca ratios against RM at capture. Mean edge ratios range from 1.3 x 10^{-3} to 3.6 x 10^{-3}. The highest value observed is from an adult tomcod collected in the polyhaline zone (RM 14) followed by a juvenile collected at RM 16 (Sr:Ca ratio =

2.21 x 10^{-3}). Mean Sr:Ca ratios from individuals collected from RM 23 to RM 72 (mesohaline and oligohaline regions) were lower than those collected downriver but not significantly so. River mile at capture showed no significant effect on Sr:Ca ratios in Atlantic tomcod ($r^2 = 0.15$, $p = 0.0954$) and individuals collected at the same RM were not significantly different ($p > 0.5$).

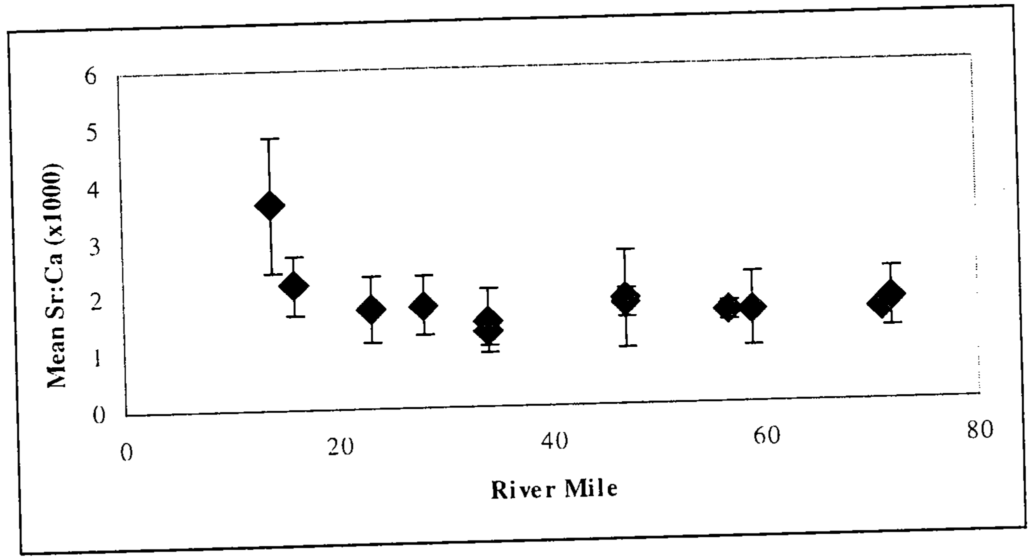

Figure 2. *Microgadus tomcod*. Otolith edge mean Sr:Ca (x1000) plotted against river mile at capture (± SD).

Tomcod life-history scans

Life-history transects (measured from the otolith core to the edge) for individuals collected across the estuarine salinity gradient are shown in Figure 3. The individual assayed from RM 16 (Fig. 3a), the most downriver site sampled, showed the highest Sr:Ca ratios observed within all transects and also had the greatest mean whole-transect Sr:Ca ratio (Fig. 4). The pattern of Sr:Ca along that transect suggests that the individual was exposed to a steady increase in salinity punctuated by a midlife peak. However,

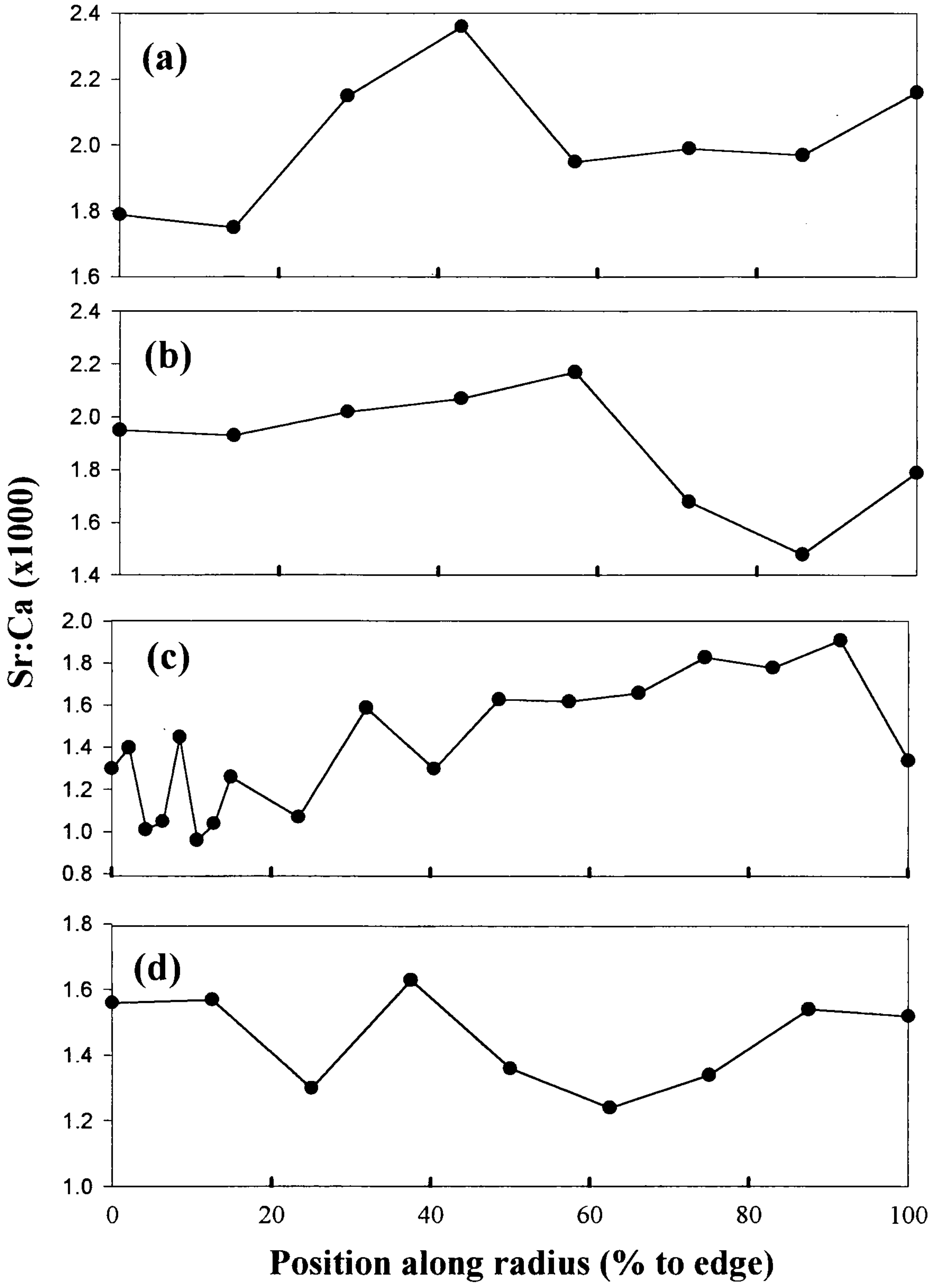

Figure 3. *Microgadus tomcod.* Sr:Ca transects from individuals collected throughout the Hudson River estuary. (a) RM 16; (b) RM 34; (c) RM 57; (d) RM 71.

Sr:Ca at capture was greater than that in the otolith core, reflecting movement into areas of higher Sr concentrations (i.e. higher salinities).

A different pattern is exhibited by an individual examined from RM 34 (Fig. 3b) which shows a gradual increase in Sr concentration, terminating in a dip. The edge ratio, however, is lower than that in the core, which is indicative of a net movement into regions of lower Sr concentrations. Another fish caught from RM 71 (Fig. 3d) shows two distinct periods of exposure to relatively low Sr concentrations. Values in the otolith core, at the Sr peak (at ≈ 40% of the otolith radius), and at the otolith edge of this individual are similar ($1.56 \times 10^{-3} \pm 0.05$), with two temporally different experiences with low Sr concentrations.

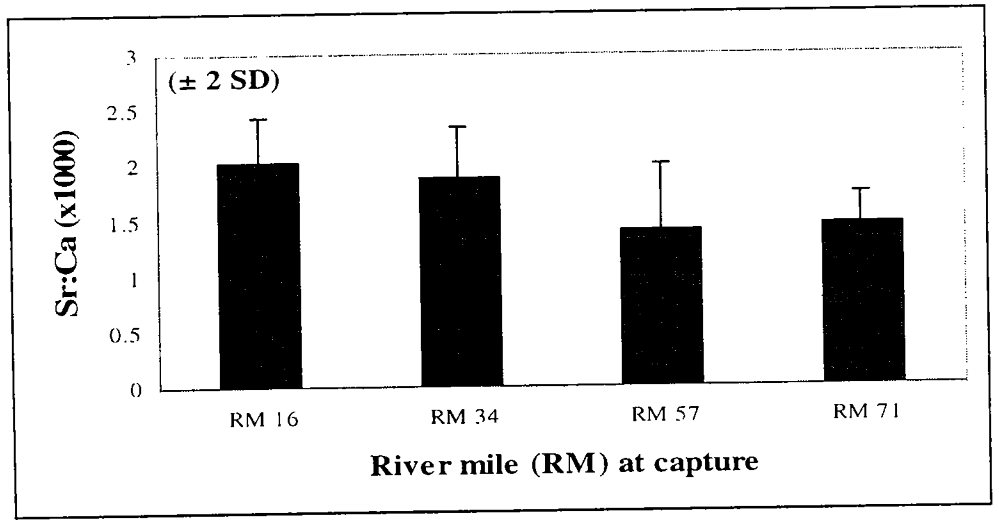

Figure 4. *Microgadus tomcod.* Mean whole-transect Sr:Ca ratios from individuals collected in different regions of the Hudson River estuary.

The Sr:Ca peak across all transects occurred between 40 and 60% of otolith radius, with the exception of the individual from RM 57 (Fig. 3c), which peaked at 91% of otolith radius. Transect measurements for this fish were initially performed on a smaller spatial scale (every 25 μm) to achieve a better resolution of Sr exposure during larval and the earliest juvenile stages (Fig. 3c). The pattern obtained on the earliest part of the transect indicates rapid changes (sawtooth) in the Sr concentration of the water mass experienced by the individual. The general trend is an overall increase in Sr, terminating in a dip. The lowest Sr:Ca obtained from all tomcod sampled (0.96×10^{-3}) occurred in this fish at 10% of otolith radius. This individual also had the lowest mean whole-transect Sr:Ca ratio (Fig. 4).

DISCUSSION

The use of trace elements incorporated into otoliths as recorders of past environmental conditions experienced by an individual fish can be of tremendous value to researchers and managers. Although otolith edge Sr:Ca ratios for weakfish were not significantly affected by salinity at capture in this study, the use of Sr:Ca ratios, as indicators of movement of this species throughout an estuary, should not be disregarded. Juvenile weakfish assayed from the lowest salinity sampled (2.5 psu) resulted in the lowest Sr:Ca ratios obtained from this species, which is consistent with other validation studies (Secor et al.1995). Limburg (1995) reviews the effect of local geology on Sr concentrations throughout the Hudson River and notes that fish passage through low Sr drainage areas is reflected in otoliths of American shad. Kalish (1989) has explored the effects of physiology and other environmental conditions (temperature) on otolith Sr concentrations. These factors, as well as movement through high and/or low Sr drainages in the Hudson, may influence Sr uptake by weakfish juveniles and should be tested experimentally.

The trend of highest ratios obtained in regions of higher salinity (downriver) was observed in the edge-analysis experiment for Atlantic tomcod. The relationship between salinity at capture and Sr:Ca ratios at the otolith edge may gain significance with an increased sample size.

The life-history transects obtained for tomcod proved more insightful. Changes in short-term exposure to various Sr concentrations were detected and some indication of overall movement and individual variation were obtained. The use of life-history transects to determine patterns of migration of Hudson River fishes have proved successful for striped bass (Secor and Piccoli 1996) and even for American shad, a species for which the strength of the otolith Sr-salinity relationship has yet to be verified (Limburg 1995).

RECOMMENDATIONS

Due to sampling limitations and cost constraints, the number of individuals sampled was not optimal. More rigorous studies for validation, which include a larger sample size and more intensive sampling across the estuarine gradient, are needed. Further exploration on the relationship of microprobe operating conditions (accelerating voltage, beam current, beam width, and counting times) on sample damage and quantification of Sr are also essential. We believe that the potential of this technique to answer key questions concerning Atlantic tomcod life-history in the Hudson River is strong; however, factors contributing to otolith Sr:Ca ratios need to be better established.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support of the Tibor T. Polgar Fellowship program. Special thanks to John Young (Consolidated Edison of New York) for providing samples and allowing the collection of additional specimens. Appreciation goes out to Mark Mattson, as well as the crew of the R/V Woody I, from Normandeau Associates for help in organizing field collections. Jim Eckert from Yale University provided invaluable information on microprobe analysis. Additional thanks to Karin Limburg for suggestions and advice as well as Rick Bennett and Steve Daniels for help with sample preparation.

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