Modification of nektonic fish distribution by piers and pile fields in an urban estuary

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Abstract

Large urban piers degrade habitat value for several estuarine benthic fish species by shading, but their effects on mobile nektonic species is less well understood due to sampling challenges. Dual Frequency Identification Sonar (DIDSON) allowed equal access to sampling in the water column of structured shaded and unshaded vs. open environments in both dark and light conditions by methods similar to video but without light. Sampling ($n = 228$, 5-minute transects) occurred under and around four large municipal piers of varying dimensions in the Hudson River estuary during day and night from summer and fall in 2007 - 2009. The distribution of small (5 - 25 cm in length) and large (25 – 850 cm) fishes were analyzed separately in recognition of functional guild differences. Small fishes occupied open water, shaded under-pier, and un-decked relict piling habitats, but were significantly more abundant during the day in open unshaded water than under adjacent piers or in piling habitats.. Small fish occurred under 3 of 4 piers of varying size and configuration at 10 - 20% of the median abundances of adjacent open water. However, while schools were rare under piers they could be very large, so that abundance greatly exceeded mean open water abundance variance so as to preclude confidence in differences among piers. The differences among habitats was not significant at night, and the difference among piers was also not significant at night. School membership for small fish appeared to mitigate adverse effects of shading and may influence scaling of their response to shading and could therefore influence pier design. Large (>25 cm) predatory fish were uncommon but responded similarly to habitat effects as did small fish. Habitats did not segregate fish by guild as small forage fish co-occurred in 65.8% of samples with large piscivores. Studies that provide species-specific and mechanistic interpretation of dynamic habitat use as well as further quantification of scaling

effects could improve our understanding of how fishes respond to piers and other structures on urban shorelines.

Key words: shoreline; structure; habitat; shading; fish; DIDSON

1. Introduction

One of the most dramatic alterations to urban shorelines worldwide is through the construction of piers and their abandonment, dilapidation, and collapse. Experiments on pilings, floating structures, and armoring in several regions have tested the premise that these alterations locally enhance fish diversity and abundance through the provision of hard structure in otherwise soft-sediment environments with low relief and liken them to artificial reefs. Results, examined mechanistically as either shelter for juvenile reef fishes or food provisioning through the support of epibiont prey, have been weak or mixed (Caine 1987, Hair and Bell 1992, Coleman and Connell 2001, Clynick et al. 2007, Moreua et al. 2008, Feary et al. 2011). Some but not all of those structures shaded habitat. When shading did occur it was conjectured to have a negative effect (Hair and Bell 1992) in contrast to shading effects in streams by banks, trees, docks, or bridges in shallow fresh water (Haeseker et al. 1996, Helfman 1981, Le Pichon et al. 2015, Penaluna et al. 2015).

Previous research in the generally turbid Hudson River estuary extended over much of the shallow water habitat along the entire stretch of both the New Jersey and New York (Manhattan) portions of the estuary (Able and Duffy-Anderson 2006), which is one of the most developed

shorelines in North America (Squires 1992). In general, these studies focused on benthic fishes inclusive of those that naturally occur in the open soft bottom habitat replaced or covered by the structures. These studies found that shade generally had a negative affect on several species of benthic fish while having no effect on nocturnal chemosensory feeders; however, the piers studied here are much more massive structures than marina docks and piers or even bridges previously studied and therefore may have different effects. This past research was valuable in pointing to shading by piers, not benthic invertebrate prey scarcity, as a critical factor impacting habitat value for small benthic fish. A multifaceted approach to evaluate the impacts of these alterations included: 1) quantifying the distribution and abundance of benthic fishes under piers, at pier edges, in pile fields, and in open water areas (Stoecker et al. 1992, Able et al. 1998, 1999, Duffy-Anderson et al. 2003, Able and Duffy-Anderson 2006); 2) feeding and growth of juvenile benthic fishes under and around piers (Able et al. 1999, Metzger et al. 2001); and 3) availability of benthic prey for fishes under and adjacent to large piers (Duffy-Anderson and Able 1999). For juvenile fish, species diversity and species abundance were depressed under piers relative to nearby habitats (Able and Duffy-Anderson 2006). However, all of these studies necessarily focused on small, primarily benthic oriented fish that would enter small traps, and growth studies were limited to selected species and early life stages within cages (Duffy-Anderson and Able 1999, Able and Duffy-Anderson 2006).

Nektonic fishes are an important part of estuarine fish assemblages (Hagan and Able 2003, Able and Fahay 2010) but were not included in these prior studies in large part due to sampling difficulties. These include small schooling planktivorous species such as Atlantic silverside *Menidia menida* (Fam. Atherinidae), bay anchovy *Anchoa mitchilli* (Fam. Engraulidae) and

clupeiforms as well as larger predatory fish. Artificial harbor shoreline structures are used as spawning substrate and perhaps shelters for nektonic fishes including *M. menidia* (Caine 1987, Balouskus and Target 2012), but at reduced levels and on a very different scale. The development of small high frequency sonars, such as the Dual Frequency Identification Sonar (DIDSON) provided a means to move into the highly structured habitats of large commercial piers to do fish surveys by using video transect sampling models in a way that nets and traps could not (see Able et al. 2013, 2014, Martignac et. al 2014). Further, DIDSON does not depend on light to produce images and thus eliminates a potential bias when an understanding of light/shading effects is the study objective (Able et al. 2014, Becker et al. 2013). Study of response by nektonic fishes to shading began at the fine scale by examining distribution across the shade/light interface of the largest piers (355 x 251 m) in New York Harbor, Pier 40 (Able et al. 2013). Both small and large nektonic fish in that study responded to shading, although somewhat differently. Small forage species, primarily bay anchovy and Atlantic silverside avoided the shaded under-pier habitat during both day and night. The abundance of large predatory fish such as striped bass (*Morone saxatilis*) increased slightly just inside the edge relative to the sunlit water away from the pier, but fell away quickly at distances of more than 10 m under the edge where light was almost extinguished during both day and night. Incident light was less under the pier even during the day than the adjacent open water was at night, suggesting that light was an important factor in determining the response of nektonic fishes as it was for benthic species. However, the pier also provides vertical structure, which may attract or repel nektonic fishes, and few piers may be as consistently dark underneath as this large pier. Therefore, it remains to experimentally separate the influences of light and structure and to examine less severely shaded piers of different size and structure.

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The objective of this study was to evaluate nektonic fish use of pier habitat relative to adjacent structured but unshaded habitats (piling fields) and also open water habitats on a broader scale. Acoustic imaging again provided an approach that was relatively unbiased to light level or to differently structured habitats. More specifically, fish preference was determined for under pier, piling field, and adjacent open water habitats during the day and night and among piers of different size.

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2. Methods

2.1 Study Site

The study was carried out along the eastern (Manhattan, New York) shore of the Lower Hudson River estuary (Fig. 1). The area has a long history of modification with very little natural shoreline remaining (Squires 1992). Bulkheads now form most of the shoreline. A shallow river bench of 1.5 to 5 m depth (at low tide) extends about 300 m from the shoreline to a sharp channel edge dropping to at least 18 m depth before sloping to the main channel depths in excess of 30 m. Piers of various configurations extend from the shoreline to the channel edge, crossing the bench and thereby delineating small embayments of shallow water. Many of these are further split by piling fields remaining from previously removed piers. The piling fields have similar length-to-width dimensions as some of the existing piers (Table 1) and are all arrayed in the same compass direction. Surveyed habitat included under piers, among uncovered piling from relict piers, and open water areas in between the piers and piling fields. Sampled piers included

those with large and small length-to-width ratios ranging from nearly 1 to about 0.125 (Table 1, Fig. 1). Additionally, clustered pilings that act as bumpers but do not support overhead structure were examined near Pier I. These were classified the same as relict piling fields because they were uncovered but had substantial eddy fields around them (Table 1, Fig. 1).

Piers were built to different designs and only some could be accessed underneath for sampling. Of these, Pier 40 is the largest pier along this shoreline and nearly square in configuration with a small extension from the southwest corner. The perimeter, with the exception of the little extension, is a multistory building that casts shade several meters beyond the northern side. Pier 54 is small and low, with no supported building. It is similar in length and width to Pier 57, which does support a tall building. All three of these, and also Pier I, have very different supporting structure. Pier 54 was (at sampling time, since modified) supported by very dense and decrepit wooden pilings which are further interlaced by cross braces and wooden walls, some collapsed. Galleries, the openings between rows of pilings, are narrow (approaching 2 m). In contrast, Pier 40 has orderly rows of smooth concrete pilings spaced about 2 m apart until well under the pier where there are some obstructions. Pier I is high and narrow and without a building so that it receives abundant light underneath and pilings are few and widely spaced. Pier 57 is supported by 3 large buoyant cassions that are anchored to the bottom by short pilings. The cassions take up most of the pier's footprint and block access to its underside except for 3 galleries of ~6 m wide between adjacent concrete cassion walls. Two of these are partially blocked by a concrete structure and all have wooden pilings approximately 2 m apart forming a "fence" across the gallery entrance.

2.2 Sampling Techniques

Dual Frequency (1.8 MHz and 1.1 MHz) Identification Sonar (DIDSON) (Sound Metrics Corp., Seattle, WA) was used to image nektonic fishes in different habitats, although only the higher frequency was applied. Resolution varies with distance from the DIDSON lens so that, for example, fishes of > 300 mm length were resolved by 140 pixels in length in the near field and 35 pixel length at the extreme downrange. Sampling was at a rate of 5-12 frames per second, dependent on range as this affected processing speed. Moderate frame rate helped to discern moving fishes from a moving (relative to moving viewer) background. The high frequency multiple beams allow visualization of diagnostic features such as fins and swimming behavior (Holmes et al. 2006, Boswell et al. 2008). The thickness of the body, position and size of dorsal fins, and caudal fin fork were especially useful in distinguish between different species of larger fish such as striped bass, bluefish, and Atlantic menhaden (Able et al. 2014).

The DIDSON was mounted under a kayak (~ 4 x 1 m) for easy, quiet access to transects under and around the structures. A splash-proof laptop computer in the kayak cockpit allowed real-time viewing so that the paddler could adjust focus and direction for closer inspection of potential targets. Tilt of the DIDSON unit was set at 23 degrees for an optimum viewing range based on earlier trials (Able et al. 2013, Able et al. 2014). The set angle was sufficient to allow the DIDSON beams to reach the bottom at all sites until near the edge of the bench, and then not for any sites. This was possible because operator could change the window length in order to keep the bottom reflection near the distal end of the frame, thus continually maximizing spread within the field. As the pixel number is fixed, this does change the appearance and resolution of fish on

the screen, but in measuring fish with the graphic user interface (GUI) tool, this effects mostly the precision of the measurement (the precision of length measures being discrete to the current size value of a pixel) but not the interpretation of the classification, since classification is based on a very coarse scale (see below). The bench drop off is similar among sites despite the difference in average depth of the sites, and we did not partition variance among distance offshore (a correlate of depth), as this is assumed to be similar.

The position of the kayak was noted using vocal annotation to DIDSON native software, as guided by landmarks while under and around piers because GPS does not function under piers. Kayak transects were also drawn on a map by observers in a nearby support skiff to graphically record for reviewers where the kayaker paddled. Time stamps from the DIDSON recordings were correlated to navigation recordings to map the position of fish. Existing DIDSON host software (version 5.14) supports several tools to help measure and count observed objects. Sample application, advantages, and problems associated with this approach are described in detail in Able et al. (2013, 2014). These included viewing fish by eye directly in the DIDSON beam in front of a docked kayak in night lights, viewing tethered fish, catching fish by hook and line while watching them first and during catch on DIDSON, cast netting into the DIDSON beams, and in the area. Collections of fish for groundtruthing at the study site specifically were made with cast nets, gill nets, and hook and line on the same days as DIDSON sampling, but after DIDSON sampling was completed. These were part of a larger effort to classify species and also to estimate size and count error from DIDSON files. These included sites on the New Jersey side of the New York Harbor as well as in the Great Bay estuary in New Jersey and also visual and diver observation. These efforts are described in detail in Able et al. (2014).

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197 DIDSON sampling was accompanied by physical-chemical sampling (temperature, salinity,
198 dissolved oxygen) using a YSI 80 (Yellow Springs Instruments, Yellow Springs, OH) at every
199 site at every sampling event and taken to be indicative of all habitat types within a site because of
200 high water flow rates. Physical-chemical sampling was reported because environmental
201 conditions are potentially variable and could influence fish assemblages.

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203 *2.3 Sample Design*

204 The study design was based on categorization of three habitat types: 1) open water with no
205 obvious anthropogenic structural component in the water column or on the bottom (essentially
206 soft bottom), nominally “open”; 2) under-pier area located beneath a pile-supported platform,
207 nominally “under”; and 3) piling field, nominally “piling” consisting of an array of pier supports
208 where the deck or platform has been removed (see Able et al. 1998). One sample was a 5 minute
209 kayak transect paddled at a rate of about 0.25 m s^{-1} . When possible, transects were separated
210 from other transects by at least one transect length; however, some habitats were too small in
211 their entirety for this. Transects occasionally ran shorter or slightly longer than the allotted time;
212 thus, all detection data were standardized in post-processing by elapsed time and given units of
213 “catch”-per-unit-effort (CPUE) on a per second basis.

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215 Sites, inclusive of their adjacent open and piling habitats, were named by their municipal pier
216 address: e.g. Pier 40, 54, 57, and I (Fig. 1). In the case where a piling field was between and near
217 two of the sampled piers (as the piling field of the former Pier 55 was between Piers 54 and 57),
218 the piling field was nominally designated as belonging to the site of the pier to the south (Pier 54

in this example). All habitats within a site were encompassed in an area of roughly 350 x 400 m (distance from shore outwards x distance alongshore) with the exception of Pier 40, which was itself almost 300 m wide (Table 1). Within a particular habitat at each particular site, sampling was equally distributed among near-shore (pier at street base if this was a pier or edge), middle, and offshore extent. Transects meandered through habitat to stay within the habitat and spatial sample designation without re-sampling the same space. Spatial autocorrelation among the three samples within a habitat within a site may exist, for example when three samples constituted most of the under habitat of a site with little or no separation; thus, there was no test for differences among nearshore, middle, and offshore rank within a habitat.

Each site was visited on numerous occasions between 2007 and 2009 during different times of the day and night periods during June through October (Table 2). Sampling generally started downriver (Pier 40) and proceeded upriver (Pier I) in phase with the low rising tide to allow access underneath piers, minimize site differences in temperature or salinity due to tidal aliasing, and to kayak during periods of minimal residual flow. Sampling events at a site were generally separated by 8 hours, and by up to several months and, in some cases, years. No temporal autocorrelation was expected among samples from a habitat because nektonic fish are mobile and tend to disperse on daily and tidal time scales (Hagan and Able 2008, Able and Fahay 2010).

2.4 Data Analysis

DIDSON files were stored with time stamps and metadata in native format and reviewed in the laboratory as movies under direct control over playback by at least two independent reviewers following Able et al. (2014). Based on earlier assessment of classification that considered length

frequency distributions for numerous nektonic forage and predatory species during summer months (Able and Fahay 2010, Able et al. 2013, Able et al. 2014) reviewers first separated nektonic fish encounter events into small (<250 mm) or large (>250 mm) size classes. Reviewers recorded the number of individual fish within an encounter event and measured length for a subset (for large schools) or all of the individuals (for small schools) and recorded the mean value. In the case where individual fish (typically large fish) were seen crossing habitat boundaries, habitat association was scored based on the habitat in which they were first encountered.

Because the focus of this work follows on previous study at a single pier (Pier 40), extending it primarily as a consideration of different pier sizes and structure and a dissassociation of the shading and structural effects, data were treated to best address the specific null hypotheses each for large and small fishes separately:

H₀₁: There is no difference in the use by nektonic fishes of shallow open water, shaded pier, and unshaded piling habitat during the day.

H₀₂: There is no difference in the use by nektonic fishes of shallow open water, shaded pier, and unshaded piling habitat during the night.

H₀₃: There is no difference in the use by nektonic fishes of shaded under-pier habitats among different piers during the day.

H₀₄: There is no difference in the use by nektonic fishes of shaded under-pier habitats among different piers during the night.

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Differences among piling habitats was not specifically addressed because these do not vary relative to incident light intensity, they cannot be readily quantified relative to other (submerged) characters, and to constrain the number of terms in the analytical model.

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Nektonic fish might arrive at or access the different sites prior to responding to any effect of the pier itself. Therefore, for the purpose of testing the abundance of fish as a response to piers, abundance was standardized as the ratio of CPUE for those fish over the mean CPUE of fish from the open habitat samples of that site on that month (day and night separately) and separately for large and small fish. Thus, abundance in under and piling habitat is standardized to local time-varying availability and can be compared, while fish abundance in open water will always center on unity at each site and should not be compared among sites. Several cases had to be dropped because no adjacent open water sample contained fish in that month's sampling period. Samples in under or piling habitat with no fish, and also no fish in the adjacent open water habitat, were defined as zero rather than left undefined, but the open water response was also left at 0 so as not to decrease the variance among open water samples.

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The problem (above) of empty samples highlighted several challenges in formulating appropriate statistical tests. First, the response data were highly heteroscedastic and zero-inflated (based on Kolmogorov-Smirnov test of large and small fish response data separately and also on their log transforms). Second, the response data are ratios but not percentage (they exceed 1 in the case where more fish were under the pier than in adjacent open water habitat) and are continuous, and thus eliminate the use of some common transformations (e.g. arcsine) or link functions to the

Poisson or Gamma distribution or limit the function of others (e.g. Negative Binomial distribution , Marschener 2011). Thus, non-parametric tests were appropriate. Further, all of the independent variables were categorical. Interaction terms would be expressed as combinations of their individual binary dummy variables for each group membership leading to a potentially unwieldy and overparameterized full model in non-parametric n-way ANOVA-like designs. The use of rank transformation to address this, while favored for univariate tests, has undesired effects in multivariate applications (Sawilowsky et al. 1989). To reduce complexity, analysis of fish distribution was thus constrained to quantifying the main effects of association with structural and shading factors only. That the distribution of pelagic fishes changes diurnally is well established and so effects were tested separately during the day and night, rather than testing the diurnal period as a main effect and then the change in distribution among habitat as an interaction.

The use of under habitat at different piers was also of interest regardless of whether or not piers are themselves different from other habitats. Further, because their configuration and artificial (street level) lighting differs, individual pier effects are of interest separately during the day and night. Difference among specific piers was tested using the Kruskal-Wallis test, a nonparametric analog to one-way ANOVA (Kruskal 1952). Because the test compares the rank order of the medians among groups instead of their means, it is insensitive to the magnitude of outliers, which are reduced to similar rank among samples. Significant tests that included more than one case within the single classification were followed by Tukey Honest significant difference (HSD) pairwise tests. Significance was defined at $\alpha = 0.05$ and a Bonferroni

correction applied to HSD. All tests were performed in MATLAB (Mathworks, Natick MA) using scripts native to the software (kstest.m, kruskalwallis.m, multcompare.m and others).

3. Results

3.1 Environmental Conditions

Temperature during the June through October study periods ranged from 16 to 22°C and was similar at all sites throughout sampling (Fig. 2). Salinity ranged from 6 to 20 (Fig. 2) and was therefore encompassed entirely within the Venice System's (Venice 1995) mesohaline ($S = 5 - 18$) zone and the biologically analogous Zone 2 of Bulger et al. (1993), so that assemblages should not be expected to differ among sites due to salinity alone. Minimum salinity encountered (6) was at Pier I, the furthest site upriver, and maximum (20) at Pier 40, the furthest site downriver but means were in a much narrower range. Dissolved oxygen stayed within the range of 77 to 92% saturation, with the exception of a low of 55% at Pier 45 and a high of 112% at Pier 40 (Fig. 2); thus, it never reached stress level.

3.2 Composition and Characteristics of Fishes

Fish large enough to be confidently discerned by DIDSON (>30 mm) were periodically abundant in the shallow bench of the Hudson River estuary with 514 events (whether an individual, group or school) totaling an estimated 12,128 individuals among 219 total samples. Mean monthly abundance (CPUE = 0.19, 0.44, 0.95, 0.17, 0.69 for June through October respectively) was highest in rank order in August, during which only 4 samples were made in one year at one pier. Variation was high and the distribution was highly skewed with more encounters containing few

fish so that similarity and differences across all months was apparent (S.D. 0.53, 0.49, 1.19, 0.49, 2.23 for June through October respectively). Kolmogorov–Smirnov tests were highly significant in rejecting normality for all cases (small fish: $p = 1.7e-047$, KSstat = 0.5, log₁₀-transformed: $p = 2.4e-018$, KSstat = 0.3; large fish: $p = 1.9e-048$, KSstat = 0.5, log₁₀- transformed: $p = 7.6e-133$, KSstat = 0.8) . The majority (96.2%) of fish encounters throughout all sites and habitats were with small nektonic fish (Fig. 3) and these occurred in 151 of the 219 samples. Most (84.7%) of these were < 101 mm in length. The majority of small fish were associated with a few large schools, but singletons and small schools were much more common as events (Fig. 4). Small nektonic fish in larger schools, although very active, were seen to mill or circle, so that the school position did not move or moved only slowly. One large school of small fish was observed to extend from open water habitat on the north side of Pier 57 all the way through a gallery between support walls to open water on the southern side. Members were actively feeding on plankton right below the kayak as seen from the surface by eye and moving only short distances within the school; however the school was absent during the next sampling visit. Single schools or aggregations of fish were also seen occasionally (by both eye and DIDSON) to extend as a narrow band alongside but not under the entire lengths of some piers.

3.3 Response of small fish

There was a significant difference in the use of open, under, and piling habitat by small fish during the day (Kruskal-Wallis Sum of Squares = 31633.9, df = 2, MS = 15816.9, $X^2 = 15.88$, $p = 0.0004$). Pairwise differences were thus tested. Small fish were less likely to use habitat under piers and also less likely to use piling habitat than adjacent open water during the day, but there

was no significant difference in distribution among under and piling habitat (Tukey's HSD, Fig. 5). The null hypothesis H_{01} that there is no difference in the use by small nektonic fishes of shallow open water versus shaded pier or piling habitat during the day is rejected. During the night time, this pattern held but weakened to become insignificant (Kruskal-Wallis Sum of Squares = 396.6, $df = 2$, $MS = 198.304$, $X^2 = 1.7$, $p = 0.4269$). Therefore, there was no pairwise comparison. The null hypothesis H_{02} , that the distribution of small nektonic fishes differs relative to habitat at night is not rejected for both under and piling habitat. Thus, small fish appeared to disperse from open habitat into under and piling habitat at night.

There was no significant difference among piers in the ratio of small fish fish using under habitat during the day (Kruskal-Wallis Sum of Squares = 616.8, $df = 2$, $MS = 308.418$, $X^2 = 2.82$, $p = 0.2348$, Fig. 6a) so no pairwise differences were examined. There also was no significant difference among piers in the ratio of small fish fish using under habitat during the night (Kruskal-Wallis Sum of Squares = 27.6, $df = 2$, $X^2 = 2.76$, $p = 0.2516$, Fig. 6b), so no pairwise differences were examined. Neither the null hypotheses H_{03} nor H_{04} were rejected. Piers were similar in that small fish were similarly less abundant in under habitat than adjacent open habitats and this was true during both the day and night.

3.4 Response of large fish

Large fish were sparsely distributed compared to small fish, occurring in only 38 samples (Fig. 4). While most of these occurrences were of striped bass (*Morone saxatilis*) or bluefish (*Pomatomus saltatrix*) as singletons or pairs, two schools of large Atlantic menhaden (*Brevoortia*

tyrannus) totaling 360 individuals and an aggregation of 19 large striped bass accounted for the majority of the 619 large fish. The two large schools of Atlantic menhaden were encountered in open water adjacent to Pier 57. During both encounters they were visible by eye from the surface. They appeared to actively avoid both the pier and the adjacent piling field because they remained in the open water in between those habitats despite rapidly swimming about within the embayment. They left the site for the channel soon after discovery. Individuals in the school were of similar size and were organized, (i.e. oriented to each other and with regular spacing following Pitcher et al. 1983). These 2 large schools of Atlantic menhaden accounted for more than half of the total large fish count but did not fit the characteristics meant to be categorized by the “large fish” guild designation since they are planktivorous filter feeders rather than piscivorous, and were thus excluded from the large fish category for testing differences among habitats for the large fish guild.

In contrast to the Atlantic menhaden, the aggregation of striped bass consisted of individuals of different sizes and those individuals were as much oriented to aspects of the structure as to each other; they milled underneath a small terminal projection of Pier 40 (see Fig. 1) so that the aggregation occupied most of that horizontal space. Although they were under a deck, this small projection from the main pier was only 16 m across and fish were always within at least 7 m of a pier edge. Generally, large fish were seen to move in all directions relative to the kayak/DIDSON (towards, away, and across the field of view and did not appear to respond to the kayak based on either speed or directional bias). Large fish were also seen to cross habitat boundaries moving along, out from under a pier, or under it from open water. Large fish were

observed by DIDSON attacking small forage fish on several occasions and also posturing towards or chasing each other short distances.

There was no significant difference in the distribution of large fish relative to habitat during the day (Kruskal-Wallis Sum of Squares = 2857.5, $df = 2$, $MS = 1428.81$, $X^2 = 3.81$ $p = 0.149$, Fig. 7a) and no pairwise test was performed. There was also no significant difference in the distribution of large fish relative to habitat during the night (Kruskal-Wallis Sum of Squares = 292.71, $df = 2$, $MS = 146.353$, $X^2 = 3.61$, $p = 0.1643$, Fig. 7b) and no pairwise test was performed. Thus for large fish, neither H_{01} nor H_{02} are rejected. Large fish were found under piers on only four occasions during the day time, all under Pier 40. However, given the large number of daytime samples under Pier 40 during which no large fish were encountered, there was no statistical confidence that this represented a difference among piers (Kruskal-Wallis Sum of Squares = 28.36, $df = 2$, $MS = 14.1818$, $X^2 = 0.79$, $p = 0.6748$). During the night, large fish were again found under Pier 40 but also under Pier I. However, large fish were so scarce as to never be found at Piers 45 and 57 in open water so that these sites remained undefined. As ratios of large fish encountered relative to those in open water there was no significant difference among piers (Kruskal-Wallis Sum of Squares = 7.5, $df = 1$, $MS = 7.5$, $X^2 = 2.42$, $p = 0.1198$), so no pairwise differences were examined. Neither null hypothesis H_{03} nor H_{04} were rejected for large fish.

4. Discussion

4.1 Limitations of the approach

Heteroscedasticity associated with dynamic school membership is a hallmark of abundance distributions in nektonic fishes (Shaw 1978, Burrow et al. 2015). These species, which are usually themselves reliant on planktonic or other nektonic prey, at least partially cue distribution on fluid hydrographic structure and prey and on each other, including for protection and improved foraging, rather than on static benthic landscape features (Partridge et al. 1980, Pitcher and Parish 1993). They therefore yield contagious distributions that challenge statistical analysis. Large sample size mitigates this to some extent, but it is also important to ask whether minor differences that are found to be statistically significant are meaningful and also whether large differences that occur with great uncertainty are not meaningful. In addition, the required transformations may make the results difficult to interpret, or may hide trends. An alternative to transformations for parametric methods is a series of one-way non-parametric tests (such as Kruskal-Wallis used here). Such a series does not allow for the testing of interaction terms. It is also counterindicated because the increased chance for Type I error in large series mandates (by convention) a prohibitive chance of finding true effects after application of the Bonferoni correction (Cabin and Mitchell 2000, Nakagawa 2004). This analysis therefore relies heavily on the use of quantitative graphics (box-whisker plots) to mitigate the drawbacks of the significance testing methods. The distribution of statistical outliers in particular stands out in this and is useful to consider both in the ecological and applied sense. It is clear from both approaches that the frequency with which nektonic fish in shallow water use artificially structured habitat is much decreased from that of natural open water habitat during the day especially, but fish do use them, and episodically do so, in much greater density than the mean concentration in adjacent open water habitat.

Another concern is the limitation in classification to species in the acoustic imaging approach. Many of the concerns with DIDSON use revolve on the use of automated processing (see review by Martignac et al. 2014), which was not used here in favor of a meticulous multiple human review approach (Able et al. 2014). Ground truthing efforts suggest that classification error is not of great concern in this particular study especially because the two primary abundant nektonic species (Atlantic silversides and bay anchovy) formed mixed schools and therefore shared behavioral response (Able et al. 2014). However, some species of concern, particularly small migratory alosines, may have behaved differently and an inability to classify them separately could have accounted for some of the variance. Size measurement error (potentially in the order of 2-3 mm dependent on range) is not a concern because sizes fell into two clearly separated modes and were used only at that level. Thus, despite some concern, this approach was unique in that it offered a quantifiable means of assessing fish distribution in turbid estuaries during the day and night without bias to light.

4.2 Nektonic Fish Response to Habitat

Both large and small nektonic fish were overall more abundant in open water than adjacent shaded or unshaded piling habitat. This pattern was very strong during the day and the difference in median value even increased at night towards open water, while the overall effect was weakened by increased variance and a decrease in outliers in all habitats. This is suggestive that extreme shading (under large low piers), but not minor shading (such as cast over the river by adjacent buildings), is an additional detriment to habitat use over structure alone. Shade might be tolerably dark during the day but too dark at night (following a threshold dynamic) as small fish appeared to more readily spread to piling fields than under pier habitat at night. The

interpretation of a threshold vs. scaling effect for shade is consistent with findings from a
 previous study at Pier 40 (Able et al. 2013). The deep shading under that pier appeared to differ
 in its impact from the lighter shade cast obliquely from buildings over adjacent open water (to a
 pier's north). No North (shaded open water) vs. South (unshaded open water) side effect was
 noted at Pier 40 (Able et al. 2013). In this study, there was little difference in among-pier effects.
 It is clear from the present work that other piers of various lengths and widths and their remains
 in this estuary also affect nektonic fish distribution. Fish were abundant in open water but also
 gathered at the outside edges of most piers and were typically an order of magnitude less
 abundant under them or among unshaded pilings than in adjacent open water. However, there
 were individual episodes when this was dramatically reversed and are reflected in the greater
 abundance of small fish under piers and among piling, similar in scale to those in open water.
 These instances of outliers point to schooling as a potential mitigating effect to structure and
 shade avoidance. A possible explanation is that the school membership takes priority as a cue
 over other local static features, especially as it is a stress response to the threat of ambush
 predation (Hoare et al. 2004). Certainly, large fish usually were found in the presence of small
 schooling fish and particularly at pier edges and predation at a pier edge during this study was
 witnessed and recorded with DIDSON (Able et al. 2014). Another possibility, particularly
 relevant to the high variance at night, is the patchiness of light or dark as a resource. Three of the
 four piers (the exception being Pier 54) were artificially lit at night from above, but Pier 40 also
 had assorted vessels, such as the the New York City Fire Department fire fighting vessel, Coast
 Guard fast boats, and a dinner cruise charter vessel moored along-side which were periodically

brilliantly lit and cast light even under the pier because of their low position just above the water line.

Previously reported work using different samples in the same general study area and season found a strong decrease in small fish abundance across the shade interface of the exceptionally large Pier 40. Small schooling nektonic fish preferred unstructured and unshaded habitat pier edges relative to shaded habitat under piers. In comparing the averages of just the open water parts of the fish abundance reported in Figure 4 of Able et al. (2013) and standardizing for those transect's partial effort (in total seconds elapsed in just that habitat) to open water abundance (catch-per-unit-effort, CPUE) at Pier 40 in this study, we find a remarkably similar CPUE, 28.2 in the earlier study vs. 25.5 in the current one. This suggests that the sample distance of 10 m into open water in the previous study was sufficient to sample beyond a possible edge effect concentration (Prevedello et al. 2013).

For large fishes in the earlier single pier study (Able et al. 2013) there was a weak response to the pier except that distribution was shifted to be just under, rather than outside the pier edge as it was for small fish, a behavior related to ambush predation (Helfman 1981). The distance between pilings relative to fish size is not sufficient for it to act efficiently as structural refuge for small fish threatened by predation (Bartholomew et al. 2000, Bartholomew and Burt 2015) and this may explain the reluctance to enter these habitats. In any case, large predators are apparently more capable than small pelagic fish in utilizing a variety of urbanized habitats and appear, in this case, to move readily through all of them (Able et al. 2013). Thus, the role of predators in urban estuaries should receive special attention. In the future, telemetry of free-

swimming fish could certainly address aspects of habitat use for large fish that would express habitat value in very different metrics than CPUE. For example, telemetry showed the hesitancy of surface-swimming smolts to access deeper passage under floating bridge pontoons with the result of higher predation (Moore et al. 2013).

These findings on nektonic fish for piers, but not pilings, are similar to those on benthic fishes in this estuary but differ from some on reef fishes in harbor or marina settings worldwide (e.g Caine 1987, Hair and Bell 1992, Clynick et al 2007). They are also similar to some findings on juvenile salmon response to structures in west coast estuaries (Toft et al. 2007, Munsch et al. 2014, Ono and Simenstad 2014). Benthic fishes and reef fishes orient to static seascape features such as uncovered pilings and forage on invertebrates attached to them if light is sufficient (Caine 1987, Hair and Bell 1992), but pier shade decreases habitat value by interfering with foraging either by loss of visual ability or by loss of stimulus (Able et al. 1998, 1999, Duffy-Anderson et al. 2001, Able and Duffy-Anderson 2006). Small nektonic fish also feed better in lit conditions and also utilize visual cues during schooling, and although some are capable of feeding and schooling in the dark, they tend to disperse at night and form into shoals during the day (Shaw 1961, Higgs and Fuiman 1996, Ryer and Olla 1998, 1999). In addition to avoiding shade, these prey fish may also avoid even lit structure that can hide ambush predators because schooling, not hiding, is their primary defense.

5. Implications

Until now, it has been very difficult to sample nektonic fishes throughout the range of habitats that are available along the shallow edge of urbanized estuaries. Together with synoptic work on

fine scale distribution (Able et al. 2013) and ongoing surveys of different shoreline types (Grothues and Able, unpublished data), this work represents the first comprehensive view of nektonic fish distribution and habitat use across a highly modified Mid-Atlantic estuarine shoreline. In general, this and prior studies support the conclusion that anthropogenic modifications may profoundly change both benthic and nektonic fish distributions but do not eliminate them.

Several important observations provide guidance for managing pier design and also for further study. Concerning large scale structures in urban waterfronts, consideration should be given to the “natural” state replaced by shoreline modifications that include piers. Piers break the shallow river bench into artificial coves and even account for some of the shoaling between them. Coves and shallows are features of natural shorelines that are lacking due to shoreline straightening and armoring. Shallow shoreline fish such as Atlantic silversides and bay anchovy might normally stay within such artificial coves during foraging and then disperse and regroup into adjacent coves over diurnal periods (Hagan and Able 2008). Note that this differs from the ecological scenario of disruption due to shading to juvenile salmonids migrating along shorelines on the western US coast (Ono and Simenstad 2014) and possibly to ecologically analogous juvenile alosines on the US east coast. However, the extent of shading likely caused the cumulative effect of large piers in this setting. Piers occupy approximately 30% of the shallow bench in the study area, and thus similarly reduces the accessibility of valued sunlit shallow habitat to fishes.

It is likely that enhancing light penetration by changing pier orientation, heights, widths, and support structures that allow fish passage would enhance habitat suitability for many nektonic and benthic species. For example, experiments measured light transmission under piers with prisms, grating, and artificial light (Grayaldo and Nelson 2006, Ona and Simenstad 2014). Controlled studies that manipulate habitat for a common group of fishes in a single shared environment along light gradients are critical to learning what mechanisms underlie these patterns, but these are very costly to achieve. A possible approach to understanding the mechanisms behind these distributions is fine spatial (sub-meter) and temporal (~5 s) scale simultaneous telemetry of numerous (~100) small fish over several hours to days. Signal processing for such an approach is already mature but is difficult to apply to such small fish because of limitations imposed mostly by transmitter battery size (Grothues 2009); however, this technology is rapidly developing. The engagement of biologists in such structural designs prior to building, demolition, or modification in urban estuaries, and the allowance of elements that can be experimentally manipulated within them, while they are still being built, is key to evaluating the enhancement of habitat suitability.

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Literature Cited

- Able, K.W., Duffy-Anderson, J.T., 2006. Impacts of piers in the lower Hudson River.
In: J.S. Levinton and J.R. Waldman (eds.), The Hudson River Estuary. Cambridge University Press, New York, NY. Pp. 428- 440.
- Able, K.W., Fahay, M.P., 2010. Ecology of Estuarine Fishes: Temperate Waters of the Western North Atlantic. Johns Hopkins University Press, Baltimore, MD.
- Able, K.W., Grothues, T.M., Kemp, I.M., 2013. Fine-scale distribution of nektonic fishes relative to a large urban pier. *Mar. Ecol. Prog. Ser.* 476, 185-198.
- Able, K.W., Grothues, T.M., Rackovan, J.L., Buderman, F.E., 2014. Application of Dual Frequency Identification Sonar (DIDSON) in an urban estuary: An approach for identifying fish species, schools, and behavior. *Northeast. Nat.* 21 (2), 192-209.
- Able, K.W., J. P. Manderson, J.P., Studholme, A.L., 1998. The distribution of shallow water juvenile fishes in an urban estuary: the effects of man-made structures in the lower Hudson River. *Estuaries.* 21(4b), 731-44.
- Able, K.W., Manderson, J.P., Studholme, A.L., 1999. Habitat quality for shallow water fishes in an urban estuary: The effects of manmade structures on growth. *Mar. Ecol. Prog. Ser.* 187, 227-235.

- Balouskus, R.G., Target, T., 2012. Egg deposition by Atlantic silverside, *Menidia menidia*: substrate utilization and comparison of natural and altered shoreline type. Estuar. Coast. 35, 1100–1109. DOI 10.1007/s12237-012-9495-x
- Bartholomew, A., Burt, J.A., 2015. Both decreasing interstructural space and increasing total cover increase shrimp abundance on artificial structures deployed in a UAE seagrass bed. Mar. Freshw. Behav. Phy. 48(3), 213-220.
- Bartholomew, A., Diaz, R.A., Cicchetti, C., 2000. New dimensionless indices of structural habitat complexity: predicted and actual effects on a predator's foraging success. Mar. Ecol. Prog. Ser. 206, 45- 58.
- Becker, A., Whitfield, A.K., Cowley, P.D., Järnegren, J., Næsje, T.F., 2013. Potential effects of artificial light associated with anthropogenic infrastructure on the abundance and foraging behaviour of estuary-associated fishes. J. Appl. Ecol. 50(1), 43–50.
- Blaxter, J.H.S., Hunter, J.R., 1982. The biology of the clupeoid fishes. Adv. Mar. Biol. 20, 1–223.
- Boswell, K.M, Wilson, M.P., Cowan, J.H., 2008. A semi-automated approach to estimating fish size, abundance, and behavior from Dual-Frequency Identification Sonar (DIDSON) data. N. Am. J. Fish. Manage. 28, 799-807.
- Bulger, A.C., Hayden, B.P., Monaco, M.C., Nelson, D.M., McCormick-Ray, M.G., 1993. Biologically based estuarine salinity zones derived from a multivariate analysis. Estuaries. 16(2), 311-322.
- Burrow, J.F., Horwood, J.W., Pitchford, J.W., 2013. Variable variability: difficulties in estimation and consequences for fisheries management. Fish. Fish. 14(2), 205-212.

- 621 Cabin, R.J., Mitchell, R.J., 2000. To Bonferroni or not to Bonferroni: when and how are the
622 questions. *ESA Bull.* 81, 246-248.
- 623 Caine, E.A., 1987. Potential effect of floating dock communities on a South Carolina estuary. *J.*
624 *Exp. Mar. Biol. Ecol.* 108, 83-91.
- 625 Castillo-Rivera, M., Moreno, G., Iniestra, R., 1994. Spatial, seasonal, and diel variation in
626 abundance of the bay anchovy, *Anchoa mitchilli* (Teleostei: Engraulidae), in a tropical
627 coastal lagoon of Mexico. *Southwest. Nat.* 393, 263–268.
- 628 Clynick, B.G., Chapman, M.G., Underwood, A.J., 2007. Effects of epibiota on assemblages of
629 fish associated with urban structures. *Mar. Ecol. Prog. Ser.* 332, 201-210.
- 630 Coleman, M.A., Connell, S.D., 2001. Weak effects of epibiota on the abundances of fishes
631 associated with pier pilings on Sydney Harbour. *Environ. Biol. Fish.* 61, 231-239.
- 632 Duffy-Anderson, J.T., Able, K.W., 1999. Effects of municipal piers on the growth of
633 juvenile fish in the Hudson River estuary: a study across a pier edge. *Mar.*
634 *Biol.* 133:409-418.
- 635 Duffy-Anderson, J.T., Able, K.W., 2001. An assessment of the feeding success of young-of-the-
636 year winter flounder (*Pseudopleuronectes americanus*) near a municipal pier in the
637 Hudson River estuary, U.S.A. *Estuaries.* 24(3), 430-440.
- 638 Duffy-Anderson, J. T., Manderson, J.P., Able, K.W., 2003. A characterization of
639 juvenile fish assemblages around man-made structure in the New York-New
640 Jersey harbor estuary, U.S.A. *B. Mar. Sci.* 72(3), 877-889.
- 641 Feary, D.A., Burt, J.A., Bartholomew, A., 2011. Artificial marine habitats in the Arabian Gulf:
642 Review of current use, benefits and management implications. *Ocean Coast. Manage.* 54,
643 742-749.

- Gerlotto, F., Bertrand, S., Bez, N., Gutierrez, M., 2006. Waves of agitation inside anchovy schools observed with multibeam sonar: A way to transmit information in response to predation. *ICES J. Mar. Sci.* 63, 1405–1417.
- Glasby, T.M., Connell, S.D., 1999. Urban structures as marine habitats. *Ambio*. 28, 595-598.
- Grayaldo, P.F., Nelson, K., 2006. Preliminary results of light transmission under residential piers in Lake Washington, King County, Washington: A comparison between prisms and grating. *Lake Reserve. Manage.* 22(3), 245-249.
- Haeseker, S.L., Carmichael, J.T., Hightower, J.E., 1996. Summer distribution and condition of striped bass within Albemarle Sound, North Carolina. *T. A. Fish. Soc.* 125, 690–704.
- Hagan, S.M., Able, K.W., 2003. Seasonal changes of the pelagic fish assemblage in a temperate estuary. *Estuar. Coast. Shelf Sci.* 56, 15–29.
- Hagan, S.M., Able, K.W., 2008. Diel variation in the nektonic fish assemblage in a temperate estuary. *Estuar. Coast.* 31, 3-42.
- Hair, C.A., Bell, J.B., 1992. Effects of enhancing pontoons on abundance of fish: initial experiments in estuaries. *B. Mar. Sci.* 51, 30-36.
- Helfman, G.S., 1981. The advantage to fishes of hovering in the shade. *Copeia*. 1981,392-400.
- Helfman, G.S., 1986. Fish behavior by day, night and twilight. In *The behavior of teleost fishes*, ed. T.J. Pitcher. Baltimore, Maryland: The John Hopkins University Press.
- Hoare, D.J., Couzin, I.D., Godin, J.-G.J, Krause, J., 2004. Context-dependent group size choice in fish. *Anim. Behav.* 67(1), 155–164.
- Horodysky, A.Z., Brill, R.W., Warrant, E.J., Musick, J.A., Latour, R.J., 2010. Comparative visual function in four piscivorous fishes inhabiting Chesapeake Bay. *J.Exp. Biol.* 213,1751-1761.

- Kelly, D.J., Bothwell, M.L., 2002. Avoidance of solar ultraviolet radiation by juvenile coho salmon (*Oncorhynchus kisutch*). Can. J. Fish. Aquat. Sci. 59, 474-482.
- Kruskal, W., 1952. Use of ranks in one-criterion variance analysis. J. Am. Stat. Assoc. 47 (260), 583–621.
- Le Pichon, C., Trancart, T., Lambert, P., Daverat, F., Rochard, E., 2015. Summer habitat use and movements of late juvenile European flounder (*Platichthys flesus*) in tidal freshwaters: results from an acoustic telemetry study. J. Exp. Mar. Biol. Ecol. 461, 441-448.
- Marschner, I. C. 2011. glm2: Fitting Generalized Linear Models with Convergence Problems The R Journal 3(2): 12-15
- Martignac, F., Daroux, A., Bagliniere, J.L., Ombredane, D., Guillard, J., 2014. The use of acoustic cameras in shallow waters: new hydroacoustic tools for monitoring migratory fish population. A review of DIDSON technology. Fish Fish. 16(3), 486–510.
- Metzger, C.V., Duffy-Anderson, J.T., Able, K.W., 2001. Effects of a municipal pier on growth of young-of-the year Atlantic tomcod (*Microgadus tomcod*): A study in the Hudson River estuary. Bull. NJ. Acad. Sci. 46(1), 5-10.
- Moore, M., Berejikian, B.A., Tezak, E.P., 2013. A floating bridge disrupts seaward migration and increases mortality of steelhead smolts in Hood Canal, Washington State. PLoS One. 8(9), 1-10. ee73427
- Munsch, S.H., Cordell, J.R., Toft, J.D., Morgan, E.E., 2014. Effects of seawalls and piers on fish assemblages and juvenile salmon feeding behavior. N. Am. J. Fish. Manage. 34, 814-827.
- Nakagawa, S., 2004. A farewell to Bonferroni: the problems of low statistical power and publication bias. Behav. Ecol. 15(6), 1044-1045.

- Ona, K., Simenstad, C.A., 2014. Reducing the effect of overwater structures on migrating juvenile salmon: An experiment with light. *Ecol. Eng.* 71, 180-189.
- Partridge, B., Pitcher, T., Cullen, M., Wilson, J., 1980. The three-dimensional structure of fish schools. *Behav. Ecol. and Sociobiol.* 6(4), 277–288.
- Penaluna, B.E., Dunham, J. B., and Noakes, D.L.G., 2015. Instream cover and shade mediate avian predation on trout in semi-natural streams. *Ecol. Freshw. Fish.*
doi: 10.1111/eff.12221
- Petrie, M.E., Ryer, C.H., 2006. Hunger, light level and body size affect refuge use by post-settlement lingcod *Ophiodon elongatus*. *J. Fish. Biol.* 69, 957-969.
- Pitcher, T.J., 1983. Heuristic definitions of shoaling behavior. *Anim. Behav.* 31, 611-613.
- Pitcher, T.J., Parrish, J.K., 1993. Behaviour of Teleost Fishes, Chp 12: *Functions of shoaling behaviour in teleosts*. Springer.
- Prevedello, J.A., Figueiredo, M.S.L., Grelle, C.E.V., Viera, M.V., 2013. Rethinking edge effects: the unaccounted role of geometric constraints. *Ecography.* 36(3), 287–299.
- Robinson, C.J., Arenas, F.V., Gomez, G.J., 1995. Diel vertical and offshore-inshore movements of anchovies off the central Baja California coast. *J. Fish Biol.* 47, 877–892.
- Rountree, R., Able, K.W., 1993. Diel variation in decapod crustacean and fish assemblages in New Jersey polyhaline marsh creeks. *Estuar. Coast. Shelf S.* 37, 181–201.
- Ryer, C.H., Olla, B.L., 1998. Effect of light on juvenile walleye pollock shoaling and their interaction with predators. *Mar. Ecol-Prog. Ser.* 167, 215-226.
- Ryer, C.H., Olla, C.L., 1999. Light-induced changes in the prey consumption and behavior of two juvenile planktivorous fish. *Mar. Ecol-Prog. Ser.* 181, 41-51.

- Sawilowsky, S., Blair, R.C., Higgins, J.J., 1989. An investigation of the type I error and power properties of the rank transform procedure in factorial ANOVA. *J. Educ. Stat.* 14 (3), 255–267.
- Shaw, E., 1961. Minimal light intensity and the dispersal of schooling fish. *Bull. I'Inst. Oceanogr.* 1213, 1-8.
- Shaw, E., 1978. Schooling fishes. *Am. Sci.* 66, 166–175.
- Squires, D.F., 1992. Quantifying anthropogenic shoreline modification of the Hudson River and estuary from European contact to modern time. *Coast. Manage.* 20(4), 343-354.
- Stoecker, R.R., Collura, J., Fallon Jr., P.J., 1992. Aquatic studies at the Hudson River Center Site. *In: C. L. Smith, (ed.) Estuarine Research in the 1980s. The Hudson River Environmental Society Seventh Symposium on Hudson River Ecology. State University of New York Press, Albany, NY. Pp. 407-427.*
- Strayer, D.L., Power, M.E., Fagan, W.F., Pickett, S.T.A., Belnap, J., 2003. A classification of ecological boundaries. *BioScience.* 53, 723–729.
- Toft, J.D., Cordell, J.R., Simenstad, C.A., Stamatiou, L.A., 2007. Fish distribution, abundance, and behavior along city shoreline types in Puget Sound. *N. Am. J. Fish. Manage.* 27, 465-480.
- Thomson, R.E., Allen, S.E., 2000. Time series acoustic observations of macrozooplankton diel migration and associated nektonic fish abundance. *Can. J. Fish. Aquat. Sci.* 57, 1919–1931.
- Venice System. 1959. The final resolution of the symposium on the classification of brackish waters. *Archo. Oceanogr. Limnol.* 11(suppl), 243–248.

Table 1. Characteristics of individual habitat types along the Manhattan shoreline in the Hudson River during 2007-2009. See. Fig. 1 for location of study area.

Location	Length (m)	Width (m)	Area(m ²)	Water Depth (m)
Pier				
Pier 40	294	240	70560	0.6-5.45
Pier 57	262	41	10742	0.6-5.7
Pier I	217	16	6472	1.2-2.7
Pier 54	233	26	6058	1.5-2.0
Open Water				
south of Pier 40	193	301	58093	1.4-4.4
between Pier 54 and 57	257	197	50629	1.2-2.8
north of Pier 57	267	133	35511	1.1-2.8
north of Pier I	222	127	28194	1.3-2.2
north of Pier 40	273	101	27573	1.1-4.1
south of Pier I	212	44	9328	2.0-2.2
Pile Field				
north of Pier 40	260	30	7800	0.7-3.5
south of Pier I	116	64	7424	1.9
north of Pier 57	227	23	5221	0.8-5.0
between Pier 54 and 57	244	11	2684	1.0-2.2

Table 2: Number of total DIDSON sample transects by individual habitat type (open water, piers, pile field) and diurnal period along the Manhattan shoreline in the Hudson River during 2007-2009. See Fig. 1 for study site locations.

	2007		2008	2009		Total
Locations	Day	Night	Day	Day	Night	
Pier						
Pier 40	20		21	23	4	68
Pier 40, west side	1			3		4
Pier 54	10	8				18
Pier 57	11		11		11	33
Pier I	4		6	3		13
Open Water						
between Pier 54 and 57		8	4		3	15
NJ bridge			3			3
north of Pier 40	3		3	2		8
north of Pier 57	5	2			2	9
north of Pier I	2	2				4
south of Pier 40				2		2
south of Pier 45					2	2
south of Pier I			3	1		4
Pile Field						
between Pier 54 and 57		2			2	4

1						
2						
3						
4						
5						
6	north of Pier 40	7		2	2	3
7						14
8	north of Pier 45				1	
9						1
10	north of Pier 57	5	3	4		3
11						15
12	south of Pier I			2		
13						2

14 743

15 744

Figure Captions

Figure 1. The lower Hudson River estuary along the Manhattan waterfront in the New York study area and its location on the east coast of the United States (inset).

Figure 2. Spatio-temporal variation in salinity, temperature, and dissolved oxygen during sampling of fishes at composite pier, piling field, and open water habitats in the lower Hudson River estuary along the Manhattan waterfront. Bars indicate standard error. Numbers in the symbol key indicate pier number.

Figure 3. Length-frequency distribution of small (shaded) and large (> 250 mm, unshaded) and nektonic fishes associated with sampled habitats as measured from DIDSON acoustic video in the lower Hudson River estuary during 2007-2009. Note that the scale differs for large fish (right axis).

Figure 4. Frequency distribution for the abundance of large (>250 mm) and small (<250 mm) fish associated with individual encounter events as sampled by DIDSON associated with composite pier, pile field, and open water sites in the lower Hudson River estuary during 2007-2009.

Figure 5. Box plot comparison of distribution of small (< 250 mm) fish among habitat types (under, piling, open) during the day (upper) and during the night (lower). The central horizontal

line of each box marks the median (a better indication of abundance than the mean for highly skewed distributions), the lower and upper edges of the box mark the 25th and 75th percentiles and the vertical whiskers extend to the most extreme non-outliers. Statistical outliers are individually indicated as “+”. Letters in the upper plot represent similar treatment effects based on Tukey HSD pairwise test.

Figure 6. Comparison of distribution of small (< 250 mm) fish among piers, with day (upper) and night (lower). There were no small fish encountered under Pier 54. Y axis is truncated in the upper plot, with an outlier for Pier 40 extending to 8.7.

Figure 7. Comparison of large (> 250 mm) fish distribution among habitat types during the day (upper) and night (lower).

Figure 8. Comparison of distribution of large (> 250 mm) fish among piers during the day (upper) and night (lower).

Figure 1.

Figure 2.

Figure 3.

Figure 4.

Figure 5.

Figure 6.

Figure 7.

Figure 8.