

Fine-scale distribution of pelagic fishes relative to a large urban pier

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ABSTRACT: Intense shading under large piers is known to negatively affect benthic fishes. However, effects on pelagic fishes are poorly known. We employed the equivalent of acoustic video, dual frequency identification sonar (DIDSON), under a kayak to evaluate the response of pelagic fishes at a large (351 × 255 m) urban pier (Pier 40) in Hudson River. A repeated measures design (322 occupations) sampled 3 transects each across both the northern and southern open water—pier edge—under pier continuum during the day and night from June 2009 to September 2010. Over 22 000 individual fish, ranging from small schooling forage species (e.g. *Anchoa mitchilli*, *Menidia menidia*) to large predators (*Morone saxatilis*, *Pomatomus saltatrix*) were detected with DIDSON and verified with conventional sampling nets. Small (<250 mm) schooling pelagic fishes avoided areas under the pier where light is dramatically reduced during both day and night (when municipal lights illuminate the water away from the pier). Less abundant large (>250 mm) predatory fish responded somewhat differently from small schooling fish in that large predatory fish were slightly more abundant under the pier than in open water, but only from the edge extending to 5 m under the pier where there was still some light. Beyond that, abundance declined sharply. Together, these observations indicate that areas under large piers are suboptimal habitats for many of the abundant pelagic fishes, a pattern similar to that for benthic fishes.

KEY WORDS: Pier · Shade · Edge · Pelagic fish · Distribution · DIDSON

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INTRODUCTION

Many urban shorelines are dominated by piers, yet we do not have a complete understanding of how fishes are affected by these large structures. Our own research, and that of others, has used a multifaceted approach, and evaluated (1) the distribution and abundance of fishes under piers, at pier edges, in pile fields (piers without decking), and in open water areas (Stoecker et al. 1992, Able et al. 1998, 1999, Duffy-Anderson et al. 2003, Able & Duffy-Anderson 2005); (2) feeding and growth of juvenile 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 & Able 1999). These studies have shown that species

diversity and abundance is depressed under piers relative to nearby habitats (Able & Duffy-Anderson 2006). The only species that were routinely collected under piers were those that do not solely rely on the use of vision to forage (Duffy-Anderson & Able 1999). The studies of the distribution of benthic invertebrate prey for fishes around piers suggest that prey abundances under piers are more than sufficient to support fish growth (Duffy-Anderson & Able 2001). However, results of directed studies indicate that feeding and growth rates of visually-feeding fish species (e.g. *Pseudopleuronectes americanus*, *Tautoga onitis*) are negative under piers (i.e. fish lose weight) (Duffy-Anderson & Able 1999, Able & Duffy-Anderson 2006). It is not likely that factors associated with pier pilings, such as reduced flow or sedimentation, affect feeding

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(although they may affect energetics, e.g. Cook & Coughlin 2010), since studies of fish growth in pile fields indicate that fish grow well in that habitat. Rather, it appears that pier decks create intense shade that impedes foraging.

Despite this extensive work, there remain several issues that confound clear interpretation of pier effects. These issues relate to temporal and spatial scales. (1) Fish response to light (Helfman 1981) and shading of man-made structures can be variable depending on the structure's shape and size (Stoecker et al. 1992, Able & Duffy-Anderson 2006, Nightingale et al. 2006). This is a particularly difficult issue to resolve in estuaries because of the varying relationship between light and turbidity (Benfield & Minello 1996, Vogel & Beauchamp 1999, De Robertis et al. 2003, Lehtiniemi et al. 2005). In addition, the daytime light level varies dramatically from the pier edge to under the pier (Able & Duffy-Anderson 2006) and so could its effect on fish. The relationship is not necessarily linear; light may have a threshold intensity below which habitat use declines precipitously, even to zero. This is an especially important issue because 'edges' can have profound effect on the distribution, abundance, and habitat use of animals (e.g. Moenting & Morris 2006) including estuarine fishes (Minello et al. 2003). (2) The amount of light changes diurnally and this has a profound effect on estuarine fish habitat use (Helfman 1986, Rountree & Able 1993, Sogard & Able 1994, Apenzeller & Leggett 1995, Hagan & Able 2008). This aspect of fish use of pier edges and under pier areas has not been investigated because the sampling methods of prior studies integrated results over 24 h and up to 10 d (Able & Duffy-Anderson 2006). (3) All of the prior studies have focused on fishes that live on or just above the bottom (see Able & Duffy-Anderson 2006 for a summary) and did not consider the pelagic fishes, which can live closer to the lit surface and be the most abundant components of the estuarine fish fauna (Able & Fahay 1998, 2010), including in the Hudson River (e.g. *Anchoa mitchilli* or *Alosa* spp.) (Schultz et al. 2000, 2003, 2005). Thus, at least these 3 issues need to be addressed before we can have a complete understanding of pier effects on fishes.

The specific objective of this project was to evaluate the effects of shading by a large pier (Pier 40) in the lower Hudson River estuary on the pelagic fish assemblage by comparing fish species composition, size, and abundance across the open water-pier edge-under pier continuum. These comparisons were made with acoustic video (DIDSON: Dual Frequency Identification Sonar, Sound Metrics) during day and night in summer and fall over 2 yr.

MATERIALS AND METHODS

Study area

Pier 40 is located on the west shore of Manhattan, New York, 3 km north of The Battery in the lower Hudson River estuary (Fig. 1). This pier is supported by a field of pilings and is 351 m long and 255 m wide. The building around the pier's perimeter, historically used for handling ship cargo, is 3 stories high. This building casts shade over open water to the north of the pier and, in the morning only, over open water of the western edge, while the southern edge is unshaded. This area is highly modified from its original contours and, as a result, has no natural, shallow water habitat. This portion of the estuary is tidally flushed; therefore, it undergoes changes

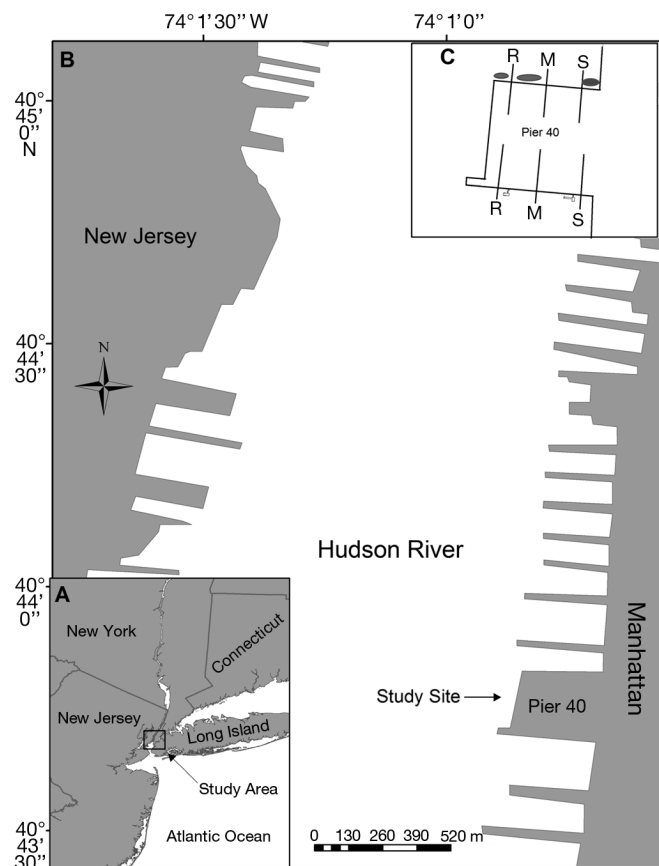


Fig. 1. (A) Location and (B) orientation of Pier 40 in the lower Hudson River estuary. (C) Six primary acoustic transects lines at Pier 40 followed a gradient across the edge of the pier coincident with degree of light penetration and crossed the pier edge on both the shaded (north) and unshaded (south) edges. The arrangement of the transects across the inshore-offshore direction allowed a determination of depth effects. S: shoreside; M: middle; R: riverside. Grey ovals: position of frequently or permanently moored large vessels

in salinity over a single tidal cycle. Temperatures during the sampling season approach 26°C (Duffy-Anderson & Able 1999). Photic depths in summer in open water vary from 3 to 6 m depending on sediment load and phytoplankton (Stross & Sokol 1989), which both influence turbidity. Average light intensities in open areas are considerably higher (10 to 50 $\mu\text{E m}^{-2} \text{s}^{-1}$, depths 2 to 3 m) than light levels underneath piers with solid concrete tops where values reach zero (Able et al. 1998, Duffy-Anderson & Able 1999).

On the shaded north and unshaded south sides of Pier 40, 3 acoustic fish sampling transect lines followed a gradient of light penetration and crossed the edge of the pier (Fig. 1). The arrangement of these transects across the inshore-offshore direction (S: shoreside, M: middle, R: riverside, respectively) allowed a determination of depth effects. A shift in the S transects between the north and south sides reflected avoidance of a permanently moored vessel and a floating dock, respectively.

Environmental conditions

A YSI 650 MDS sensor package (Yellow Springs Instruments) was used to measure temperature, salinity, pH, and dissolved oxygen at both the surface and the bottom of the water column. The depth of the bottom reading was also recorded. All of these parameters were usually measured on each side of the pier during each sampling rotation, ~4 times a sampling day in 2009 and 2010.

Light intensity was measured in 2 ways with different units to account for different scales in both spatial and temporal variation. Instrumentation available for these 2 scales used 2 different methods. A radiometric method measured unweighted total light photons in the 400 to 700 nm wavelength band incident on a spherical surface (irradiance), while a photometric method weighted certain wavelengths of light incident on a flat surface and rejected others because they do not contribute to vision (illuminance, in lm m^{-2}). The scales for these 2 methods cannot be directly interconverted. Photometric methods are more applicable to the current work, which deals with vision, but radiometric measures indicate very low incident light, including visible light, and are therefore also useful. To account for fine spatial scale variation with distance under the pier and light extinction with depth, we used a Licor LI-1000 light meter with an LI-193SA spherical underwater quantum light sensor (LI-COR Environmental). The com-

bined unit was factory calibrated prior to use. The unit reports photosynthetic photon flux fluence rate (PPFFR) photon units ($\mu\text{mol m}^{-2} \text{s}^{-1}$) or quantum scalar irradiance (hereafter irradiance). The sensor was lowered on a frame from a kayak along each transect. Irradiance was recorded at 1, 2, and 3 m depth as water depth allowed, starting 10 m from the pier edge in open water, directly at the pier edge, and thereafter under the pier at 2.5 m increments. Measures were made on both the north and south sides of the pier among the pilings adjacent to the one in which the DIDSON transect was being performed during both nighttime and daytime DIDSON deployments. The timing of these measurements was normally off by ~1/2 h to avoid possible disturbance of sampled fishes. Licor deployments were performed along with fish sampling in each of the sampled months. Irradiance was plotted for every transect or side separately.

Moored autonomous Hobo® Light Intensity Loggers (Onset) were used to measure photometric illuminance at fixed locations and depths over daily timescales. Loggers were set to record every 4 min. Two light loggers each were attached to 3 different lines suspended from small floats at 1 and 2 m from the surface, so that logger depth was constant despite tide. They were deployed in random (coin toss) stratified (by transect) locations for 12 h before being pulled and redeployed in a different location in June and July and 24 h in August. Loggers were deployed only on the south side of the pier because of concerns with propeller wash and entanglement from vessels using the north side of the pier.

Acoustic sampling of fishes

Our general approach was to acoustically sample shoreside, middle, and riverside transects on the north and south sides of the pier (S, M, R north and S, M, R south, respectively) across the entire gradient from open water to the middle of Pier 40 (Fig. 1C) and analyze these for fish distribution relative to light intensity and distance from pier edge during the day and night. The spatial and temporal (diurnal or nocturnal) sampling structure was designed to decompose the potential confounding effects of light gradient, structural affinity, and depth or distance from shore during the day and night. Acoustic targets along open water-pier edge-under pier transects were groundtruthed for species identity and abundance using fish-collection methods appropriate to pelagic species (Table 1).

Table 1. Dual frequency identification sonar (DIDSON) imagery and groundtruthing effort by sampling gear at Pier 40 in the Hudson River during 2008 to 2010

Sampling gear and date	No. of deployments or transects		No. of imaged or captured fish		No. of species captured	
	Day	Night	Day	Night	Day	Night
DIDSON						
Jun 2009	68	36	349	21	–	–
Jul 2009	29	25	743	634	–	–
Aug 2009	50	38	5538	7930	–	–
Jul 2010	27	15	1816	486	–	–
Aug 2010	38	15	1291	146	–	–
Sep 2010	36	47	1103	2237	–	–
Cast net						
Oct 2008	8	–	–	–	–	–
Jun 2009	10	–	–	–	–	–
Jul 2009	30	20	–	–	–	–
Aug 2009	10	28	–	207	–	3
Jul 2010	5	6	–	286	–	4
Aug 2010	–	5	–	19	–	3
Sep 2010	–	24	–	5	–	1
Umbrella net						
Aug 2009	15	32	38	4	3	2
Jul 2010	5	–	10	–	1	–
Gill net						
Jun 2009	1	1	–	–	–	–
Jul 2009	2	1	–	–	–	–
Aug 2009	1	2	–	2	–	2
Hook and line						
Jun 2009	1	–	–	–	–	–
Jul 2009	2	2	–	–	–	–
Aug 2009	1	2	–	–	–	–
Jul 2010	2	6	–	–	–	–
Aug 2010	5	2	3	–	1	–
Sep 2010	3	1	1	8	1	1
Dip net						
Aug 2009	–	7	–	6	–	2
Total DIDSON samples	248	176	10840	11454	–	–
Total ground-truthing samples	133	205	54	568	6	14

We used DIDSON to image individual fish under and around piers (K. W. Able et al. unpubl. data). As used with 96 beams in the high frequency (1.8 MHz) mode at the applied ranges of 1.25 to 10 m out from the lens, the width resolution varied between 6.5 and 52.1 mm per pixel. The pixel height resolution depends on the window length, and at the applied settings of 2.5 to 10 m window lengths, the height resolution varied between 4.8 and 19.5 mm per pixel. Thus, a fish of 250 mm length that was oriented in profile across the screen and 2 m from the lens would be represented by an image 24 acoustic pixels long, but only 4 pixels long if it were 10 m away from the lens. At this resolution, objects as small as 40 mm

could be readily identified as fishes in the very near field, but would be represented by only 1 pixel in the extreme downrange. At that minimum size, individual fish are difficult to discern and cannot be measured, but schools or aggregations could be apparent. Sampling was at a rate of 5 to 10 frames s^{-1} , dependent on range, as this affected the host software's processing speed. Moderate frame rate helped to discern moving fish from a moving background (actually a static background moving relative to a moving viewer). Fish movements can be diagnostic and help to break fish outlines from their background. DIDSON images can even detect individual fins in larger fish. Fins generally have low reflectance but are valuable to identification. Existing DIDSON host software (version 5.14) supports several tools to help measure and count observed objects.

The DIDSON was mounted with a hinge below the bow of a sit-on-top kayak for easy access to waters under and around the piers. It was pointed forwards and tilted at 23° for an optimum viewing range based on preliminary trials (K. W. Able et al. unpubl. data). 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. The paddler used a small red headlamp for kayak navigation during nighttime sampling to minimize the potential effect on the fishes. The position of the kayak was noted using vocal annotation supported by the DIDSON host software to link it with the video. Painted numbers on the pilings provided landmarks because GPS signals do not penetrate under the pier. Time stamps from the DIDSON recordings were mapped to navigation recordings to determine the location of fish.

Acoustic sample design

The acoustic transects bisected the pier parallel to the river axis (along the ~6, 12, and 16 m isobaths) (Fig. 1). Each transect began in open water 10 m outside the pier and crossed under and to the middle of the pier (137.5 m transect length, Fig. 1). These transects were at a constant distance relative to the shoreline and to the western pier edge. This also had the effect of stratifying sampling relative to light

angle, and penetration relative to the south or north side of the pier. Each transect on the south and north side ended ~52.5 and ~35 m under the pier, respectively. Overhead and underwater obstacles prevented further penetration.

Sampling with the DIDSON occurred over the span of monthly 4 d trips in June, July, and August 2009 and July, August, and September 2010, with some preliminary sampling in October 2008 (Table 1), a period during which many species are resident in the estuary and some species begin to move downstream and out of the estuary in the fall (Able & Fahay 1998, 2010). Sampling at each location was accompanied by hydrographic data collection.

Groundtruthing

Preliminary comparison of DIDSON files relative to fish samples occurred at a boat basin in southern New Jersey and the Hudson River (K. W. Able et al. unpubl. data). Additionally, groundtruthing on site during this study (Table 1) included cast net fishing and angling in open water next to the pier and under the pier edge. One gill-net station was used for large-volume collections of the water column synoptic with acoustic sampling. Cast nets (6.35 mm mesh and 1.2 m radius; 9.5 mm mesh and 0.9 or 1.2 m radius, with a weighted circumference line) were thrown by hand from a boat in open water during the day and at night from the pier railing to target concentrations of fish seen in the pier light field and visible in DIDSON sonograms (see Baker & Minello 2011 for considerations associated with cast net sampling). A gill net (multi-mesh and 25 m in length) was set ~10 m out from the pier at multiple locations in 2009 to sample larger pelagic fishes in the open water surrounding the pier. In June and July the net soaked for 12 h and was checked twice a day. In August the net was left in for ~24 h. An umbrella net (6.35 mm mesh, 1 × 1 m) was used to sample smaller pelagic fishes on the surface. The nets were suspended ~1 m under the surface and soaked for intervals of 5 to 30 min before being retrieved. Fishes from all gears were identified, enumerated, measured (nearest mm, total length or fork length) and released at the site of capture.

Data analysis

DIDSON files were viewed by 2 independent reviewers in the host software (Sound Metrics, 2007). A third reviewer also viewed all files and checked

any disparities between reviewers for a final decision to produce a master data set. Reviewers recorded each event of fish presence (either school or individual fish). Abundances were either counted manually (for few fish) or by taking an estimate (for schooling fish) using the average of 3 grid squares (using the superimposed grid application in the DIDSON software) and multiplying that by the number of squares with fish in them. A range of measurements were also taken for both length and body depth of the fish using a graphic user interface tool in the DIDSON software. The reviewer used the matched audio file and written notes, as well as underwater landmarks visible in the sonogram, to reference the position of the fish or fishes to the pier structure and location.

Features of the ensonified targets provided identification of sonogram features to fish species or categories of ecological groups. The relationship between acoustic targets and fish identity and abundance in groundtruth samples was based, in part, on comparison sampling. Measures from a single file reviewer were used to control for observer effect.

Data for small pelagic schooling fish were analyzed for patterns of the abundance and the frequency of encounters separately. Many pelagic fishes school, and the strength of association with schoolmates may override individual habitat preferences. Therefore, it is possible that a large school is no more indicative of habitat preference than a small school. It is also conceivable that light affects school size through mechanisms of availability or sensory perception. The lack of knowledge on this dictated that we treat abundance and encounter events as orthogonal measures of habitat use. Larger fish were not commonly in schools, so these were treated based on abundance only.

In considering the dynamic range of environmental conditions under the influence of this large pier, we recognized the major habitat factor of interest to be distance under the pier (as a proxy of correlated light level) under the specific null hypotheses that fish abundance and occurrence were unstructured relative to distance. We also recognized that several habitat factors could interact or obfuscate a shading effect: diurnal stage (day or night), tide level (as a proxy of flow direction relative to the baffling effect of pilings), distance from shore, and pier side (due to shading and flow). We therefore used a nested multi-factor model testing the effects of distance (D) from edge in 12 classes of 2.5 m increments, nested within the 3 transects (T : S, M, R) per side, and crossed categorical effects of pier side (S : North or South), diurnal stage (N : Day or Night) and tide stage (F : Ebb,

Flood, Slack Low, related to flow direction and strength). It was not possible to sample under the pier at or approaching slack high because of reduced overhead clearance.

We used a generalized linear model (GLM) to partition fish response (Y) among environmental effects:

$$Y_{D(T)SNF} = \mu + \beta_D (\alpha_T) + c_F + \delta_N + g_S + \beta_D (\alpha_T) \\ c_F + \beta_D (\alpha_T) \delta_N + \beta_D (\alpha_T) g_S \\ + \dots \text{all other interactions} + \varepsilon \quad (1)$$

where $Y_{D(T)SNF}$ is log transformed abundance (or log transformed number of encounter events) at D , T , S , N , and F , μ is the overall mean response at all combinations of factor classes, α_T is the transect factor (fixed, S, M, or R), β_D is the Distance under the pier factor (15 discrete blocks of 2.5 m, from -10 m outside the pier to 20 m under the pier) nested within transect, c_F is the Tide factor (Flood, Ebb or Low Slack), δ_N is the Diurnal factor (Day or Night), g_S is the Pier side factor (North or South), and ε is error. We treated repeated transect occupations within a month as pseudoreplicates because of the potential for temporal autocorrelation (the probability that the same fish schools or individuals are still present in the same area) and so require treatment as repeated measures. Therefore, all transect or station occupations within a given tide stage, diurnal period, and side were averaged within a monthly rotation, but not among monthly rotations. This resulted in averaging values of from 1 to 3 samples depending on how many times a particular transect with identical class values was sampled within a month. Samples among months were not averaged and were treated as replicates. Thus, variation among pseudoreplicates is not a test parameter. We used the SAS software, PROC GLM, for statistical analysis. Pairwise Tukey's studentized range tests demonstrated which pairwise combinations differed for those multiple combinations that differed significantly.

Data were separated into cases of small (<250 mm TL) and large (>250 mm TL) pelagic fish for the purpose of GLM in reflection of a functional ecological partitioning between small prey fish (primarily *Anchoa mitchilli*, *Menidia menidia*, *Brevoortia tyrannus*, and *Alosa* spp.) and large predatory fish (primarily *Morone saxatilis* and *Pomatomus saltatrix*) as identified on the basis of groundtruthing (K. W. Able et al. unpubl. data) and a review of life history (Able & Fahay 2010). However, in reporting results qualitatively, we used categories of small aggregations of small pelagic fish, large aggregations of small pelagic fish, small schools of small pelagic fish, large schools of small pelagic fish, single small pelagic fish,

single large pelagic fish, schools of large pelagic fish, and unidentified fish to communicate what we encountered on a level that integrates both occurrence and abundance (Table 2). Benthic fishes were not treated in this analysis because they have been treated in detail elsewhere (Able et al. 1998, 1999, Duffy-Anderson et al. 2003, Able & Duffy-Anderson 2005).

RESULTS

Environmental conditions

During both 2009 and 2010, environmental conditions were similar between the surface and the bottom of the water column in the water depths sampled during all 3 mo. Temperature increased during the sampling period from ~18°C during initial sampling to ~22 to 24°C during August. Salinity in 2009 ranged from 10–12 to 22–24 with the variability during each sampling period corresponding to tidal changes. Salinity was consistently higher at both the surface and the bottom in 2010 with values ranging from 20.2 to 23.1. Dissolved oxygen values were slightly higher in 2009 with values ranging from 5.4 to 10.1 in 2009 and 3.7 to 6.7 in 2010. pH ranged from 6.8 to 8.2 during 2009 but was not measured in 2010.

Ambient light under and outside the pier varied as a function of day, distance under the pier, and tide level as well as with the nighttime cycle of artificial lighting at the pier edge. Irradiance at 1, 2 and 3 m depth outside of the pier decreased to negligible levels under the pier within 5 m of its edge even during daytime low tide, when maximum light penetration occurred (Fig. 2A). This pattern consistently

Table 2. Categories of fish taxa or ecological groups from dual frequency identification sonar (DIDSON) files compiled during 2009 and 2010 in the study area. See text for further definition and limits of categories. aggr. = aggregation

Category	2009		2010	
	Number	%	Number	%
Benthic fish	85	12.1	66	9.7
Small aggr. of small fish	18	2.6	3	0.4
Large aggr. of small fish	24	3.4	0	0
Small school of small fish	114	16.2	125	18.4
Large school of small fish	20	2.8	19	2.8
Single small fish	377	53.6	413	60.9
Single large fish	38	5.4	30	4.4
School of large fish	0	0	1	0.1
Total	676		657	

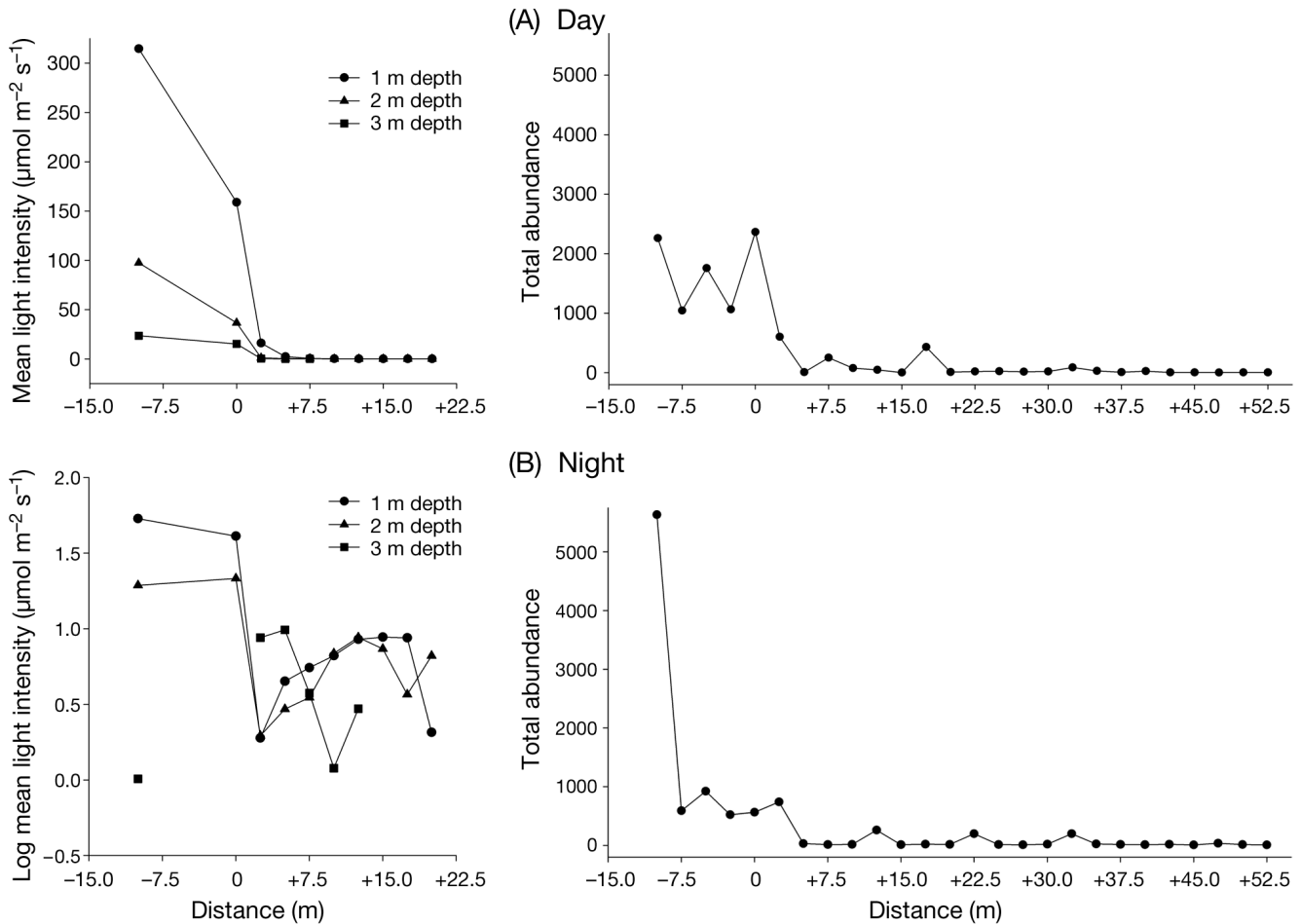


Fig. 2. (A) Day and (B) night mean light intensity (left panels) at multiple depths relative to distance under the pier, in comparison to total abundance of pelagic fish (right panels; small school fish or all fish). Negative values = distance away from pier, positive values = distance under pier, 0 = pier edge. Note the change to log scale in (B) left panel, to visualize low-level variation

occurred during all months for which data is available during both years. Along transect R, during low tide and during afternoon (westerly sun), light penetrated along the entire length of this western edge transect (both northern and southern sections). Light was greatest at low tide, when albedo allowed side-welling light above the water under the pier when the water was shallower. Light outside and under the pier was at very low levels at night, with irradiance sometimes falling to zero under the pier at least along transects S and M on both sides, but in general, light could be detected (seen only in logarithmic scale, Fig. 2B, left panel), due to artificial lights in Manhattan and on the pier.

The time varying illuminance logged at fixed locations showed 2 important effects of distance under the pier relative to the reference 10 m away in open water (Fig. 3). The first was the magnitude

of illuminance and the second was the shape of the curve, which reflects the time of exposure above any given light level. In general, the shape of illuminance curves for different depths of a position were similar but lower in magnitude at deeper depths, while the location (distance of the logger under the pier) greatly affected the shape of the curve. The slopes of morning increase and evening decrease were less steep and reached a pronounced peak relative to the platykurtic reference curve. The location affected magnitude of illuminance more so than logger depth. By a distance of 7.5 m under the pier, illuminance rarely rose above the threshold of either striped bass or bluefish detection (as calculated from Horodysky et al. 2010) for a daytime spectrum neural response but did rise above the threshold for nighttime spectrum detection of both species for ~12 h (Fig. 3).

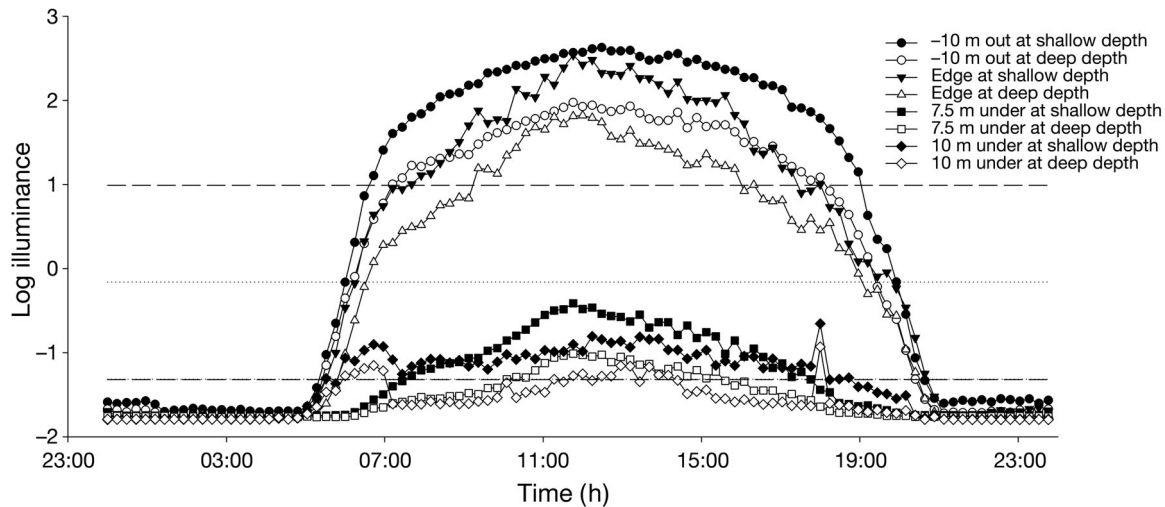


Fig. 3. Illuminance (lm m^{-2}) under and adjacent to Pier 40 as measured by Hobo Light Loggers. Horizontal lines: measured daytime (top) and nighttime (bottom) minimum illumination levels in log cd m^{-2} that elicit a neural response from *Morone saxatilis* (dashed) and *Pomatomus saltatrix* (dotted) in air in otherwise dark enclosures (calculated as $K_{50} - 0.5$ dynamic range, from data in Horodysky et al. 2010). Sensitivity is lower at night because of the spectral sensitivity of the fish eye. Nighttime minima coincide for both species

Fish taxa or categories, size composition and abundance

Preliminary research (K. W. Able et al. unpubl. data) and our prior experience allowed us to identify several categories of fishes based on DIDSON images at the study site (Table 2). Of these, single, small pelagic fish (53.6% of total fish in 2009, 60.9% in 2010) and small schools of small pelagic fish (16.2% in 2009, 18.4% in 2010) were the most frequently occurring events. The next most frequently occurring categories in both years were benthic fish (12.1% in 2009, 9.7% in 2010, not discussed further) and single large pelagic fish (5.4% in 2009, 4.4% in 2010). Large schools of small pelagic fish were less abundant than the previous categories in both years

but similar between years. Other categories were more abundant in 2009 including small and large aggregations of small pelagic fish.

The fish fauna in the vicinity of Pier 40 based on groundtruth sampling included several species that are common components of this and other estuaries in the region (Table 3). The most abundant species captured were *Anchoa mitchilli* and *Menidia menidia*. The next most abundant species were *Alosa pseudoharengus* and *Pomatomus saltatrix*. A notable fish species not sampled during groundtruth sampling but observed with the DIDSON was *Morone saxatilis* (K. W. Able et al. unpubl. data). The size of fish detected ranged from 40 mm (the assumed lower limit of detection by DIDSON) up to 750 mm (Fig. 4). During both

years the vast majority of individual fish were in the 50 to 100 mm size class. The values for *M. menidia* (61–80 mm TL, mean 69.6 mm from umbrella nets; and 63–92 mm TL, mean 75.8 mm, from cast nets) and *A. mitchilli* (60–76 mm TL, mean 71.1 mm; and 55–79 mm, mean 67.6 mm) overlapped with the size range for the smaller fishes as detected with the DIDSON. This pattern helps to confirm that these species are likely some of the dominant individu-

Table 3. Composite fish species composition and abundance by pelagic groundtruthing gear in the Hudson River during 2008–2010 (see Table 1 for details of sampling effort)

Fish species		Groundtruth gear				
Scientific name	Common name	Umbrella net	Cast net	Gill net	Hook and line	Dip net
<i>Anchoa mitchilli</i>	Bay anchovy	12	139	–	–	–
<i>Alosa pseudoharengus</i>	Alewife	–	35	–	–	–
<i>Brevoortia tyrannus</i>	Atlantic menhaden	–	–	1	–	–
<i>Menidia menidia</i>	Atlantic silverside	34	341	–	–	1
<i>Peprilus triacanthus</i>	Butterfish	4	–	–	–	–
<i>Pomatomus saltatrix</i>	Bluefish	–	1	–	12	–
<i>Prionotus evolans</i>	Striped searobin	1	–	–	–	–

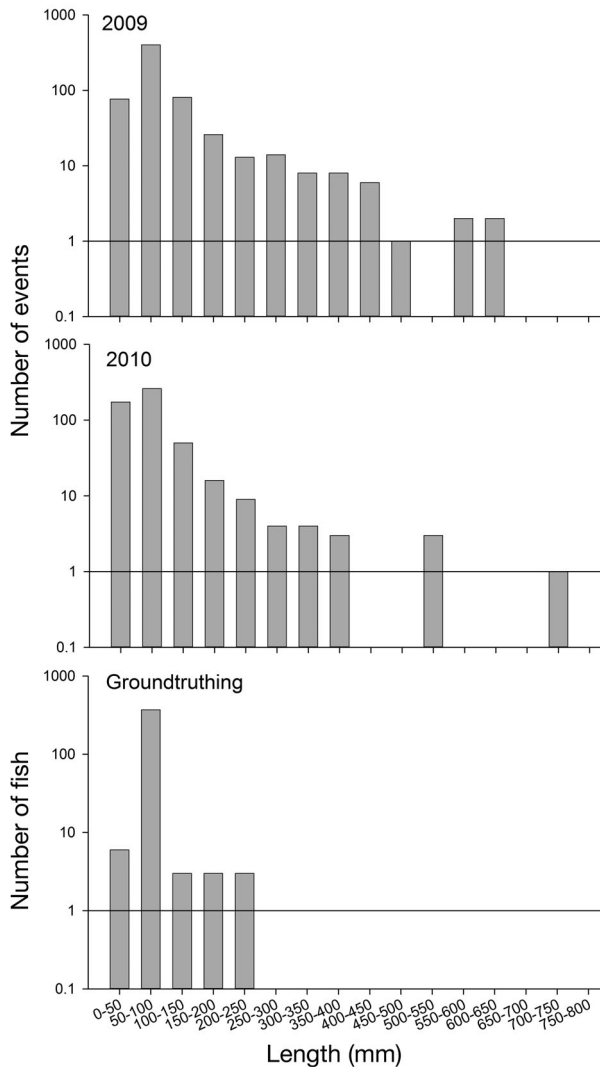


Fig. 4. Length frequency distribution of fish found in dual frequency identification sonar (DIDSON) transects and from groundtruthing in 2009 and 2010

als observed with the DIDSON. However, in general, very few of these identified in groundtruthing (Table 3) could be identified to species with DIDSON sampling. Thus, the use of general categories (Table 2) allowed for fish groups to be consistently categorized.

Response of fish to piers

The values from several different metrics from DIDSON images indicate that few small pelagic schooling fish, the most abundant categories encountered (Table 2), use the under pier of 40 relative to adjacent open waters and that the differences are

correlated with light levels influenced by pier shading. In combined daytime values over both years, the abundance of small pelagic schooling fishes was highest at the pier edge and in open water and consistently lower at all distances from the edge under the pier (Fig. 2A). This was closely correlated with light levels, which were highest in open water, declined abruptly at the pier edge, and continued at very low levels everywhere under the pier. The pattern of small pelagic schooling fish abundance relative to light was similar at night; schools were abundant in open water and not very abundant at all distances under the pier (Fig. 2B).

Given that small pelagic fish of several different categories dominated the DIDSON images in both years (Table 2), we examined the occurrence, organization and size of schools in more detail relative to pier habitats both during the day and night separately (Fig. 5). In both years, the occurrence of schools averaged higher in open water away from the pier and at the pier edge during the day and night although there was considerable variation, and this was highest outside the pier. Under the pier, the occurrence of schools and aggregations of small pelagic fish was consistently lower. The spacing between individuals of small pelagic fish in aggregations and schools did not appear markedly different in the different pier habitats during either the day or night, but the reduced number of schools under the pier made comparisons difficult and prone to be weighted by the values of rare occurrences. Average school size, i.e. the number of individuals in the school, was somewhat higher outside the pier and at the pier edge, relative to under the pier during both the day and night (Fig. 5).

The mean length of all fishes varied in a similar manner with those fish in open water and under the pier edge averaging smaller than those fish at all distance under the pier (Fig. 6). This average size shift reflects fewer small fish under the pier, so that large fish under the pier weight the size average of that habitat more.

Small pelagic schooling fish abundance and occurrence

Significance testing quantified the variation due to the tested pier habitat features (GLM and pairwise Tukey's test) as well as their interactions (GLM) and demonstrated some differences in how different classes of fishes responded. There was a highly significant effect of distance along the open water-pier

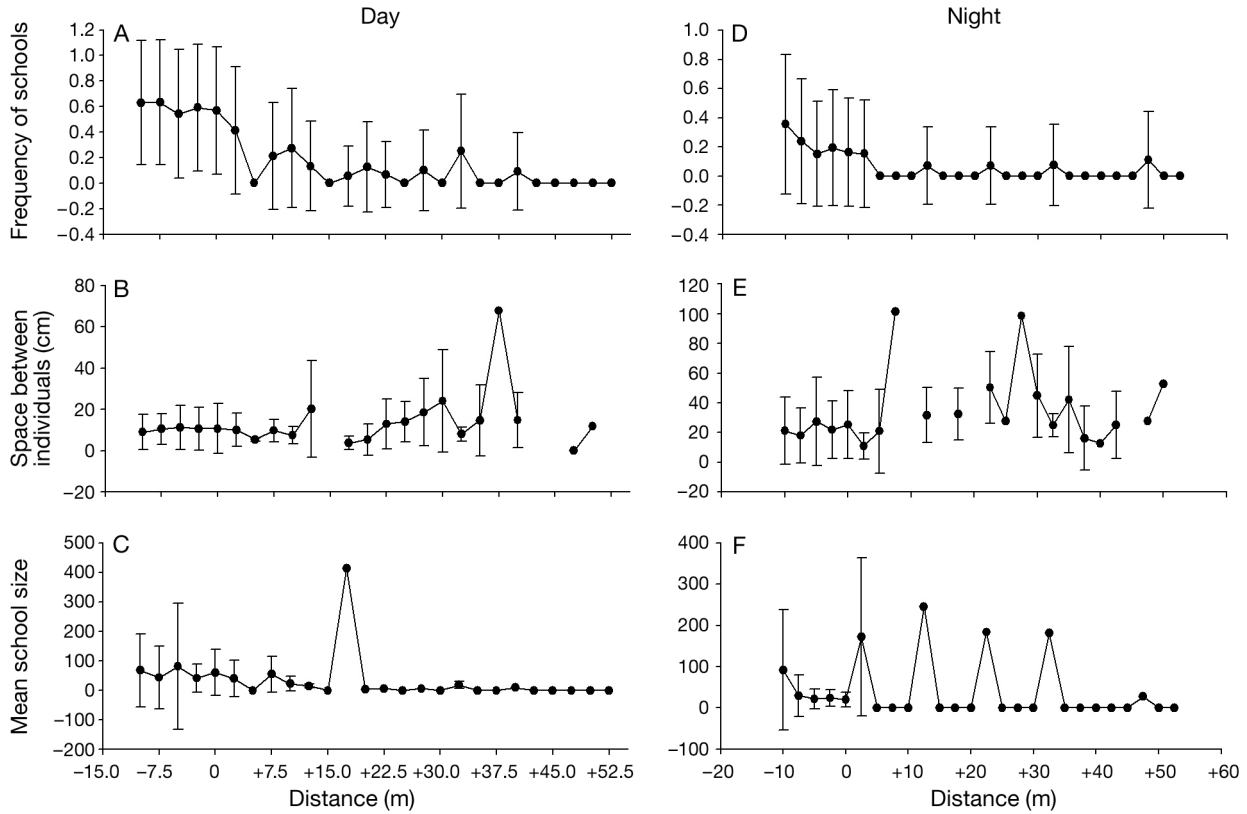


Fig. 5. (A–C) Daytime and (D–F) nighttime (A,D) frequency of encounter events of schools of small pelagic fish, (B,E) spacing between individuals in a school, and (C,F) school size relative to the distance under and away from the pier. Distance code as in Fig. 2

edge-under pier continuum (within transect) on the abundance of small schooling fish for all transects, with more of these fish outside of the pier (Table 4A). There was no significant difference in the overall abundance of small schooling pelagic fish with pier

side or with day or night. There was a significantly greater (Tukey’s test, error mean square = 0.180, critical value of studentized range = 3.317 with 1755 df) abundance of small schooling pelagic fishes at ebb tide than at flood (difference between means = 0.053), between ebb and slack low tide (0.150), and between abundance at flood and slack tide (0.097). Distance did interact significantly with diurnal stage (peak abundance shifted away from pier at night) and also with side (which was not significant by itself), and there was a significant interaction between side and diurnal period and between tide and diurnal period (Table 4). No 3-way or 4-way interactions were significant.

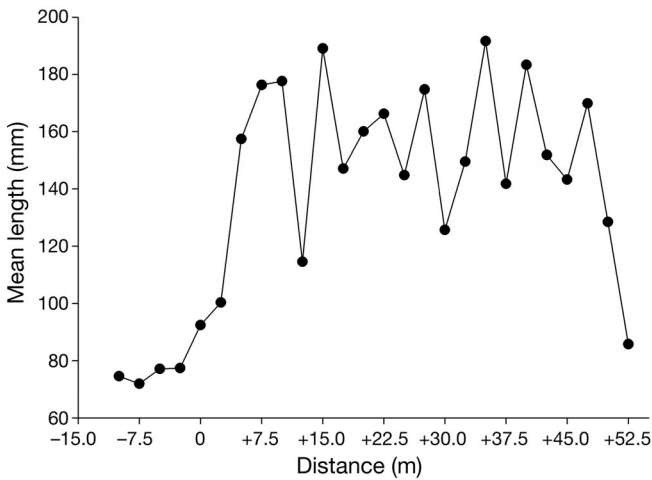


Fig. 6. Lengths of all fish (n = 20 330) relative to the distance under and away from the pier with both 2009 and 2010 combined. Distance code as in Fig. 2

As with the number of encounter events, there was a highly significant effect of distance along the open water-pier edge-under pier continuum (within transect) on the number of events of small pelagic fish (Table 4B). Also, similarly to measure of abundance, there was no significant difference between small pelagic schooling fish occurrence with pier side or relative to day or night. There was a significantly (Tukey’s test, error mean square = 0.008) greater number of encounter events with small pelagic

Table 4. Significance testing for treatment effects on (A) abundance of small schooling pelagic fish, (B) frequency of encounter events for small pelagic fish, and (C) abundance of large pelagic fish, using 2250 observations. (Transect): effect is tested only within a transect, rather than across all transects because distances within transects are not treated as replicates of each other. $Pr > F$ = probability that $r > F$. Only factors for which tests indicate a significant effect are shown

Factor	df	MS	F	Pr > F
A Distance (Transect)	44	1.58	8.75	<0.01
Distance × Side (Transect)	1	0.61	3.40	0.07
Distance × Diurnal (Transect)	44	0.32	1.76	0.00
Side × Diurnal	44	0.36	1.98	0.00
Tide	1	1.03	5.71	0.02
Diurnal × Tide	2	2.48	13.77	<0.01
B Distance (Transect)	44	0.08	9.26	<0.01
Distance × Side (Transect)	44	0.01	1.44	0.03
Distance × Diurnal (Transect)	44	0.01	1.49	0.02
Side × Diurnal	1	0.04	5.06	0.02
Tide	2	0.11	13.19	<0.01
Diurnal × Tide	2	0.08	9.05	0.00
C Distance (Transect)	44	0.00	1.48	0.02
Diurnal	1	0.02	9.32	0.00
Tide	2	0.01	3.34	0.04
Diurnal × Tide	2	0.01	5.15	0.01

schooling fish at ebb tide than at slack tide (difference between means = 0.033), and also more so at flood than at slack tide stage (=0.026), but no difference in the number of small pelagic schooling fish events between ebb and flood tide (<0.006). Tide interacted significantly with diurnal period. There was a significant interaction between pier side and transect distance under the pier, even though there was no significant effect of side alone. Pier side also interacted significantly with distance along the transect, and the diurnal stage interacted significantly with side. No 3-way or 4-way interactions were significant. These were the same factors and interactions found to be significant for abundance.

Large pelagic fish abundance

The effect of location along the open water-pier edge-under pier continuum, nested within transect, was significant for large pelagic fish (Table 4C). The mean values were highest 5 m under the pier but declined with further distance under the pier. There was no significant difference in the abundance of large pelagic fish with pier side but there was significantly higher abundance at night than during the day. Also, the abundance of large pelagic fishes was

significantly (Tukey's test, error mean square = 0.002) higher at flood tide than at slack low tide (difference between means = 0.009), but there was no difference between other tide stages (0.002 and 0.007 for flood vs. ebb tides and ebb vs. slack low tides, respectively). GLM also identified a significant interaction between the diurnal effect and tide, but not between these effects and distance (Table 4C).

DISCUSSION

Environmental conditions

The values for a variety of environmental measures, e.g. temperature, salinity, and dissolved oxygen, during this study appear to be representative for the area based on prior research (Stoecker et al. 1992, Able & Duffy-Anderson 2006); thus, we would expect the fish response to be representative of summer and early fall conditions in the Hudson River near Manhattan. The light levels observed were also similar to the general values determined in prior studies in open water away from piers, at the pier edge, and under the pier (Able & Duffy-Anderson 2006). The current study provided more detail regarding the light regime than previously available and demonstrated that it differed with depth and relative to the different sides of Pier 40. This detail allowed for statistical separation of shade effects from structural effects, i.e. there was strong significant effect of distance under the pier, and a significant difference in the way fish responded relative to the shaded and unshaded sides of the pier. However, the response did not vary significantly relative to tide as it would if the response mechanism was related to a structural (baffling) effect from tidal currents. Further, our study provides for insight into scale of effects to be expected relative to size of other piers. Pier 40 is the largest (~89 500 m²) pier on the Manhattan waterfront; by starting with the largest pier, we captured the entire available gradient. This informs future interpretation of scaling studies on different, smaller, or narrower piers.

Responses of fishes to piers

Our findings clearly indicate, for the first time, that many pelagic fish species avoid using the under-pier areas at Pier 40 relative to adjacent open water areas. This is supported by several different metrics including pelagic fish occurrence, abundance, and size.

Further, aspects of the behavior of schooling and aggregating fishes, the most abundant types represented, are evident in differences in organization of schools and spacing of individuals in schools with these factors changing along the open water-pier edge-under the pier continuum. All of these changes appear to be tightly correlated with underwater light levels, which decrease markedly at the pier edge during the day. These kinds of pier edge effects have been previously reported for benthic fishes at this pier and others along the Manhattan waterfront including effects on occurrence, abundance, diet, and growth (see Able & Duffy-Anderson 2005, 2006). In these prior studies, the response in terms of fish species composition, abundance, and growth was most evident at the pier edge (Duffy-Anderson & Able 1999, 2001, Duffy-Anderson et al. 2003). We assume that almost all of these negative responses to piers are due to the important role that vision plays in the ecology and behavior of fishes even in highly turbid estuaries. An additional observation that helps to understand the fish response to piers is the difference in the average size of fish across the pier edge. The under pier area and especially the edge was typically dominated by larger fishes; most of these appear to be *Morone saxatilis*. These piscivorous predators (Juanes et al. 1994, Tupper & Able 2000, Nemerson & Able 2003) may use the shade from the pier as a way to hide from and eventually attack prey (Helfman 1981) that are very abundant at and near the pier edge. Another alternative is that *M. saxatilis* may prefer pier edge shade because it provides a more advantageous part of the light spectrum (Horodysky et al. 2010).

The observations with DIDSON at night in these habitats provide further insights into the fish response to piers. Most fishes, and especially small pelagic fishes, were most abundant in open water and at the pier edge during the day where ambient light levels were higher. At night, when there was little light even in open water, the fish still avoided the even darker under pier areas. These greater values of fish abundance in open water, even more at night than during the day, might be explained by the positive response of fishes to the urban light sources at the pier edge. This positive response to light at night has been detected for some of the same fishes in a New Jersey estuary in summer and fall (Hagan & Able 2008).

While light is likely an important cue that is responsible for many fishes avoiding under pier areas, it is clearly not the only pier effect as indicated by some significant GLM interaction terms. Some of

these may be artifacts of the pier's occurrence in shallow water, and have little to do with the pier itself. For example, schooling pelagic fishes were more abundant during ebb tide than flood or low slack because they may have moved out of strong central river currents into shallower, slower moving water during ebb tide as part of a strategy to avoid advection from the estuary. A similar strategy of vertical migration by larval *Anchoa mitchilli* (selective tidal stream transport) has been previously demonstrated in this river (Schultz et al. 2000). This vertical movement into surface waters may allow fish access to the shallower shoreline waters where the pier was located. Likewise, the greater abundance of large pelagic fishes such as *Pomatomus saltatrix* and *Morone saxatilis* at night and at high tide may simply be due to a diurnal movement of these fish from the deeper central river contours towards the shoreline, as demonstrated by telemetry in another estuarine system (Ng et al. 2007).

Our findings indicate that the pattern of distribution relative to pier edge was different for large than it was for small pelagic fishes. Large pelagic fish were, on the whole, only slightly more abundant in open water and were common under the pier just inside of the edge, and the patterns varied with transect and with day versus night. At Transect R (both North and South), large pelagic fishes could be found a considerable distance from the edge under the pier based on measures from the northern and southern edges. This transect was always near the western edge and thus some light penetrated several meters under the pier.

Very little is known yet about spectral sensitivity for estuarine fishes, with the Horodysky et al. (2010) treatment of 4 piscivorous species being the notable exception. A fish may be in a well-illuminated place relative to total photon flux, but see only dark because the spectrum is not in a range it can sense. The wavelength shift under the pier, first as reflected light from the pier underside, and then absorption in the water relative to light outside of the pier perimeter, is unknown. This is confounded by findings that nighttime vision is more sensitive for *Pomatomus saltatrix* and *Morone saxatilis* than is daytime vision (Horodysky et al. 2010) because of a spectral shift in nighttime illumination that may or may not be altered in nature by the shading of the pier. If pier shading simply mimics nighttime, then *M. saxatilis* and *P. saltatrix* may be more sensitive to light under the pier than when they are outside of it; in other words, compensation occurs. This may help explain the weaker or even positive modal response of large pelagic

fish to shading relative to benthic fishes. Further, the maximum in occurrence of *M. saxatilis* several meters underneath the pier may represent an optimum light level for ambush predation. At further distances under the pier it is clearly too dark to see all of the time at all depths.

IMPLICATIONS

The New York City waterfront is not a natural environment and is likely to remain a human-dominated landscape that provides for many other resources, such as commercial and recreational access and property protection. However, our findings allow for natural processes to be considered in planning for the development of these resources in a way that is not mutually exclusive. Further, the fishes detected with DIDSON, and verified with groundtruthing, appear to be those species and sizes typical of estuaries, including their seasonal patterns (see Able & Fahay 2010). Among them are many ecologically (e.g. *Anchoa mitchilli*, Schultz et al. 2003, 2005; *Menidia menidia*) and economically (e.g. *Morone saxatilis*, *Brevoortia tyrannus*) important species (Hagan & Able 2008). Thus, our findings should be considered representative of many northeast US estuaries.

Clearly, fishes continue to utilize this highly modified environment and some species may utilize piers as substitute for natural habitat features that are now missing, such as marshes, undercut shorelines, tree falls and rafts, or rocky outcrops. An understanding of the role of light and shading as separated from structural effects provides a way to mitigate these effects while still allowing important human functions. For example, piers can be built to allow more light penetration or be artificially counter-lit during the daytime. In addition, the shape of the illuminance curves from our light logger measures under the pier relative to known light sensitivity in some estuarine fishes (Horodysky et al. 2010) shows that relatively little additional light is needed to greatly increase the duration over which illuminance crosses this threshold, at least in shallow water. In addition, the ratio of edge to under-pier area can be changed with smaller, narrower piers. In fact, scaling the effects of shading remains an important course of further study. This study began with the largest pier on the New York City side of the lower Hudson River Estuary, with the understanding that an effect would be most easily discovered and quantified in such an extreme case. Now it remains to determine if the effects of shading have a linear relationship with scale.

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LITERATURE CITED

- Able KW, Duffy-Anderson JT (2005) A synthesis of impacts of piers on juvenile fishes and selected invertebrates in the lower Hudson River. Rutgers University, Institute of Marine and Coastal Sciences Tech Rep #2005-13, New Brunswick, NJ
- Able KW, Duffy-Anderson JT (2006) Impacts of piers in the lower Hudson River. In: Levinton JS, Waldman JR (eds) The Hudson River estuary. Cambridge University Press, New York, NY, p 428–440
- Able KW, Fahay MP (1998) The first year in the life of estuarine fishes in the Middle Atlantic Bight. Rutgers University Press, New Brunswick, NJ
- Able KW, Fahay MP (2010) Ecology of estuarine fishes: temperate waters of the western North Atlantic. Johns Hopkins University Press, Baltimore, MD
- Able KW, Manderson JP, Studholme AL (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):731–744
- Able KW, Manderson JP, Studholme AL (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
- Appenzeller AR, Leggett WC (1995) An evaluation of light-mediated vertical migration of fish based on hydro-acoustic analysis for the diel vertical movements of rainbow smelt (*Osmerus mordax*). *Can J Fish Aquat Sci* 52: 504–511
- Baker R, Minello TJ (2011) Trade-offs between gear selectivity and logistics when sampling nekton from shallow open water habitats: a gear comparison study. *Gulf Caribb Res* 23:37–48
- Benfield MC, Minello TJ (1996) Relative effects of turbidity and light intensity on reactive distance and feeding of an estuarine fish. *Environ Biol Fishes* 46:211–216
- Cook CL, Coughlin DJ (2010) Rainbow trout *Oncorhynchus mykiss* consume less energy when swimming near obstructions. *J Fish Biol* 77:1716–1723
- De Robertis A, Ryer CH, Veloza A, Brodeur RD (2003) Differential effects of turbidity on prey consumption of piscivorous and planktivorous fish. *Can J Fish Aquat Sci* 60: 1517–1526
- Duffy-Anderson JT, Able KW (1999) Effects of municipal piers on the growth of juvenile fish in the Hudson River estuary: a study across a pier edge. *Mar Biol* 133:409–418
- Duffy-Anderson JT, Able KW (2001) An assessment of the feeding success of young-of-the-year winter flounder

- (*Pseudopleuronectes americanus*) near a municipal pier in the Hudson River estuary, USA. *Estuaries* 24:430–440
- Duffy-Anderson JT, Manderson JP, Able KW (2003) A characterization of juvenile fish assemblages around man-made structure in the New York-New Jersey Harbor estuary, USA. *Bull Mar Sci* 72:877–889
- Hagan SM, Able KW (2008) Diel variation in the pelagic fish assemblage in a temperate estuary. *Estuar Coast* 31: 33–42
- Helfman GS (1981) The advantage to fishes of hovering in the shade. *Copeia* 1981:392–400
- Helfman GS (1986) Fish behavior by day, night and twilight. In: Pitcher TJ (ed) *The behavior of teleost fishes*. Johns Hopkins University Press, Baltimore, MD
- Horodysky AZ, Brill RW, Warrant EJ, Musick JA, Latour RJ (2010) Comparative visual function in four piscivorous fishes inhabiting Chesapeake Bay. *J Exp Biol* 213: 1751–1761
- Juanes F, Buckel JA, Conover DO (1994) Accelerating the onset of piscivory: intersection of predator and prey phenologies. *J Fish Biol* 45(Suppl A):41–54
- Lehtiniemi M, Engstrom-Ost J, Viitasalo M (2005) Turbidity decreases anti-predator behaviour in pike larvae, *Esox lucius*. *Environ Biol Fishes* 73:1–8
- Metzger CV, Duffy-Anderson JT, Able KW (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* 46:5–10
- Minello TJ, Able KW, Weinstein MP, Hays CG (2003) Salt marshes as nurseries for nekton: testing hypotheses on density, growth, and survival through meta-analysis. *Mar Ecol Prog Ser* 246:39–59
- Moenting AE, Morris DW (2006) Disturbance and habitat use: Is edge more important than area? *Oikos* 115:23–32
- Nemerson DM, Able KW (2003) Spatial and temporal patterns in the distribution and feeding habits of *Morone saxatilis* in marsh creeks of Delaware Bay, USA. *Fish Manag Ecol* 10:337–348
- Ng C, Able KW, Grothues TM (2007) Habitat use, site fidelity, and movement of adult striped bass in a southern New Jersey estuary based on acoustic telemetry. *Trans Am Fish Soc* 136:1344–1355
- Nightingale B, Longcore T, Simenstad CA (2006) Artificial night lighting and fishes. In: Rich C, Longcore T (eds) *Ecological Consequences of Artificial Night Lighting*. Island Press, Washington, DC, p 257–276
- Rountree RA, Able KW (1993) Diel variation in decapod crustaceans and fish assemblages in New Jersey polyhaline marsh creeks. *Estuar Coast Shelf Sci* 37: 181–201
- Schultz ET, Cowen RK, Lwiza KMM, Gospodarek AM (2000) Explaining advection: Do larval bay anchovy (*Anchoa mitchilli*) show selective tidal-stream transport? *ICES J Mar Sci* 57:360–371
- Schultz ET, Lwiza KMM, Fencil MC, Martin JM (2003) Mechanisms promoting upriver transport of larvae of two fishes in the Hudson River Estuary (USA). *Mar Ecol Prog Ser* 251:263–277
- Schultz ET, Young J, Martin JM, Lwiza KMM (2005) Tracking cohorts: analysis of migration in the early life stages of estuarine fish. *Estuaries* 26:394–405
- Sogard SM, Able KW (1994) Diel variation in immigration of fishes and decapods crustaceans to artificial seagrass habitat. *Estuaries* 17:622–630
- Stoecker RR, Collura J, Fallon PJ Jr (1992) Aquatic studies at the Hudson River Center Site. In: Smith CL (ed) *Estuarine Research in the 1980s*. Hudson River Environ Soc 7th Symp Hudson River Ecol. State University of New York Press, Albany, NY
- Stross RG, Sokol RC (1989) Runoff and flocculation modify underwater light environment of the Hudson River Estuary. *Estuar Coast Shelf Sci* 29:305–316
- Tupper M, Able KW (2000) Movements and food habits of striped bass (*Morone saxatilis*) in Delaware Bay (USA) salt marshes: comparison of a restored and a reference marsh. *Mar Biol* 137:1049–1058
- Vogel JL, Beauchamp DA (1999) Effects of light, prey size, and turbidity on reaction distances of lake trout (*Salvelinus namaycush*) to salmonid prey. *Can J Fish Aquat Sci* 56:1293–1297

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