QUANTIFYING LARVAL FISH HABITAT IN SHORELINE AND SHALLOW WATERS OF THE TIDAL HUDSON RIVER

A Final Report of the Tibor T. Polgar Fellowship Program

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ABSTRACT

Shoreline and backwater nursery areas are important for spawning and early life development for many fishes. During the larval stage, or 'critical period,' mortality often exceeds 90%. Nursery areas provide abundant food and cover, which has been shown to be more favorable habitat for developing fishes. Shoreline and shallow water habitats have been structurally and biologically altered along much of the Hudson River. The effect of changes in microhabitat conditions on larval habitat occurrence has not been quantified. The purpose of this study was to quantify larval fish occurrence within a range of shallow water microhabitats in order to determine the importance of habitat variables for larval fish distribution.

Larval fish samples were collected from Tivoli North Bay and the Magdalen Island shallow waters using a w-fold throw trap and mesh seine from May 25 – July 1, 2010. Samples were preserved in 10% buffered formalin and successively transferred to 70% ethanol. Fish were measured and identified to family level. A MANOVA test was applied to microhabitat variables according to larval presence by family. Results indicate microhabitat differentiation by families Moronidae, Clupeidae, Cyprinidae, and Fundulidae. Differential shallow water habitat use between larval fish taxa has implications for fish habitat restoration and shoreline development.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

INTRODUCTION

The larval period is characterized by high mortality, and considered a 'critical period' in the population dynamics of many fish species (Hjort 1914; Marr 1956; May 1974). The post-yolk sac larval period starts when fishes are able to capture food organisms and extends to the size and age marked by the formation of the axial skeleton and the development of the embryonic finfold into fins with rays and spines. During the post-yolk sac larval stage, organs and fins are still forming, limiting locomotion and rendering larvae particularly susceptible to predation and starvation (Moyle and Cech 2004). Due to this increased susceptibility, larval fish have environmental requirements, behaviors, and habitat needs that are distinctly unlike that of juveniles and adults (Snyder 1990). Larval size plays a larger factor in determining suitable environment and larvae are especially sensitive to their surrounding habitat (reviewed in Snyder 1983).

Low velocity habitats such as backwaters, tributaries, and near-shore areas have been shown to support high densities of larval fish (Odom 1987; Scott and Nielsen 1989). The Hudson River has experienced thousands of hectares of nursery habitat losses from navigation channel development and physicochemical changes (Miller et al. 2006). Shoreline wetlands have been altered by the construction of railroads along the river and dams in the upper drainage (Squires 1992; Schmidt and Cooper 1996). Other changes in the river environment impacting nursery habitat include zebra mussel colonization and plankton reduction (Strayer et al. 1999), water intakes and larval impingement, changing littoral fish assemblages (Strayer et al. 2004; Daniels et al. 2005) and non-native plant invasion of shallow water areas (Schmidt and Kiviat 1988; Coote et al 2001; Findlay et al 2006).

Research on post-yolk sac larvae in the Hudson River by Limburg (1996) found highest fish concentrations in or near aquatic vegetation and quiet waters. Leslie and Timmins (1991) and Penáz et al. (1992) found that river margins were able to support greater abundances of larvae than adjacent offshore habitats. This habitat selection behavior was observed as a mechanism for larval fish to avoid being flushed out of nursery areas. Sustained swimming speed for most fish, including larvae, is 3 to 7 body lengths per second (Webb 1975). Scheidegger and Bain (1995) calculated a maximum current velocity of 8.4 cm/s (i.e., 7 body lengths x 12-mm long larvae) to define the upper velocity limit (i.e., critical maximum velocity) for potential nursery habitat. Precise sampling of fish larvae in waters at or below the critical maximum velocity revealed orientation behavior toward habitat characteristics such as substrate, vegetation, cover density, and water depths, while offshore habitats with current velocities greater than the critical maximum contained fish larvae being passively transported by river currents. Different fish taxa varied in the parameters defining their preferred habitats.

The Hudson River shoreline habitats are tidal and experience a range of current velocities and water depths. Furthermore, there exists great structural heterogeneity along the river's edge. It is not known how varying microscale conditions in tidal rivers influence habitat selection and use by fish larvae. The purpose of this study was to test the hypothesis that post-yolk sac larval fish occurrence within shoreline and shallow waters is correlated with exposure to different localized hydrodynamics and habitat structure in order to inform the ecological implications of future shoreline restructuring decisions.

METHODS

Site Description

Tivoli North Bay is a cattail freshwater marsh composed of a network of tidal creeks and pools located around river km 159 in Dutchess County. As part of the Hudson River National Estuarine Research Reserve, Tivoli North Bay is an important refuge for Hudson River resident marsh flora and fauna. The Tivoli Bays are an important spawning and nursery ground for several anadromous and resident freshwater fish species (Yozzo et al 2005). Tivoli North Bay receives freshwater inputs from both the Hudson River and Stony Creek, which drains into the northern portion of the marsh. The bay is separated from the main channel by the Metro-North railroad and receives tidal water exchange with a diurnal tidal change of >1 m through bridges within the railroad bed.

Magdalen Island is located west of the railroad divide separating the Hudson River and Tivoli North Bay. While the western bank of Magdalen Island is primarily steep, scoured bedrock, the eastern shoreline is characterized by finer substrates and abundant aquatic vegetation. The aquatic habitat on the eastern side of the island is composed of a silty bottom, shallow water, and low velocity pockets.

Site Protocol

Samples were collected from 25 May - 1 July, 2010 in Tivoli North Bay and along the shoreline and shallows of Magdalen Island. Sites were sampled for larval fish by random 'point abundance sampling' (Copp and Penáz 1988; Copp 1990) over the daytime tidal cycle. Larval fish were trapped using a 1 m^2 w-fold throw trap (Cotroneo and Yozzo 2010). A deep-water extension net was attached to the aluminum frame for samples taken in water deeper than 0.5 m.

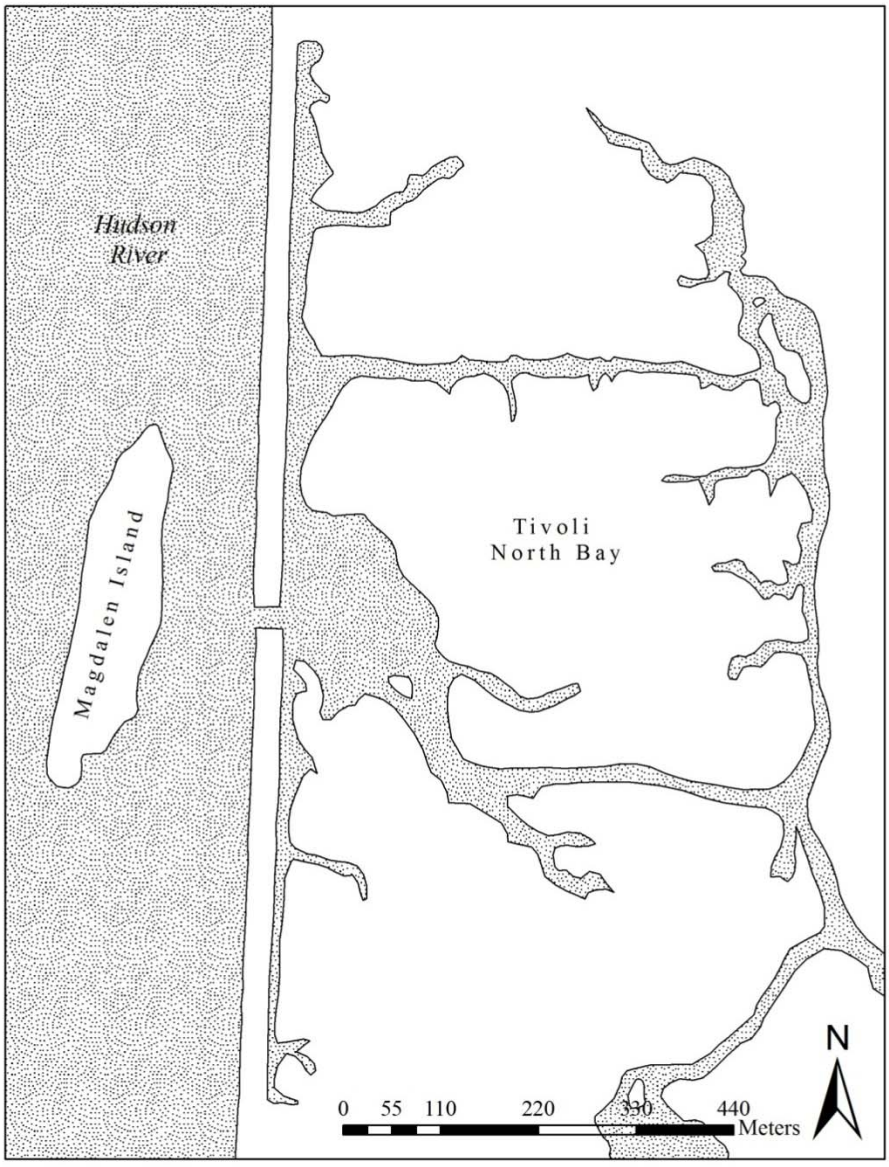


Figure 1. Map of Tivoli North Bay and Magdalen Island study sites

Figure 2. W-fold throw trap and bar seine

Microhabitat conditions were recorded immediately after trap deployment. For each trapping sample, the following habitat attributes were recorded: position (grid point and GPS coordinates), day and time, depth (nearest 0.1 m), current velocity (cm/s at 0.4 depth with a digital flow meter), density of cover, vegetation density and type (Bain and Boltz 1992), and dominant substrate (classes of Bain et al. 1985). Tidal stages were included from tide tables and Hudson River Environmental Conditions Observing System (HRECOS) water depth gauge information for Tivoli North Bay and Tivoli South Bay.

After recording microhabitat variables, fish were removed from the throw trap with a bar seine (Rozas and Odum 1987; Cotroneo and Yozzo 2010). The 1 m^2 500-micron bar seine was reinforced with horizontal crossbars and edged with door sweeps to create a seal with the throw trap and maximize catch efficiency. Larval fish were removed from the bar seine mesh with forceps. Live fish were contained in a separate

vessel with water until all individuals were extracted from the trap. Each trap was seined multiple times until no fish were caught for two consecutive seine passes. All fish larvae and unrecognized fishes were simultaneously euthanized by MS-222 overdose and immediately transferred to 10% buffered formalin. Other known post-larval fish were identified, measured, and released.

Sample Processing

Fish samples were fixed in 70% formalin for a minimum of 2 weeks after collection. After the fixation period, larvae were placed in deionized water for 24 hours and transferred to 70% ethanol for long-term storage and identification. All larvae from each sample were counted and sorted to family level. Subsequently, each fish was measured and classified as yolk sac larva, post-yolk sac larva, or juvenile. Only post-yolk sac larvae were included in this study. Yolk sac larvae and juvenile fish were excluded after classification. Juveniles were identified by the loss of the embryonic finfold and the presence of all spines and rays in each fin. Fish were identified and measured to 0.1 mm tail length (TL) using a dissecting microscope. Fish identifications were based on taxonomic keys by Auer (1982), Kay et al (1994), Jones et al (1978), published taxa descriptions, the Cornell University Shackleton Point biological field station reference collection, and expert consultation (personal communication, Dr. Robert E. Schmidt).

Analysis

A multivariate analysis of variance (MANOVA) was used to test the hypothesis that different microhabitat conditions are related to larval fish presence. Fish presence and habitat variables were coded into numeric values and tested by family. The MANOVA model compares habitat composition differences between groups of samples

with and without fish families present. Significant test results for the MANOVA model indicate microhabitat conditions that were different for present and absent samples for each family. Non-significant whole model results for family presence indicate no distinct habitat association and exclude such taxa from further analysis. The family groups showing distinction in microhabitat occurrence were further tested using analysis of variance (ANOVA) to indicate which habitat variables were significantly different between groups with and without larval fish present. In these analyses, test significance is determined to be $p<0.05$.

A principal component analysis (PCA) was performed to display each family microhabitat distribution in relation to all other microhabitat conditions sampled. The first two components were reviewed with respect to the total data variance captured using habitat variable loadings. Habitat variable scores were plotted along the first two component axes and habitat characteristics were interpreted from each component's eigenvalues.

A standard least squares model was constructed to examine the effects of habitat variables on fish size distribution. This analysis was considered to test the hypothesis that larval fish habitat tolerances change as they grow and their swimming ability increases. All fish size data were entered into the model with their respective sample velocity, distance from shore, and depth measures. Model inputs were analyzed by family and all results were reviewed.

RESULTS

A total of 180 throw trap samples were collected and 2465 post-yolk sac larvae were counted, measured, and identified. Fish sample sizes ranged from 0 - 490 larvae per sample and densities ranged from 0 - 1832 larvae/m^3. There were 104 trap samples collected inside Tivoli North Bay and 76 samples collected around Magdalen Island. A total of 1509 larvae were collected from the Hudson River and 956 larvae were collected from Tivoli North Bay (Table 1). Fundulids and percids were caught in higher densities in Tivoli North Bay and cyprinids were caught in higher densities in the Hudson River.

Table 1. Total catch by family for Hudson River throw trap samples and Tivoli North Bay throw trap samples. Families are Centrarchidae (cen), Clupeidae (clu), Moronidae (mor), Percidae (per), Fundulidae (fun), and Cyprinidae (cyp).

Family	Hudson River	Tivoli North Bay
Cen	345	23
Clu	54	23
Cyp	1042	677
Fun	11	156
Mor	25	25
Per	32	52
All	1509	956

Centrarchid (mostly *Lepomis*) larvae were not collected until the fourth sampling week while cyprinid (including spottail shiner *Notropis Hudsonius*, golden shiner *Notemigonus crysoleucas*, and goldfish *Carassius auratus auratus*), clupeid (river herring, *Alosa*), and percid (tessellated darter *Etheostoma olmstedi*) larvae were collected at a higher frequency earlier in the season. Fundulids (mostly mummichog *Fundulus heteroclitus*) were collected consistently throughout the sampling period (Table 2).

Table 2. Number of post-yolk sac larvae by family collected between Julian date 146 and 182 in the Hudson River and Tivoli North Bay combined. Families are Centrarchidae (cen), Clupeidae (clu), Moronidae (mor), Percidae (per), Fundulidae (fun), and Cyprinidae (cyp).

Family	Julian date						
	146-148	152-155	159-162	166-169	173-176	180-182	Total
Cen	0	0	0	212	153	3	368
Clu	23	25	23	4	2	0	77
Cyp	286	664	596	149	9	15	1719
Fun	1	9	61	29	33	34	167
Mor	0	15	11	21	3	0	50
Per	9	53	5	14	2	1	84
All	319	766	696	429	202	53	2465

Throw trap samples were collected over a range of conditions. Water depth ranged from 0.1 - 1.08 m, water velocity ranged from 0.00 - 0.35 m/s, and distance from shore ranged from 0.05 – 51.0 m. Samples were collected in non-vegetated and vegetated areas; dominant aquatic vegetation included *Vallisneria americana*, *Nuphar luteum*, *Myriophyllum spicatum*, and *Peltandra virginica*. Fish were collected over the tidal cycle.

Non-target collections from throw trapping included over 1500 juvenile fishes, 25 adult American eel, 7-30 cm in size, 2 adult white perch, 3 blue crab, and many adult tessellated darters. The throw trap was successful at capturing fish in all vegetation and substrate types. The upper velocity collection limit for the throw trap was 0.35 m/s. At higher velocities, the trap was not heavy enough to maintain its position in the water column.

The MANOVA analysis indicated significant habitat differentiation for families Clupeidae, Cyprinidae, Fundulidae, and Moronidae. Clupeid and cyprinid presence differentiated by depth, moronids differentiated by water velocity and substrate, and fundulids differentiated by depth and substrate (Table 3). PCA analysis inputs were the

significant variables from the MANOVA analysis: water velocity, water depth, distance from shore, and substrate.

Table 3. Family presence, mean, range, and analysis of variance results for significant habitat variables. Families are Centrarchidae (cen), Clupeidae (clu), Moronidae (mor), Percidae (per), Fundulidae (fun), and Cyprinidae (cyp). Mean and standard error habitat conditions are marked with asterisks if there is a significant distinction between groups with and without family presence. Significant test results are indicated at the mean values and are defined as p<0.001 (***), p=0.001-0.01 (**), and p=0.01-0.05 (*). Insignificant variable relationships within the 90% confidence interval (p=0.05-0.1) are also indicated (+).

Family	Samples	MANOVA *P*	Depth (m)		Velocity (m/s)		DFS (m)		Substrate (coded)	
			Mean	SE	Mean	SE	Mean	SE	Mean	SE
Cen	7	0.0971+	0.44	0.109	0.01	0.006	2.28+	0.687	1.11	0.114
Clu	17	0.0003***	0.75**	0.045	0.05	0.010	9.83+	3.145	1.49	0.246
Mor	31	0.0013**	0.52	0.044	0.05**	0.007	6.91	1.936	1.05***	0.025
Per	30	0.1681	0.48	0.043	0.04	0.006	6.12	1.446	1.14	0.080
Fun	38	<.0001***	0.33***	0.031	0.02	0.003	1.89	0.583	1.24***	0.117
Cyp	49	0.0003***	0.36**	0.032	0.02+	0.003	2.34	0.543	1.77	0.150

Variable loading interpretation indicated that the first two components account for 70.27 percent of model variance. Clupeids were found in deeper water over a range of velocities and substrate sizes (Figure 2a). Moronids were found in higher velocity habitats with silty substrate. Depth and distance from shore had no effect on moronid habitat occupancy (Figure 2b). Fundulids were found in shallow areas with silty substrate, while velocity and distance from shore had no effect on their presence (Figure 2c). Cyprinids were also found in shallow water with the same distribution as fundulids. Unlike fundulids, cyprinids were found in coarse and fine sediment habitats (Figure 2d). Non-significant, but notable trends include clupeids occurring in habitat far from shore and cyprinids occurring in low velocity areas.

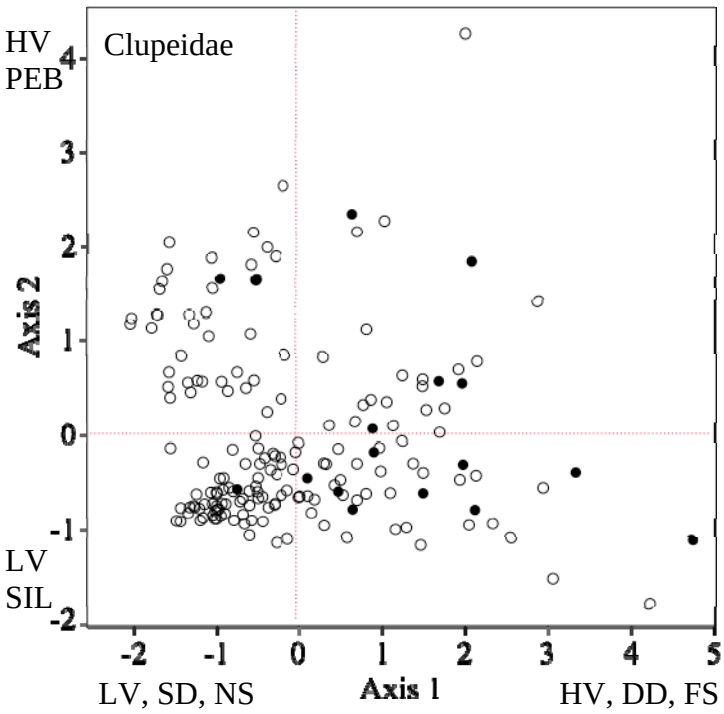
The standard least squares model included velocity, depth, and distance from shore analyzed by family. Clupeidae was the only family showing significant differences

in habitat variables by fish size while also capturing a high amount of model variance (R^2=0.620, p<0.0001). Changes in fish size showed significant correlation with changes in velocity (p<0.0001), depth (p>0.0001), and distance from shore (p=0.0049).

DISCUSSION

Study data and the statistical analyses provide strong evidence that larval fish were distributed nonrandomly within the sampled shallow water environments. These results indicate that there are differences in habitat occupancy for larval fish between taxa. The trend of differential occupancy is consistent with past research on littoral and open water larvae in the Tivoli Bays region. Schmidt (1986) found that fundulids, spottail shiners, white perch, and tessellated darters prefer shallow intertidal areas while herrings occupy deeper channels. Furthermore, there is no difference in fish presence between bay and river samples for most taxa, signifying that both shallow water in the river and bay backwaters function similarly in supporting larval fish. Shallow and shoreline waters along the mainstem appear to be as important as protected bays for supporting the region's larval fish community.

a.



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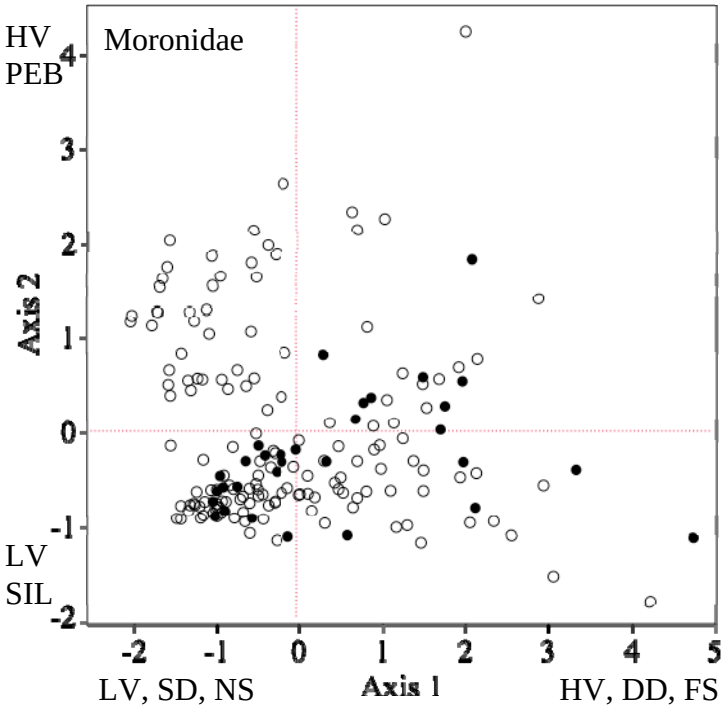
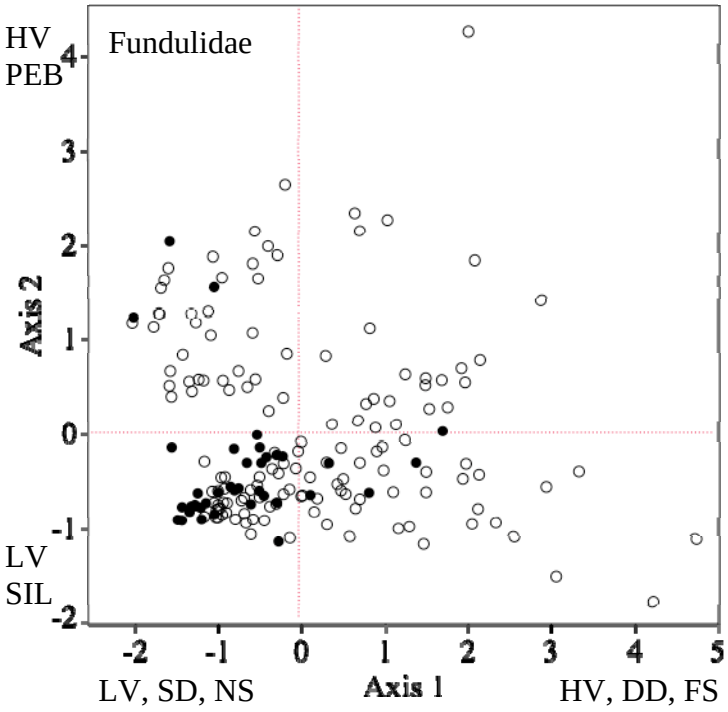


Figure 3ab. PCA analysis of families Clupeidae (a) and Moronidae (b) by depth, velocity, distance from shore, and substrate. The first two components account for 70.27 percent of model variance. LV: low velocity, HV: high velocity, SD: shallow water depth, DD: deep water depth, NS: near to shore, FS: far from shore, PEB: pebbly substrate, SIL: silty substrate.

c.



d.

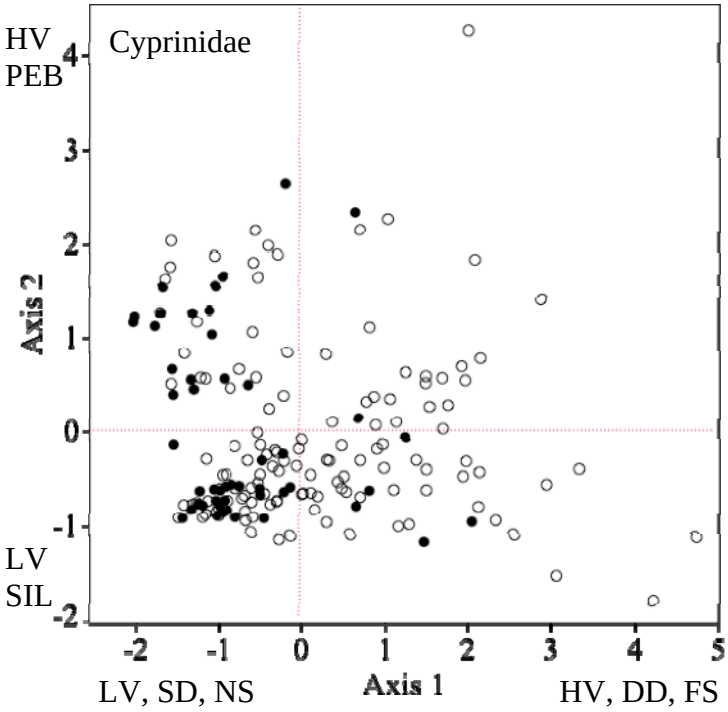


Figure 3cd. PCA analysis of families Fundulidae (c) and Cyprinidae (d) by depth, velocity, distance from shore, and substrate. The first two components account for 70.27 percent of model variance. LV: low velocity, HV: high velocity, SD: shallow water depth, DD: deep water depth, NS: near to shore, FS: far from shore, PEB: pebbly substrate, SIL: silty substrate.

Depth rather than velocity appeared to be the most significant indicator of habitat differentiation. Depth was a significant habitat indicator for three out of the four families distinguished by environmental variables. Velocity was only significant for distinguishing moronid habitat. Other larval fish habitat studies have shown velocity to be a dominant indicator of fish presence and survival (Scheidegger and Bain 1995; Freeman et al 2001; Humphries et al 2002; Niles 2004). In this study, most areas sampled were not exposed to high velocities, which may be why velocity is not a stronger habitat differentiator.

Clupeid larvae were consistently found in deep water and tended to be further from shore. They occurred primarily in the bay and river main channels. Clupeidae was the only family to show significant habitat association by size. Larger fish were found in faster water, deeper habitat, and slightly closer to shore. Clupeid size distribution may support the theory that fish utilize different portions of their habitat as they develop, even in early life stage fishes.

Moronid larvae were present in relatively high velocity water with silty substrate. They occupied habitat up to more than twice the calculated maximum sustainable velocity (8.4 cm/sec). Most of the moronid larvae collected were far into their larval development and would nearly be classified as juveniles. The ability to forage in faster water may be advantageous in a system where most larvae occur in slower water.

Fundulids were primarily found in bay samples. These results suggest that the bay interior has a larger function as a spawning and nursery area for fundulids than the mainstem Hudson. Fundulids were found in shallow water habitat with a silty substrate. Substrate preference is significant because fundulids occurred predominantly in Tivoli

North Bay, which has silty substrate throughout its channels and backwaters. Fundulids were collected throughout Tivoli North Bay backwaters and along the shallow edges of the channels.

Cyprinids were also found in shallow water within the same depth range as fundulids. Unlike fundulids, cyprinid larvae were equally distributed between bay and mainstem samples and were found in habitats with both coarse and fine sediments. Cyprinids appear to occur more frequently in low velocity water. Shallow shoreline areas in both Tivoli North Bay and along the mainstem Hudson were the most suitable collection sites for cyprinid larvae.

Centrarchids and percids did not show significant habitat differentiation. In the case of the centrarchids, this may be due to the low sample presence. Centrarchid larvae occurred in 7 out of 180 trap samples, which is not a sufficient number of samples for a robust MANOVA comparison. Continued sampling until later in the season may have increased centrarchid sample count since centrarchids were not collected until the latter period of sampling. No habitat differentiation was detected for percid larvae, even though they were present in 30 out of 180 samples. This resolution was strong enough to show habitat differentiation in other taxa, but may not be strong enough for percids if their habitat differentiation is more variable than that of other taxa. Another explanation is that percid larval habitat differentiation was broader than the range of conditions sampled so differentiation could not be detected.

Aquatic vegetation stands have been considered important nursery areas for estuarine fishes. Studies conducted within Hudson River backwaters have concluded several cases of larval fishes association with aquatic vegetation. Water-milfoil

(*Myriophyllum spicatum*) and water-celery (*Vallisneria americana*) support a variety of centrarchids and cyprinids (Schmidt and Kiviat 1988). Water-chestnut (*Trapa natans*) stands were found to support greater densities and diversity of larval and juvenile fish (Anderson and Schmidt 1989). High densities of larval and juvenile mummichog were observed in shallow vegetated waters, cattails, and newly established common reed stands (Harm et al 2003). The fact that no significant differences in family presence were detected for vegetated and unvegetated areas is surprising. Changes in sampling design may account for this lack of detection by using paired sampling methods rather than random point abundance sampling.

Differential habitat presence displayed by clupeids, moronids, fundulids, and cyprinids may have implications for habitat restoration and future shoreline development decisions. The Hudson River Estuarine Research Reserve (HRNERR) has an interest in restoring Hudson River backwaters. The aim is not to restore backwaters to their former condition, but to understand the functioning of the current ecosystem with its environmental constraints and human influence (Miller et al 2006). Based on the results of this study, designing habitat appropriate for larval fish would depend on the type of taxa considered for restoration and the range of taxa included in the restoration plan. Efforts aimed towards planning habitat suitable for many groups of fish must take a range of habitats into consideration while efforts to boost individual family larval survival may focus on maximizing taxa-specific habitat parameters.

The Hudson River shoreline around Magdalen Island appeared to be as significant as the bay for larval fish occupancy. Continued shoreline alteration in the Hudson River has the potential to alter or restrict mainstem larval fish sites to be inappropriate for larval

occupancy and development. Even though the presence of larval fish within a given habitat is not a clear indicator of habitat choice or better survival, it is an indicator of how larval fishes are distributed within their aquatic environment. Having more information about larval fish distribution can increase awareness of how future changes may affect microhabitat conditions identified as important to early life fish.

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REFERENCES

Anderson, A. B. and R. E. Schmidt. 1989. A survey of larval and juvenile fish populations in water-chestnut (*Trapa natans)* beds in Tivoli South Bay, a Hudson River tidal marsh. Section VI in E. A. Blair and J. R. Waldman (eds.), Final Reports of the Tibor T. Polgar Fellowship Program, 1988. Hudson River Foundation, New York, New York.

Auer, N.A. 1982. Identification of larval fishes of the Great Lakes Basin with emphasis on the Lake Michigan Drainage. University of Michigan, Special Publication 82-3, Ann Arbor, Michigan.

Bain, M. B., J. T. Finn, and H. E. Booke. 1985. Quantifying stream substrate for habitat analysis studies. North American Journal of Fisheries Management 5:499–500.

Bain, M. B., and S. E. Boltz. 1992. Effect of aquatic plant control on the microdistribution and population characteristics of largemouth bass. Transactions of the American Fisheries Society 121:94–103.

Cotroneo, C., and D.J. Yozzo. 2010. W-fold throw trap: A folding, transportable 1-m2 throw trap for use in densely vegetated aquatic habitats. Journal of Freshwater Ecology. 25(1):73-78

Copp, G. H. 1990. Shifts in the microhabitat of larval and juvenile roach, *Rutilus rutilus* (L.), in a floodplain channel. Journal of Fish Biology 36:683-692.

Copp, G. H., and M. Penáz. 1988. Ecology of fish spawning and nursery zones in the Floodplain, using a new sampling approach. Hydrobiologia 169:209-224.

Coote, T. W., R. E. Schmidt and N. Caraco. 2001. Use of a periodically anoxic *Trapa natans* (water-chestnut) bed by fishes in the Hudson River. Section IV: 20pp. In J. R. Waldman & W. C. Nieder (eds.), Final Reports of the Tibor T. Polgar Fellowship Program, 2000. Hudson River Foundation. New York, New York.

Daniels, R. A., K. Limburg, R. E. Schmidt, D. L. Strayer, and R. C. Chambers. 2005. Changes in fish assemblages in the tidal Hudson River, New York. American Fisheries Society Symposium 45:471–503.

Findlay, S., D. Strayer, M. Bain, and W. C. Nieder. 2006. Ecology of Hudson River Submerged Vegetation. Final Report to the New York State Department of Environmental Conservation.

Freeman, M. C., Z. H. Bowen, K. D. Bovee, and E. R. Irwin. 2001. Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes. Ecological Applications 11(1):179-190.

Harm, L., E. Salak, and D. Osgood. 2003. Effects of *Phragmites australis* on the early life stages of *Fundulus heteroclitus* at Iona Island Marsh, Hudson River, New York. Section IV in J. R. Waldman and W. C. Nieder (eds.), Final Reports of the Tibor T. Polgar Fellowship Program, 2002. Hudson River Foundation, New York, New York.

Hjort, J. 1914. Remarks on the fluctuations in number and growth in marine populations. Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer 80:1-8.

Humphries, P., L. G. Serafini, and A. J. King. 2002. River regulation and fish larvae: variation through space and time. Freshwater Biology 47:1307-1331.

Jones, P.W., F.D. Martin, and J.D. Hardy, Jr. 1978. Development of Fishes of the Mid-Atlantic Bight. Vol. 1., US Fish & Wildlife Service FWS/OBS-78/12.

Kay, L. K., R. Wallus, and B. L. Yeager. 1994. Reproductive biology and early life history of fishes in the Ohio River drainage, Volume 2: Catostomidae. Tennessee Valley Authority, Chattanooga, Tennessee.

Leslie, J. K., and C. A. Timmins. 1991. Distribution and abundance of young fish in Chenal Ecarte and Chematogen Channel in the St. Clair River delta, Ontario. Hydrobiologia 219:135-142.

Limburg, K. E. 1996. Growth and migration of 0-year American shad (*Alosa sapidissima*) in the Hudson River estuary: otolith microstructural analysis. Canadian Journal of Fisheries and Aquatic Sciences 53:220–238.

Marr, J. C. 1956. The "critical period" in the early life history of marine fishes. ICES Journal of Marine Science/Journal du Conseil International pour l'Exploration de la Mer 21: 160-170.

May, R. C. 1974. Larval mortality in marine fishes and critical period concept, p. 3-19. In J. H. S. Blaxter [ed.] The early life history of fish. Springer-Verlag, Heidelberg.

Miller, D., J. Ladd, and W. C. Nieder. 2006. Channel morphology in the Hudson River Estuary: Historical changes and opportunities for restoration. pg 29-39 In Waldman, J. R., Limburg, K. E., and Strayer, D. L. [ed.] Hudson River Fishes and their Environment. American Fisheries Society Symposium 51.

Moyle, P. B. and J. J. Cech. 2004. Fishes: an introduction to ichthyology. Pearson Benjamin Cummings, San Francisco. 5th ed.

Niles, J. M. 2004. Examination of experimentally engineered larval fish habitat in the Marmet Pool, Kanawha River, West Virginia. Master's Thesis. West Virginia University, Morgantown, West Virginia.

Odom, M. C. 1987. Distribution of larval fishes in the Winfield Pool, Kanawha River, and direct impacts of commercial navigation traffic on larval fish survival. Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Penáz, M., A. L. Roux, P. Jurajda, and J. M. Olivier. 1992. Drift of larval and juvenile fishes in a by-passed floodplain of the upper River Rhone, France. Folia Zoologica 41:281-288.

Rozas, L.P. and W.E. Odum. 1987. Fish and macrocrustacean use of submerged plant beds in tidal freshwater marsh creeks. Marine Ecology Progress Series 38:101-108.

Scheidegger, K. J., and M. B. Bain. 1995. Larval fish in natural and regulated rivers: assemblage composition and microhabitat use. Copeia 1995:125–135.

Schmidt, R. E. 1986. Fish community structure in Tivoli North Bay, a Hudson River Freshwater Tidal Marsh. NOAA Technical Report OCRM/SPD, 47pp.

Schmidt, R. E. and E. Kiviat. 1988. Communities of larval and juvenile fish associated with water-chestnut and water-celery in the Tivoli Bays of the Hudson River: A Report to the Hudson River Foundation. Hudsonia, Ltd., Bard College Field Station, Annandale, NY.

Schmidt, R. E., and S. Cooper. 1996. A catalog of barriers to upstream movement of migratory fishes in Hudson River tributaries. Final report to Hudson River Foundation, New York.

Scott, M. T., and L. A. Nielsen. 1989. Young fish distribution in backwaters and main channel borders of the Kanawha River, West Virginia. Journal of Fish Biology 35:21-27.

Snyder D. E. 1983. Fish eggs and larvae. Pages 165-197 in L. Nielsen and D. Johnson [ed] Fishery techniques. American Fisheries Society, Bethesda, MD.

Snyder D. E. 1990. Fish larvae – ecologically distinct organisms. Pages 20-23 in M. B. Bain, ed. Ecology and assessment of warmwater streams: workshop synopsis. US Fish and Wildlife Service Biological Report 90(5), Washington, DC.

Strayer, D. L., N. F. Caraco, J. J. Cole, S. Findlay, M. L. Pace. 1999. Transformation of freshwater ecosystems by bivalves. BioScience 49(1):19-27.

Strayer, D. L., K. A. Hattala, and A. W. Kahnle. 2004. Effects of an invasive bivalve (*Dreissena polymorpha*) on fish in the Hudson River estuary. Canadian Journal of Fisheries and Aquatic Sciences 61:924-941.

Squires, D. F. 1992. Quantifying anthropogenic shoreline modification of the Hudson River and estuary from European contact to modern time. Coastal Management 20:343–354.

Webb P. W. 1975. Hydrodynamics and energetics of fish propulsion. Bulletin of the Fisheries Research Board of Canada. 190:1-159.

Yozzo, D. J., J. L. Anderson, M. M. Cianciola, W. C. Nieder, D. E. Miller, S. Ciparis, and J. McAvoy. 2005. Ecological Profile of the Hudson River National Estuarine Research Reserve. NYSDEC Contract No. C004646, Barry A. Vittor & Associates, Inc., Kingston, New York.