Association of Adult Fishes with Piers in the Lower Hudson River:

Hydroacoustic Surveys for an Undersampled Resource

Final Report to the Hudson River Foundation

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Executive Summary

The effect of pier structures on habitat quality for fishes in the Hudson River has received some attention, but requires further study to determine their use, benefits and impacts. Prior efforts to address these issues have focused on small benthic fishes but study of larger pelagic fishes has been impaired by the complexity of habitats and the difficulty of sampling under and around piers. The development of new acoustic imaging technology (Dual Frequency Identification Sonar, DIDSON) has made dark and turbid environments available to interpretation with acoustic videos. Subsequent census sampling occurred in the Hudson River under and around several piers along the Manhattan shoreline annually during 2007 - 2009. Both schooling and non- schooling fishes (5 - 90 cm in length) were found across all habitat types during every sampling period, but were slightly more abundant along piers edges during the day. Large fish (e.g. striped bass, bluefish, American eel) were most often oriented to structure alone or in loose aggregations of a few individuals, but schools occurred in open water away from structure, which could be reflective of a difference in the way different habitats are utilized. Smaller fish co-occurred in about 50% of those samples with large fish.

In summary:

- DIDSON technology proved useful in quantifying fish distribution in previously unsampled complex and dark environments without adding light (for video) as a bias.
- Small schooling fishes (< 25 cm, e.g. Atlantic silversides, bay anchovy, alewife) outnumbered large fishes by more than 13 fold (9600 vs 692) in abundance and occurred mostly at pier edges during all sampling periods.
- Large fish were uncommon, with 87 occurrences (mostly single individuals) distributed in 58 transects out of 239.
- Large fish were slightly more abundant in open water near piers or habitat adjacent to piers, at pier edges, and also under piers.
- When large fish occurred under piers, it was most often at night and at dawn and dusk.
- Overall, the response of pelagic fish to pier habitats is more complex than that of benthic fishes because:
    - they are more mobile and thus their habitat use is more dynamic
    - some species may use pier edges as a surrogate shoreline (edge)
- Further studies that provide a species specific and mechanistic interpretation of dynamic habitat use could improve our understanding of how fishes use urban shorelines and help to mitigate for shoreline modifications.

Introduction

The importance of temperate estuaries has been described for juvenile fishes (Able and Fahay 1998, Elliott and Hemingway 2002, Able 2005, Secor and Rooker 2005), but less so for adults, which are less abundant and harder to sample (Able and Fahay 2010). In fact, early works attributed the importance of estuaries as nursery grounds to a low abundance of large predatory fish (Boesch and Turner 1984), an idea that is now being challenged (Sheaves, 2001, Sheaves et al. 2006, Baker and Sheaves 2006, 2007). The Lower Hudson River is one such estuary. The value of this estuary to the persistence of healthy populations for several important fish species has been well documented (Waldman et al. 1990, Waldman 2006, Waldman et al. 2006a). As an example, the Hudson River estuary is important habitat for sub-adult (age 0-2+) striped bass (*Morone saxatilis*). Many of these juveniles remain in the lower estuary at least through their first winter (Hurst and Conover 1998) and beyond (Dunning et al. 2006). Also, it is used extensively by the adults that spawn upriver during spring runs of fish returning there from other overwinter habitats (Richards and Rago 1999, Waldman et al. 2006b). While there is pronounced seasonal abundance of adult striped bass passing through the lower river estuary, it is also apparent that many adults remain in the estuary even after spawning (Secor et al. 2001, Dunning et al. 2006).

Further, many other fish species (e.g. bluefish *Pomatomus saltatrix*, Atlantic sturgeon *Acipenser oxyrhincus*, weakfish *Cynoscion regalis*, tautog *Tautoga onitis*, and river herring, *Alosa spp*.) visit the estuary seasonally as adults as evidenced both from surveys (Waldman et al. 2006b) and by the recreational fishing opportunities in this region (Euston et al. 2006). However the Hudson River, and especially its estuary, have been greatly altered through urbanization, but are recovering (Brosnan and O'Shea 1996, Hudson River Foundation 2004, Daniels et al. 2005, Levinton and Waldman 2006). Currently no natural, shallow-water habitat remains. Concrete bulkheads dominate on both sides of the Lower Hudson River and make the transition from the street to the water level abrupt; depths at the water line average 3-5 m. In addition, much of the harbor bottom is dredged so there is a marked vertical drop off toward the channel (from 3 m to 16 m). The lower Hudson River Estuary is tidally flushed so that, like other estuaries with extensive freshwater input, the zone undergoes dramatic changes in salinity over a single tidal cycle, as much as 7-21 ppt (Duffy-Anderson, personal observation), though average ranges over one tidal cycle are approximately 5-10% (Able and Duffy-Anderson, 2006).

One of the most dramatic alterations of the shoreline is through the construction of piers and the resulting remnants of piers that dominate the shoreline, extending 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 2005). Our own research, and that of others in the Hudson River, has used a multifaceted approach to evaluate the impacts of these alterations. These include: 1) the distribution and abundance of fishes under piers, at pier edges, in pile fields, and in open water areas (Stoecker et al. 1992, Able et al. 1997, 1998, 1999, Duffy-Anderson et al. 2003, Able and 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 and Able 1999). Our studies show that, 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 fish that would enter small traps, and growth studies were limited to selected species and early life stages within small cages (Duffy-Anderson and Able 1999, Able and Duffy-Anderson 2006). These studies were valuable in pointing to shading by piers, not benthic invertebrate prey scarcity, as a critical factor impacting habitat value and use by small benthic (bottom) fish.

Large mobile pelagic (water column) fish such as adult striped bass, bluefish, weakfish, and river herring that are typical in estuaries were not included in these prior studies. A negative response to pier shading could conceivably be the case for large fish, especially visual predators. Alternately, shade could be used to the advantage of large predators that ambush prey by hiding in shadows (Helfman 1981). Further, pier pilings may be the most abundant objects big enough for adult fish to use as current baffles and may thus provide an important function through bioenergetic conservation (Hurst and Conover 2001).

While the response of pelagic (water column) fish to environmental impacts is of great interest due to the inclusion of a number of large economically and ecologically important species, this group of fishes presents some serious challenges to further study. These challenges include: 1) their relative scarcity in comparison to smaller fish, especially in estuarine systems, 2) their great mobility, which allows them to continually react to environmental stimuli and also to use, visit, or pass through unfavorable habitat, or to utilize disparate habitats for different services rather than staying in an environment that offers the best average returns, 3) many are social or schooling, which clumps their distribution, 4) they cannot be caged as a means of controlling or fixing variables that are not of interest in focused *in situ* studies. Addressing these challenges requires a stepwise effort beginning with survey of the environment and a census to quantify distribution along the numerous gradients and factors, as described below, to provide an estimate of sample size, locations, and statistical techniques needed to address the role of specific habitats, such as piers. In addition, quantitative definition of habitat for fishes is difficult because of their rare distribution relative to available habitat (Able 1999). Parameters that define a habitat can be very complex, including both dynamic (e.g. hydrographic) and static (e.g. substrate) factors, which may interact. Aside from the attraction to a habitat for the service that it provides, a particular habitat may be chosen over unoccupied but appropriate habitat simply as a function of social entrainment for schooling fishes.

The goal of this two-year study was to quantitatively explore the association of adult or large sub-adult fish (> 25 cm) with piers and related structures in the Lower Hudson River in order to determine the use, benefits, or impacts of these structures. In this effort, we focused primarily on rapid but wide spatial coverage in order to: 1) quantify seasonality of adult and large sub-adult fish distribution and abundance in under-pier, pile fields, and adjacent open water habitat; 2) assess the diurnal cycle of pier related habitat use by these fishes; 3) describe the orientation of fishes relative to pier support structure and flow.

Approach

Study Area

The study was carried out primarily along sections of the eastern shore of the Lower Hudson River along Manhattan, New York (Fig. 1). Surveyed habitat included overwater piers and uncovered pile fields from relict or collapsed piers interspersed with open water areas stretching from Pier 40 to Pier I. Piers included those with large and small aspect ratios (length to width ratio) ranging from nearly 1 to about 0.125. Additionally, clustered pilings that act as bumpers (dolphins), but do not support overhead structure, were examined near Pier I, where no relict pile fields were available in sufficiently deep water for sampling; these were classified the same as pile fields here because they were uncovered but had substantial eddy fields behind them.

Sampling

Conventional sampling techniques are inappropriate for large fishes in the study area. Under-pier habitats cannot be sampled effectively with nets because sufficiently large trawls cannot be quickly towed under piers and because piles offer refuge. Snags also prevent the use of both towed and set (gill) nets especially in areas of flow or vessel wake. Larger fish easily avoid cast or pop nets that are suitable for smaller schooling fishes. Hook and line fishing can potentially identify the use of these habitats but is non-quantitative and biased to species and particular times of the day (when fish are feeding). Further, the expected statistical rare occurrence of large fishes in any habitat requires wide spatial and temporal sampling effort, which is rarely spatially discrete. Visual census (by divers or video, e.g. Bortone et al. 2000) is potentially rapid and discreet but is prevented by turbidity, shade, and safety issues.

We used dual frequency (1.8 MHz and 1.1 MHz) identification sonar (DIDSON) (Sound Metrics Corp., Seattle, WA) to image fishes under piers. At the applied ranges of 2-7 m and a 1.25 x 5 m (across by downrange) window, the resolution varied between 2.5 mm and 10 mm per pixel. Thus, 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 5-10 frames per second, dependent on range as this affected processing speed. Moderate frame rate helped to discern moving fishes from a moving (relative to viewer in moving kayak) background. Fish movement is diagnostic, helping to break fish outlines from their background. Dual beam ensonification mitigates many of the concerns of commercial-scale acoustic fish surveys that rely on sound reflection mainly from the swim bladder (Kalikhman and Yudanov 2006). Even individual fins, which generally have low reflectance but are valuable to identification, are discernible in DIDSON images (Brown et al. 2007). Existing DIDSON host software (version 5.14) supports several tools to help measure and count observed objects.

In this study, the DIDSON was mounted with a hinge under and behind the bow of a sit-on-top kayak for easy access for transects under and around the piers (Fig. 2). Tilt was set at 23 degrees for an optimum viewing range based on earlier trials. 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 navigation during nighttime sampling to minimize the potential effect on the fishes. A nearby motor skiff, outside of the immediate study area, provided logistical support and safety. The position of the kayak was noted using vocal annotation supported by the DIDSON host software to link it with the video because GPS does not function under piers. Painted numbers on the pilings provided landmarks. In addition to the voice annotation, kayak transects were drawn on a map by observers in the skiff to show where the kayaker paddled. Time stamps from the DIDSON recordings were correlated to navigation recordings to map the position of fish. These are similar methods to those used to video-record fish on submersible dive surveys (Sullivan et al. 2000, 2003).

Calibration

In an attempt to determine the congruence between observations made with the DIDSON and more traditional sampling devices, we compared several sampling gears designed to capture both large and small fishes before we began the regular sampling program (Table 1). This groundtruthing approach included a popnet (Hagan and Able 2003), experimental traps (see Able et al. 1998), cast nets (Johnston and Sheaves 2008), wire mesh traps (Able and Hales 1997), and gill nets during the day and night and, to a lesser degree, visual observations from the surface and while snorkeling. Several of these gears were designed to capture fishes in the water column (popnet, cast net, gill net) while others were designed to capture benthic fishes (experimental traps). Sampling at night included the use of lights to attract and retain fishes in a manner similar to that previously used (Hagan and Able 2008). All of those fishes captured with groundtruth sampling gears were identified and measured.

Calibration between DIDSON images and observer identifications occurred at the Rutgers University Marine Field Station (RUMFS) boat basin in southern New Jersey, which contains three small pile-supported piers (Table 1). This sampling,which was able to target individual schools for DIDSON imaging and net capture simultaneously, was analyzed independently from the Hudson River pier sampling data set using principle components analysis to train observers in interpretation of DIDSON images. The fish fauna is typical of the adjacent Great Bay estuary and has been the focus of numerous sampling approaches (Able et al, 1998, Able and Fahay 1998, Able et al, 2005). Other calibration occurred in the Hudson River study area. Features of the target in both locations (position in water column, length at depth, reflection strength, spacing, school dimensions, etc.) provide probability scoring of sonogram features to some fish species.

Sample Design and Statistical Analysis

The study design was based on categorization of primarily five habitat types: 1) underpier area located beneath a pile-supported platform; 2) pile field consisting of an array of wooden pier supports where the deck or platform had been removed (Able et al. 1998); 3) pier edge allowing for both light and shade with some pilings; 4) bulkhead creating a barrier wall between the land and water; 5) open water habitat with no intentional anthropogenic structural component (essentially soft bottom although scattered low profile debris was common throughout). In some instances, these habitat types are treated together because DIDSON transects crossed habitat boundaries.

Sampling for distribution relative to piers occurred in 2007, 2008, and 2009. In 2007, each monthly sampling event consisted of three 8-hr sample cycles. In 2008, we sampled for 5-8 hour cycles throughout the study area. A single three-day sample rotation in 2009 followed a similar design as in 2008. We attempted to visit each habitat type several times throughout a sample cycle to assess shifts in habitat use with tide, diurnal period, and fish behavior. One sample was a five minute transect separated from other transects by at least one transect length. In practice, sampling was less stratified owing to restrictions of legal and security concerns by several agencies, an inability to sample some piers during high tide levels because of insufficient overhead space for even the kayak, leaking acoustic lenses that required repair, and closing of previously sampled sites by onset of construction and barge positioning. DIDSON sampling was accompanied by physical-chemical sampling (temperature, salinity, dissolved oxygen, secchi disk, tidal stage) at every major pier using a YSI 80 (Yellow Springs Instruments, Yellow Springs, OH).

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 the reviewer. Playback controls included frame advance rate and direction, magnification (zoom), and graphic user interface tools for super-position of a grid to aid counts and point-drag paths to measure fish lengths. Files were viewed and scored by at least two independent reviewers. Reviewers recorded each event of a fish presence (either school or individual fish). Abundances were either counted manually or by taking an estimate using the average of three grid squares (using the superimposed grid) 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. Both fish depth and bottom depth were calculated using a formula [cos((radians(90-sonar tilt))*hypotenuse] based on the sonar tilt and hypotenuse (target distance). If the event was a school, then the reviewers also measured the distance between individuals in the school. Reviewers also categorized school organization on a ranked basis of 1-4 from highly organized (Rank 1 = parallel swimming, reaction to nearest neighbor) to random milling (Rank 4) as a potential metric for classification. The reviewer used the matched audio file and drawn notes, as well as underwater landmarks visible in the sonogram to reference the position of the fish or fishes relative to pier structure. The reviewer also scored the amount of debris found on the bottom using a range from 1-4 (least to most) as well as qualitatively categorizing small and large debris as a measure of structure.

The distribution of fishes was examined relative to variables of year, month, tide (ebb, slack low, flood, slack high), solar phase (day, night, crepuscular [inclusive of 1 hr before and after sunset]), habitat (pier edge, open water, pile field, under pier, and bulkhead and various combinations of some of these) and debris (ranked quantity of small debris, ranked quantity of large debris), and pier number. Pier number was used to rank upriver distance, e.g. the open water adjacent to Pier 40 was also categorized as Pier 40, as were the adjacent pile fields. Each variable was scored as present/absent (1/0) for each transect and used to construct a similarity matrix on the Euclidean distance matrix. Similarities were then displayed as a non-metric multidimensional scaling (nMDS) ordination using Primer 5 software (Plymouth, UK). All transects, including those without fish present, were thus scaled, and the presence of fish did not enter into the ordination calculation as a variable. After ordination, resulting plot points were coded by symbol relative to fish presence (number of "events", whether school or individual fish) and total number of fish to examine latent trends in distribution relative to any temporal/spatial trends. Any such trends are assumed to contain spatial autocorrelation, and numerous factors, such as piling type or orientation and debris type and quantity, are unique to different piers and invariant over time within a pier area, and so variation cannot be readily partitioned among component variables. However, habitat types (see above list) were common to different piers and over time, and the number of fish events in a transect was related to habitat type, season, and day/night/crepuscular period using a one-way non-parametric Mantel family ranked regression (Spearmans' Rank method, procedure RELATE, also Primer 5). In general, the statistical approach was constrained to be one of explorative quantification (survey) using multivariate ordinations and correlations rather than hypothesis testing.

The majority of works analyzing fish response to habitat factors, regardless of sampling technique, utilize statistical tools that test hypothetical associations in fish abundance (i.e. response) with one or two variables at a time. They provide a dichotomy for accepting or rejecting a null hypothesis that fish do not respond to a tested factor. They are carefully constrained to mitigate Type I error, the rejection of a true null hypothesis (Underwood 1993, Sokal & Rohlf 1994). Type I error is seen as potentially more damaging to the advancement of understanding than Type II error, the acceptance of no response when there actually is one. Use of a Bonferroni correction to numerous tests of single variables greatly enhances the probability of Type II error even to the elimination of ever finding significance when examining responses to multiple factors. This may bias researchers towards reporting of fewer variables than originally examined in order to avoid depressing acceptable α level (Yoccoz 1991, Nakagawa 2004). This weakens the important observational phase of the scientific process.

As precursors to focused hypothesis testing, survey studies that consider multiple variables help define the scales on which such experiments should be conducted to be informative and confident (Wiens 1989). Gradients in fish distribution are sought among multiple variables simultaneously (using ordination techniques) and the strength of these compared to examine which factors have the potential to confound focused testing of a particular factor of interests. Multivariate ordinations describe relationships without constraining scientists to acceptance or rejection of hypotheses, and appropriately have a different function in the scientific process and literature (Sokal & Rohlf 1994, Gray et al. 1990, Clarke et al. 2006). These techniques are particularly useful for exploration and communication of complex patterns, as in this study.

Results

Calibration

DIDSON images during initial groundtruthing in the RUMFS boat basin provided accurate and clear imagery of the structural components of the pier habitats and the associated fishes (Table 2). This resulted in 176 DIDSON transects during the day and 27 at night. Each transect record ranged from 30 sec to 5 min in duration. During these deployments, as examples, pier pilings and remnants of crab pots were clearly visible (Fig. 3). Fishes, both in the water column and on the bottom were also easily detected and the length determined with DIDSON software (Fig. 4). However, as in other studies with DIDSON, identification of small fish species is difficult (Boswell et al. 2008). Identification of fishes detected with the DIDSON during groundtruthing was aided by sampling with a variety of gears including pop nets, cast nets, gill nets for pelagic fishes and experimental traps for benthic fishes during the day and night (Table 2). In other instances we tethered fishes (black sea bass, tautog) to monofilament line and deployed them in front of the DIDSON sensor in order to record their image for later identification of free-living animals.

Of the 15 species collected across all groundtruthing gears, 5 fish species were also identified with the DIDSON, including Atlantic menhaden, black sea bass, Atlantic silverside, tautog and bluefish (Table 2). While visual details were less distinguishable for smaller fish, behaviors did add to the ability to identify species in some cases. Variation in character metrics of school organization, size distribution, and spacing in echograms of small fish schools that were compared to composition of individuals in net captures in groundtruth efforts at RUMFS aided these classifications (Fig. 5). Resolution by PCA was moderate, with the primary eigenaxis explaining 29% of the variation and the second eigenaxis explaining an additional 15% (Fig. 5). Atlantic menhaden were distinguishable from other fishes based on the deeper body to length morphometry and moderate school cohesiveness, but the small schools became scattered in the presence of bluefish. Bluefish by themselves were highly unorganized, with individuals appearing to move independently of other visible fishes. Atlantic silverside schools took on many different school forms based on the time of day or night, due to disturbance from predatory bluefish or cast netting activity as well as from unknown factors (Fig. 8). Mummichog were also discernable in RUMFS samples from species other than Atlantic silversides, but no mummichog were seen or captured in opportunistic groundtruth sampling in the Hudson River (Table 2). Several species collected in groundtruth sampling would not be expected to be detected with the DIDSON because they were too small (e.g. naked goby) or cryptic on the bottom or buried (e.g. winter flounder). In another instance an American eel was clearly visible (Fig. 7) but this species was not detected by any of the groundtruth sampling. Additionally, we identified a small shark during groundtruthing at RUMFS (likely smooth dogfish, *Mustelus canis*, based on the presence of a heterocercal caudal fin and the subcarangiform swimming motion).

Image Analysis and Reference Images

In the Hudson River, we completed 239 sample transects of 5 minute duration each specifically for this project. We sampled six different piers, Nos. 40, 54, 57, 59, 61, and I, (designated in graphs as “100”) along the Manhattan waterfront (Fig. 1, Table 3). Samples included the major pier microhabitats such as under pier (n=46 transects), pier edge (n=60), and adjacent open water (n=31) with the DIDSON (Table 4, 5). We also surveyed nearby relict pile fields (n = 25) in order to understand fish use patterns at these former piers which lacked the pier surface but retained large numbers of pilings. Transects often contained multiple habitat types and the fact that single fish schools could cross these boundaries, or that fish moved across them during the survey, precluded clean categorization of some transects. Thus, transects were categorized by all of the habitats that they sampled. Several transects were also completed of rip-rap and bulkhead habitat on the New Jersey side of the Hudson River when conditions prevented us from crossing to the study sites.

The DIDSON was useful in detecting and determining the size of both large and small fishes in these habitats (Fig. 4, 6). Identification of large schools of fish and individual fish relied on characteristics such as caudal fin shape, number of dorsal fins and shape of pectoral fins as well as swimming behavior. In many cases striped bass were readily identified in DIDSON echograms (Fig. 4c) by the presence of two separate dorsal fins, shallow forked tails, and thick bodies when seen in dorsal view. Large (~1 m in length) bluefish were in some cases distinguishable from striped bass based on profile. Identification was aided, in some instances, by the acoustic shadows cast by structural components of the piers (e.g. pilings, Fig. 7) and of the fishes (Fig. 6a, b). However, reviewers often were unable to confidently identify other individuals that may have been striped bass or similarly shaped bluefish or weakfish, largely because they were actively swimming, which changed their profile. While actively swimming, all three of these perciform fishes lower their first (spiny) dorsal fin, and fold their forked caudal fin to a narrower profile. Further, all of these commonly overlap in size range and co-occur temporally in estuaries. As a group, these three species would have been distinguishable from some other perciformes that may occur in the Hudson River estuary, based on shape or maximum size, or both (e.g. black drum), but fishes of such distinguishable forms were not seen. Several individuals were identified to a type that suggests either black sea bass or tautog on the basis of stiff body (pectoral sculling) swimming movements and contact with the bottom as seen during groundtruthing. These species and small cunner could also be cryptic to DIDSON if they did not move, again as noted during groundtruthing. However, these species do enter traps and represent a component of the fauna that has been studied by other means. Swimming eels (presumably American eel) are also readily identified (Fig. 7), as were horseshoe crabs when they were mobile (Fig. 7). No images were consistent with sharks, skates, or sturgeon.

Environmental characteristics of samples

Sampling included spring, summer, and fall periods. An expected tide-mediated salinity gradient along the study area between Pier 40 and Pier I was not strongly evident because sampling effort moved spatially along with tide (for reason of pier access), so as to alias salinity dynamics (tide phase lags in the upriver direction) (Fig. 9). While this had the effect of “controlling” salinity variation among piers during a sample rotation, it may hide a salinity gradient that fish respond to on a longer-than-daily time scale. Bottom salinity was generally about 2 units above surface salinity. Temperature fluctuated only moderately among stations within season (Fig. 9). Surface temperatures were similar to bottom temperatures. Dissolved oxygen generally remained above the 50% saturation but dropped to below 30 % near in bottom samples during June of 2009.

Species and Size Composition and Abundance

Relative to our specific objective, it appears that fish are abundant in the study area, based on DIDSON sampling, during all the periods sampled, i.e. late September and late October 2007 and June and October 2008, and June July and August 2009. Of 239 transects, 58 contained large (>250 mm) fish in 87 unique events totaling an estimated 692 individuals either alone or in schools. Thus, single transects had as many as 5 events (different occurrences of fishes as individuals or schools or both) as judged by a discontinuous occurrence in different frames or oriented to different structure within the transect. However, given the mobility of large fish, and the relatively narrow viewing area of the DIDSON, no judgment can be made about the independence of occurrences. In fact, the difference among reviewers in parsing and therefore counting the number of events was the greatest source of accountable experimental error. For example, one reviewer might count 3 individual fish as 2 events (singleton and a pair) while the other reviewer counted 3 and both reviewers arrived at the same total (3) fish count.

Fish smaller than 250 mm (average size when in schools) outnumbered large fish, both in frequency of occurrence (events) and in the average number of fish in an event; the cumulative being an order of magnitude greater (~9600 small fish and 692 large fish) (Fig. 10). Although even very small (5 cm in length) fish were frequently observed alone, they also occurred in schools estimated to contain many hundreds of individuals. Most large fish occurred as individuals with a few aggregations of striped bass containing as many as 21. However, a single large school consisting of an estimated 471 individuals accounted for 68% of the total large fish abundance. These were identified as Atlantic menhaden (Grothues, pers. observ.) based on visual observations from the surface (they were breaking water around the boat and were readily observable just below the surface). The numerical dominance of this single school thus also set the mode for the length frequency distribution with individuals between 30 and 45 cm TL (Fig. 11). Several large striped bass were above 700 mm; these sometimes co-occurred in aggregations with smaller striped bass.

Of a total 687 scored fish events (all fish sizes), 66 were scored as small, schooling fishes consistent with groundtruth analysis (here and for a complimentary study of smaller scale ongoing study funded by New York City Department of Parks and Recreation) indicating Atlantic silversides and bay anchovy, often in mixed schools. An additional 381 events were occurrences of small fish that were not readily characterized because they were not in a school, were of intermediate size, or exhibited behavior or orientation suggesting small benthic species (e.g. small tautog, black sea bass, cunner, oyster toadfish). A subset of these was analyzed further (see *Small fish distribution* section below), although the major study focus remains on larger fish. Of the 87 large fish events, 50 were single individuals, 12 events consisted of 2 individual fish, 11 of 3 individual fish, 2 of 4 individual fish, 3 of 6 individual fish, 8 between 9 and 21 individual fish, and 3 events with between 140 and 187 individuals each. These last three events, although scored separately by reviewers because of separation in the DIDSON file, appeared to be a dynamic school (occupying much of the open water between Pier 40 and the adjacent relict pile field) that split and merged again several times during our occupation of that station, as viewed from the surface. It is treated here as a single event. Unlike schooling small fish, which maintained a uniform pattern of orientation to each other throughout an observation period that could be used to help classify them quantitatively (e.g. by canonical variates analysis), most large fish encounters could not be scored on the basis of orientation to schoolmates because they were alone or because orientation was dynamic (e.g. milling).

Pier Habitat Use Patterns

Large fish occurred throughout the sampling period and across all habitats from Pier 40 to Pier I (Fig. 12A, B, C). Ordination by nMDS did not reveal any clusters. The occurrence of large fish in events occurred most often in transects that contained both pier edge and relict pile field habitats or open water and relict pile field habitats and less frequently under piers (Fig. 13). However, the correlation between habitat type of a transect and the number of events occurring in it was very weak as demonstrated by a Spearman's correlation coefficient $\rho=0.008$, (significance level $p= 0.314$). In contrast, small fish occurred mostly in transects containing both open water and edge habitat, but seldom under piers. By number (standardized effort), large fish were most abundant in open water habitat or transects with open water and pier edges, but seldom under piers (Fig. 14); this abundance in open water was an effect of the large number of Atlantic menhaden in a single event. In contrast, small fish were most abundant in transects of edge or edge and under pier. In a single instance, one large school of small fish stretched through Pier 57 from open water on the north side unbroken through to open water on the south side, a distance of more than 42 m.

The occurrence of large fish in all habitats was cumulatively highest in June of 2009 (0.59 events per transect average across all habitat), followed by June of 2008 (0.39 events per transect average across all habitat) and October of 2007 (0.37 events per transect average across all habitat) (Fig. 15). There was no strong shift across habitat types with season. Abundance of large fish per unit effort was highest in June 2009 owing to the occurrence then of the large Atlantic menhaden school in open water and lowest in August 2008, when no large fish were encountered (Fig. 16), although sample effort then was low.

Large fish were found during the day (n= 47 fish events), night (23 fish events), and during the crepuscular (designated here as one hr before and after sunset or sunrise) period (n= 17 fish events). However, large fish were twice as often encountered per unit effort during the night (cumulative = 4.99 fish per night transect), and secondarily during crepuscular periods (cumulative 3.14 fish crepuscular transect), as during the day (cumulative = 2.44 fish per day transect) (Fig. 17). Encounter rates were greater in darkness (night and crepuscular) for both open water and under pier habitats (which are comparable in relative sample effort), suggesting that large fish may often move into deeper water away from the pier during the day, thus avoiding both shallow pier and open habitats in our shallower study sites. During the day, large fish were most encountered (per-unit-effort) at similar rates in all habitats except more so in relict pile field/open water, but this category consisted of only 3 samples in one month. At night, large fish were slightly more likely to be encountered under piers, but were encountered in all habitats where nighttime sampling occurred. Abundance per unit effort was highest during the day in open water because the events there included large schooling Atlantic menhaden as opposed to the events under piers (Fig. 18).

Along the Manhattan waterfront, large fish were most often encountered near Pier 57 (Fig. 19). Here the encounter rate was similar during pier edge and open water transects (standardized to unit effort) and these were about 4 fold greater when compared to under pier or relict pile field habitat. Pier 57 is unique among sampled piers in that its support structure consists of wide, long concrete supports instead of individual pilings. At pier 61, large fish were most often encountered at pier edge habitat, although effort there was low and not evenly distributed by season or year. At this recently renovated pier, built over existing relict pilings, "fencing" prevented sampling by the kayak. The few encounters with large fish at Pier 76 were under the pier. Encounters at other habitats (inclusive of adjacent open water and relict pile fields) were below 0.5 per transect (less than one event for two transects) (Fig. 20). At Pier 40, the largest sampled pier, encounters were infrequent but most likely to occur at pier edge habitat or under the pier. The abundance (per unit effort) was highest there in open water owing to the previously mentioned school of Atlantic menhaden (Fig. 20).

Behavior and orientation

Behavior and orientation is difficult to categorize in this analysis because of its diversity and a lack of published metrics for use in diverse habitats, and because of dynamic re-orientation. In general, fishes were observed moving among (or through) locations, (e.g. eel swims across the field, entering and exiting the transect), stationary (e.g. black sea bass resting on the bottom or against a piling, sometimes vertically, or changing orientation but not location), milling, (in an aggregation, but not swimming with parallel orientation or unified in speed, and sometimes not swimming at all, this included occasional social interaction such as chasing), schooling (moving in unison with regular spacing, oriented to each other), and in events of ambush predation on small fish (n=2). Large striped bass were occasionally seen to move between pilings or edge but within a small area; thus, it was difficult to clearly associate occurrences with specific habitat features.

Small fish distribution

As facilitated by a NSF Research Experience for Undergraduates (REU) grant to Rutgers University, we performed further analysis of small fish from 42 transects at Pier 57, all from daytime sampling in September and October of 2007 and June of 2008 (Table 6). Principal components analysis (PCA) of characteristics measured from echograms revealed a weak gradient in small fish occurrence in different habitats (Fig. 21). More and larger schools tended to occur in pier edge habitat. Pier edge/under pier samples had smaller numbers of variably sized fish, although observational notes show a tendency for schools to disappear further under the pier. Relict pile field samples were similar to open water samples in encounter rate and total number of fish, but variation was greater at relict pile fields. Differences in fish depth may have been an artifact of differences in water depth among habitat types.

The standardized average number of small fish per minute at the pier edge was greater than in any other habitat (Table 7), and was significantly greater than in open water and pile fields (Bonferroni test, 95% confidence interval, Table 8). The occurrence of schools was greatest in open water (Table 7), but not significantly different between any of the habitats (Bonferroni test, 95% confidence interval, Table 8). Size of "small" fish was greatest in pile fields and smallest at pier edges (Table 7), but this was the only size difference that was significant (Bonferroni test, 95% confidence, Table 8). Size of schools was largest along pier edges (Table 7), and there was a significant difference between school size in this habitat and all other habitats (Bonferroni test, 95% confidence, Table 8). Small pelagic fish did not appear to avoid any particular habitat, of those sampled. The trend in fish size relative to habitat use was ambivalent, as the PCA only supported the Bonferroni test when analyzed on its second axis. In summary, there was a weak trend of increased small fish abundance and occurrence of schools at the edge of Pier 57. School size was significantly greater in edge samples than in other habitats at this pier during daylight.

Discussion

Sampling techniques and design

This study represents the first attempt to survey large fish underneath and around piers that dispenses with capture techniques of any kind. Aside from being invasive, capture techniques, whether hook and line, net, or trap, are inherently limited or biased in function by the pier structures themselves (see Stoecker et al. 1992, Able and Duffy-Anderson 2006). Visual survey, as approximated by DIDSON's sonar-to-image processing, is less limited in access but also may be biased against some types of fishes by behavioral traits that limit detection, such as swimming immediately under the surface, or associating closely with structure, or by patterns of movement. These same issues have been addressed for visual or video census (e.g Bortone et al. 2000). One major concern is the potential counting bias created by a tendency of different species to move or remain sedentary. Sedentary species (or those active but with orientation to a small kernel area) are best counted by transect designs while very active swimmers are best counted by fixed radius or point-count survey (as expressed in Petit et al. 1995 for forest birds). Preliminary observations tested two sample strategies, one of static fixed radius counts similar to those used for bird counts in forests (USDA Forest Service 1995), and a strategy of roving or transect occupation with pelagic fishes in mind. Both single fish and fish schools tended to occupy an area during sampling, although not exclusively, and the roving method was adopted in order to increase the chance of encountering fishes as based on reef fish surveys for sedentary and statistically uncommon species (see Petit et al. 1995, Bortone 2000).

The choice of sample technique is itself reflective of the finding that large fishes are uncommon in shallow water habitats under and among piers of the Hudson River Estuary. However, at the species aggregate level they can consistently be found in low abundance across many habitat types during both day and night, although more so at night. It is clear from the episodic nature of encounters in this study that fishes such as striped bass do actually utilize a number of different habitats along the urban waterfront, including under and along piers and relict pile fields. These habitats likely provide different ecological services and are visited accordingly. Fishes caged under piers in earlier experiments (Able and Duffy-Anderson 2006) were necessarily limited to single habitat types, and several species caged under piers experience negative growth or mortality as a result of starvation. But food is not the only concern related to survival and reproduction. A large group of striped bass was observed under the Pier 40 extension, and smaller groups were subsequently encountered there together with large schools of small prey species, but the striped bass were not seen to actively target the forage fish at that time. This group of fish presents an opportunity to study periodicity of pier use because it could be targeted for an acoustic telemetry tagging study that could follow a number of individuals in sub-meter resolution over an area of up to 2 km^2.

While this study benefited from a wide spatial scale that was representative of many pier structures along the Manhattan waterfront, environmental factors could not be disassociated because of covariance. For example, pier support structures varied with specific piers and thus also upriver distance and salinity, as were relict pile fields. Further, sampling was constrained by security and legal concerns of numerous agencies and thus could not occur randomly. This confounds confident partitioning of variation among all of the component variables, because these were not evenly stratified by season, pier or diurnal period. The uncommon occurrence of large fishes overall (76% of transects on average encountered no large fish) makes the sample size for any one factor small despite a high sample effort. A large number of transects will be needed, well separated in time to prevent temporal autocorrelation, to obtain statistical confidence in factor effects during studies designed to test specific hypotheses about structure use; these would best be carried out at a limited number of piers such as Pier 40 (these are ongoing) and 57 to control covariance with other factors.

Despite a relatively sparse set of observation points, pier size does seem to be an important consideration at least to striped bass habitat use. Striped bass were not typically found far under Pier 40, but occasionally were found to distances of about 8 – 10 m underneath. This distance is half to a quarter of the total width of other sampled piers (e.g. 100, 54, 57), suggesting that piers of that size might enhance rather than restrict habitat use by striped bass in particular because of their increased edge to covered surface ratio. In fact, the association of fishes with Pier 40 relative to other piers may have been weakened by the fact that the unit-effort at Pier 40 is necessarily inclusive of much more sample time spent at considerable distances under that pier (exceeding 100 m from any edge). This larger under-pier habitat necessitated sampling effort that did not exist for other piers, so that sampling is naturally biased towards proximity to edge in other piers. This is a testable hypothesis that could be the focus of further investigation. The detailed orientation of fishes to pier structure is also being approached in a different sampling design by an ongoing project funded by the New York City Department of Parks and Recreation.

Piers and other urban habitats are infrequently evaluated relative to habitat quality for estuarine organisms (Glasby and Connell 1999, Glasby 1999, Connell 2001). This is especially true for fishes with the exception of our prior efforts on small benthic fishes (see Able and Duffy-Anderson 2006 for a review). Many of these suggest that the intense shading that occurs under large piers may interfere with feeding and many aspects of fish behavior. This is not surprising for fishes because many species rely on vision for a variety of behaviors (McFarland 1986) including feeding and habitat use (Helfman and Schultz 1984, Ryer and Olla 1999, Petrie and Ryer 2006) and social and antipredator behavior including schooling (Shaw 1961, Ryer and Olla 1998). Our own studies of small benthic fishes in the study area have shown clearly that the intense shading under piers can interfere with habitat selection (Able et al. 1998, 1999), feeding (Duffy-Anderson and Able 2001, Metzger et al. 2001), and growth (Duffy-Anderson and Able 1999).

In contrast to small benthic fishes, small pelagic fishes utilize schooling rather than hiding in structure to avoid predation. Small fish could be forming larger schools around pier and other edges because the shadow lines provide a break that may confuse visual predators, or because the shadow itself provides cover in a way that cannot be obtained at any other type of edge habitat and still be in relatively deep water. The difference between school occurrence and size in pier edge samples vs. pile field samples suggests that it is not the structure itself that is attracting small fish. This does not mean that there is no detrimental effect to small fishes by piers. The lower mean school size under the pier may indicate that fish are less likely to form stable schools there. Further explorations of the relationship of small fish to shade, as in the New York City funded study under Pier 40 which is currently underway, will address shade on a finer scale than absence or presence.

In this study of pelagic fish habitat use in the vicinity of piers, it is clear that both large predators and their small prey are not abundant under large piers with intense shading but can be abundant at pier edges and in open water, perhaps in response to light availability. Many of the small species identified, e.g. anchovies and silversides, are schooling species and presumably rely on light mediated vision to school (see Shaw 1961 for evidence for silversides and other species and Ryer and Olla 1998 for a more recent account for other species). Given the low light levels under piers it is not surprising that these obligate schooling fishes do not utilize under-pier areas and instead are more abundant at pier edges and in open water. In response, those species which feed on such schooling species, e.g. striped bass (Tupper and Able 2000, Nemerson and Able 2003), are not found as frequently under piers where their prey are much reduced or absent. A potential exception is at night. Perhaps at that time the visually orienting fishes such as striped bass may have decreased ability to orient relative to pier structures and could thus be found across more habitat types at night, or may use shadows to ambush bait fish that gather along the often artificially lit pier edges.

In summary, the dynamic habitat use of mobile, pelagic fishes makes specific habitat distinctions difficult, especially as they change from dusk to dawn. In the future, further studies that provide a species specific and mechanistic interpretation of dynamic habitat use would improve our understanding of how fishes use urban shorelines and help to mitigate for shoreline modifications.

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Literature Cited

Able, K.W. 1999. Measures of Juvenile Fish Habitat Quality: Examples from a National Estuarine Research Reserve. Pp. 134-147 *In*: Benaka L. R. (ed.) Fish Habitat: Essential Fish Habitat and Rehabilitation. American Fisheries Society Symposium 22, Bethesda, MD.

Able, K.W. 2005. A reexamination of fish estuarine dependence: evidence for connectivity between estuarine and ocean habitats. Estuarine and Coastal Shelf Science 64:5-17.

Able, K. W, and J.T. Duffy-Anderson. 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 Technical Report #2005-13, New Brunswick, NJ.

Able, K.W. and J.T. Duffy-Anderson. 2006. Impacts of piers in the lower Hudson River. Pp. 428- 440 *In*: J.S. Levinton and J.R. Waldman (eds.), The Hudson River Estuary. Cambridge University Press, New York, NY.

Able, K. W, and M.P. Fahay. 1998. The First Year in the Life of Estuarine Fishes in the Middle Atlantic Bight. Rutgers University Press, New Brunswick, NJ.

Able, K. W. and M. P. Fahay. 2010. Ecology of Estuarine Fishes: Temperate Waters of the Western North Atlantic. Johns Hopkins University Press, Baltimore, MD.

Able, K.W. and L.S. Hales, Jr. 1997. Movements of juvenile black sea bass, *Centropristes striata* (Linnaeus), in a southern New Jersey estuary. Journal of Experimental Marine Biology and Ecology, 213: 153-167

Able, K.W., J.P. Manderson, and A.L. Studholme. 1997. The distribution and growth of shallow water juvenile fishes in an urban estuary: a preliminary report on the effects of manmade structures in the Hudson River Estuary. Pp. 181-184 *In*: Management of Atlantic Coastal Marine Fish Habitat, ASMFC Habitat Management Series #2. June 3-6, Philadelphia, PA.

Able, K.W., J. P. Manderson, and AL. Studholme. 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., J. P. Manderson, and A.L. Studholme. 1999. Habitat quality for shallow water fishes in an urban estuary: The effects of manmade structures on growth. Marine Ecology Progress Series 187: 227-235.
Able, K.W., M.J. Neuman and H. Wennhage. 2005. Ecology of the adult and juvenile stages: distribution and dynamics of habitat associations. Pp. 164-184 *In*: R.N. Gibson (ed.), Flatfishes: Biology and Exploitation Blackwell Publishing, Oxford, UK.
Baker, R. & M. J. Sheaves. 2006. Visual surveys reveal high densities of large piscivores in shallow estuarine nurseries. Marine Ecology-Progress Series. 323:75 – 82
Baker, R. and M. J. Sheaves. 2007. Shallow-water refuge paradigm: conflicting evidence from tethering experiments in a tropical estuary. Marine Ecology-Progress Series. 349:13–22
Boesch, D. F., and R.E. Turner. 1984. Dependence of fishery species on salt marshes: the role of food and refuge. Estuaries 7(4A):460-468
Bortone, S. A., M. A. Samoilys and P. Francour. 2000. Fish and macroinvertebrate assessment methods. Pp. 127-164 *In:* Seaman, W. Jr. (ed.) Artificial Reef Evaluation. CRC Press, Boca Raton, FL.
Boswell, K. M, M.P. Wilson, and J.H. Cowan. 2008. A semiautomated approach to estimating fish size, abundance, and behavior from Dual-Frequency Identification Sonar (DIDSON) data. Journal of Fisheries Management 28:799-807.
Brosnan, T. M., and M. L. O'Shea. 1996. Long-term improvements in water quality due to sewage abatement in the lower Hudson River. Estuaries 19:890-900.
Brown, L. M., K. J. Magowan, D. A. Fox, and J. E. Hightower. 2007. Comparison of split- beam and hydroacoustic gears for conducting sturgeon surveys. Presented at Mid Atlantic Chapter Amer. Fish. Soc. Meeting, Lewes, DE, Feb. 1-3.
Clarke, K. R., P. J. Somerfield, A. Airoldi, and R. M. Warwick . 2006. Exploring interactions by second stage community analyses. Journal of Experimental Marine Biology and Ecology 338:179-192.
Connell, S. D. 2001. Urban structures as marine habitats: an experimental comparison of the composition and abundance of subtidal epibiota among pilings, pontoons and rocky reefs. Marine Environmental Research 52:115-125.
Daniels, R.A., K.E. Limburg, R.E. Schmidt, D.L. Strayer, and R.C. Chambers. 2005. Changes in fish assemblages in the tidal Hudson River, New York. Pp. 471-503 *In*: J. N. Rinne, R. M. Hughes and B. Calamusso (eds.), Historical Changes in Large River Fish Assemblages of America. American Fisheries Society Symposium 45, American Fisheries Society, Bethesda, MD.
Duffy-Anderson, J. T., and K.W. Able 1999. Effects of municipal piers on the growth of juvenile fish in the Hudson River estuary: a study across a pier edge. Marine Biology 133:409-418.
Duffy-Anderson, J.T., and K.W. Able. 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, U.S.A. Estuaries 24(3):430-440
Duffy-Anderson, J. T., J. P. Manderson, and K.W. Able. 2003. A characterization of juvenile fish assemblages around man-made structure in the New York-New Jersey harbor estuary, U.S.A. Bulletin of Marine Science 72(3):877-889.

Dunning, D. J., J. R. Waldman, Q. E. Ross, and M. T. Mattson. 2006. Dispersal of age 2+ striped bass out of the Hudson River. Pp. 287-294 *In*: J. Waldman, K. Limburg, and D. Strayer (eds.) Hudson River Fishes and Their Environment. American Fisheries Society Symposium 51. American Fisheries Society, Bethseda, MD.

Elliott, M., and K. L. Hemingway. 2002. Fishes in Estuaries. Blackwell, Oxford, UK.

Euston, E. T., S. A. Haney, K. A. Hatalla, and A. W. Kahnle. 2006. Overview of the Hudson River recreational fishery with and emphasis on striped bass. Pp. 295-315. *In:* J. Waldman, K. Limburg, and D. Strayer (eds.) Hudson River Fishes and Their Environment. American Fisheries Society Symposium 51. American Fisheries Society, Bethesda, MD.

Glasby, T. M. 1999. Effects of shading on subtidal epibiotic assemblages. Journal of Experimental Marine Biology and Ecology 234:275-290.

Glasby, T. M., and S. D. Connell. 1999. Urban structures as marine habitats. Ambio. 28:595-598.

Gray, J. S., R. K. Clarke, R. M. Warwick, R. M. Hobbs. 1990. Detection of initial effects of pollution on marine benthos: an example from the Ekofisk and Eldfisk oilfields, North Sea. Mar. Ecol. Prog. Ser. 66: 285-299.

Hagan, S. M. and K. W. Able. 2003. Seasonal changes of the pelagic fish assemblage in a temperate estuary. Estuarine Coastal and Shelf Science. 56:15-29

Hagan, S. M. and K. W. Able. 2008. Diel variation in the pelagic fish assemblage in a temperate estuary. Estuaries and Coasts 31:3 3-42

Helfman, G. S. 1981. The advantage to fishes of hovering in the shade. Copeia 1981: 392-400.

Helfman, G. S., and E. T. Schultz. 1984. Social transmission of behavioural traditions in a coral reef fish. Anim. Behav. 32:379-384.

Hudson River Foundation. 2004. Health of the harbor: the first comprehensive look at the state of the NY/NJ Harbor estuary. New York/New Jersey Harbor Estuary Program. 82 pp.

Hurst, T. P., and D. O. Conover. 1998. Winter mortality of young-of-the-year Hudson River striped bass (*Marone saxatilis*): size-dependent patterns and effects on recruitment. Canadian Journal of Fisheries and Aquatic Sciences 55:1122-1130.

Hurst T. P., and D. O. Conover. 2001. Activity-related constraints on overwintering young-of-the-year striped bass (*Morone saxatilis*). Canadian Journal of Zoology 79:129-136

Johnston, R. and M. Sheaves. 2008. Cross-channel distribution of small fish in tropical and subtropical coastal wetlands in trophic-, taxonomic-, and wetland depth-dependent. Marine Ecology Progress Series 357:255-270.

Kalikhman, I. L. and K I. Yudanov. 2006. Acoustic Fish Reconnaissance. CRC Press, Boca Raton, FL.

Levinton, J. S. and J. R. Waldman. 2006. The Hudson River Estuary. Cambridge University Press, New York, NY.

McFarland, W. N. 1986. Light in the sea – correlations with behaviors of fishes and invertebrates. Am. Zool. 26:389-401.

Metzger, C. V, J. T. Duffy-Anderson, and K.W. Able. 2001. Effects of a municipal pier on growth of young-of-the year Atlantic tomcod (*Microgadus tomcod*):A study in

the Hudson River estuary. Bulletin of the New Jersey Academy of Science 46(1):5-10
Nakagawa, S. 2004. A farewell to Bonferroni: the problems of low statistical power and publication bias. Behavioral Ecology 15(6):1044-1045
Nemerson, D.M. and K.W. Able. 2003. Spatial and temporal patterns in the distribution and feeding habits of *Morone saxatilis*, in marsh creeks of Delaware Bay, USA. Fisheries Management and Ecology 20:337-348.
Petit, D. R., L. J. Petit, V. A. Saab, and T. E. Martin. 1995. Fixed-radius point counts in forests: factors influencing effectiveness and efficiency. Pp 49-56 *In*: Ralph, C. J, J. R. Sauer, and S. Droege (eds.). Monitoring Bird Populations by Point Counts. USDA Forest Service General Technical Report PSW-GTR-149.
Petrie, M. E., and C. H. Ryer. 2006. Hunger, light level and body size affect refuge use by post-settlement lingcod *Ophiodon elongatus*. Journal of Fish Biology 69:957-969.
Richards R. A. and P. J. Rago. 1999. A case history of effective fisheries management: Chesapeake Bay striped bass. North American Fisheries Management 19:356-375.
Ryer, C. H., and B. L. Olla. 1998. Effect of light on juvenile walleye Pollock shoaling and their interaction with predators. Marine Ecology Progress Series 167:215-226.
Ryer, C. H. and C. L. Olla. 1999. Light-induced changes in the prey consumption and behavior of two juvenile planktivorous fish. Marine Ecology Progress Series 181:41-51.
Secor, D. H., and J. R Rooker. 2005. Connectivity in the life histories of fishes that use estuaries. Estuarine, Coastal and Shelf Science 64:1-3.
Secor, D. H., J. R. Rooker, E. Zlokovitz, and V. S. Zdanowicz. 2001. Identification of riverine, estuarine, and coastal contingents of Hudson River striped bass based upon otolith elemental fingerprints. Marine Ecology Progress Series. 211:245-253.
Shaw, E. 1961. Minimal light intensity and the dispersal of schooling fish. Contribution No. 1211, Woods Hole Oceanographic Institution.
Sheaves, M. 2001. Are there really few piscivorous fishes in shallow estuarine habitats? Marine Ecology Progress Series 222: 279-290
Sheaves, M., R. Baker, and R. Johnston. 2006. Marine nurseries and effective juvenile habitats: an alternative view. Marine Ecology Progress Series 318: 303-306
Sokal, R. R., and F. J. Rohlf. 1994. Biometry: The Principles and Practices of Statistics in Biological Research. 3rd Edition. W. H. Freeman and Co., New York, NY.
Stoecker, R. R., J. Collura, and P. J. Fallon, Jr. 1992. Aquatic studies at the Hudson River Center Site. Pp. 407-427 *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.
Sullivan, M.C., R.K. Cowen, K.W. Able and M.P. Fahay. 2000. Spatial scaling of recruitment in four continental shelf fishes. Mar. Ecol. Prog. Ser. 207: 141-154.
Sullivan, M.C., R.K. Cowen, K.W. Able, and M.P. Fahay. 2003. Effects of anthropogenic and natural disturbance on a recently settled continental shelf flatfish. Mar. Ecol. Prog. Ser. 260: 237-253.

Tupper, M. and K.W. Able. 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(5/6): 1049-1058.

Underwood, A.J. 1993. The mechanics of spatially-replicated sampling programs to detect environmental impacts in a variable world. Australian Journal of Ecology 18: 99-116.

Waldman, J. R. 2006. The diadromous fish fauna of the Hudson River: life histories, conservation concerns, and research avenues. Pp. 171-188 *In*: Levinton, J. S. and J. R. Waldman (eds.) The Hudson River Estuary. Caimbridge University Press, New York, NY.

Waldman, J.R., D.J. Dunning, Q.E Ross and M. T. Mattson. 1990. Range dynamics of Hudson River striped bass along the Atlantic Coast. Transactions of the American Fisheries Society 119:910-919

Waldman, J, R., T. R. Lake, and R. E. Schmidt. 2006a. Biodiversity and zoogeography of fishes in the Hudson River watershed and estuary. Pp 129-150 *In:* Waldman, J., K. Limburg, and D. Strayer (eds.) Hudson River Fishes and Their Environment. American Fisheries Society Symposium 51. American Fisheries Society, Bethseda, MD.

Waldman, J., K. Limburg, and D. Strayer. 2006b. The Hudson River environment and its dynamic fish community. Pp. 1-8. *In:* Waldman, J., K. Limburg, and D. Strayer (eds.) Hudson River Fishes and Their Environment. American Fisheries Society Symposium 51. American Fisheries Society, Bethesda, MD.

Wiens, J. A. 1989. Spatial scaling in ecology. Functional Ecology 3:385-397.

Yoccoz, N. G. 1991. Use, overuse, and misuse of significance tests in evolutionary biology and ecology. ESA Bulletin 72:106-111.

Table 1. Groundtruthing efforts by sampling gear in the Rutgers University Marine Field Station boat basin and surrounding areas in the Mullica River – Great Bay estuary in southern New Jersey. Trap samples occurred over day and night combined.

Sampling Gear	Sampling Dates	Number of Times Deployed		Number of Fish Captured		Number of Species Captured	
		Day	Night	Day	Night	Day	Night
DIDSON	18-20 September 2007 30-31 October 2007 18-22 June 2008	176	27	-	-	-	-
Pop Net	24-30 July 2007	13	3	2325	39	4	7
Cast Net	24-30 July 2007 25-31 July 2007	10	6	4	18	4	4
Experimental Trap	25-31 July 2007	30	-	49	-	7	-
Gill Net	26-30 July 2007	3	0	3	0	1	0
Visual Surveys	28 June 2008	29	31	-	-	-	-

Table 2. Fish species composition and abundance by groundtruthing gear and DIDSON images based on sampling in the Rutgers University Marine Field Station boat basin in the Mullica River – Great By estuary in southern New Jersey. X indicates species identified but not counted.

Species	Groundtruth Gear					DIDSON
	Pop Net	Cast Net	Trap	Gill Net	Visual Survey	
Anchoa mitchilli	8	1	0	0	0	
Anchoa sp.	1	0	0	0	0	
Alosa pseudopharengus	1	11	0	0	0	
Alosa mediocris	1	0	0	0	0	
Brevoortia tyrannus	1	0	0	0	0	x
Centropristis striata	0	0	3	0	x	x
Fundulus heteroclitus	0	2	24	0	0	
Gobiosoma sp.	1	0	2	0	0	
Menidia menidia	2328	2	2	0	x	x
Pomatomus saltatrix	8	5	0	3	0	x
Pseudopleuronectes americanus	1	0	1	0	0	
Sphyraena borealis	14	0	0	0	0	
Tautoga onitis	0	0	1	0	x	x
Tautogolabrus adspersus	0	0	16	0	2	
UID Clupeid	2	1	0	0	0	
Limulus polyphemus	0	0	0	0	x	x

Table 3: Number of DIDSON transects by habitat type for day, night, and crepuscular sampling in the Hudson River during 2007-2009. In some instances, these habitat types are treated together because DIDSON transects crossed habitat boundaries.

	2007			**2008**			**2009**		
	Day	Crepuscular	Night	Day	Crepuscular	Night	Day	Crepuscular	Night
bulkhead	8	0	0	4	0	0			
open water	10	5	8	10	0	0	4	6	3
pile field	13	3	3	6	0	0	2	1	2
pier edge	15	0	1	8	0	0	10	10	6
under pier	7	1	2	12	0	0	23	1	2
mixed	19	1	3	23	0	0	1	4	2
Total	72	10	17	63	0	0	40	22	15

Table 4: Number of DIDSON transects by habitat type and by pier number in the Hudson River during 2007-2009. See Fig. 1 for pier locations.

		Pier									
Year		NJ	40	45	55	57	59	61	76	P100	Total
2007	bulkhead	6	2								8
	open water		4		7	7	1			4	23
	pile field		7		6	1	3			2	19
	pier edge		9		2		1			4	16
	under pier		5		2		1			2	10
	mixed		6	8	8					1	23
	Total	6	33	8	25	8	6			13	99
2008	bulkhead	4									4
	open water	3	2	4						1	10
	pile field		2	4							6
	mixed									2	2
	pier edge		5	3							8
	mixed	8	5	4				3		1	21
	under pier	1	11								12
	Total	16	25	15				3		4	63
2009	open water		3	9						1	13
	pile field		2	3							5
	pier edge		10	16							26
	under pier		21	1					1	3	26
	mixed			6					1		7
	Total		36	35					2	4	77
Total		22	93	58	25	8	6	3	2	21	239

Table 5: Characteristics of the piers in the study area

Pier	Length (m)	Width (m)	Orientation (°)	Distance to nearest pier (m)
40	294	240	276	191
45	260	30	271	79
54	233	26	278	70
57	262	41	278	134
59	254	44	277	66
61	263	41	276	67
76	221	85	299	84
100	217	16	266	755

Table 6. Percentage of Pier 57 transects that included schooling fish (S) and non-schooling fish (NS) based on DIDSON images. Pier edge (i.e. along the long axis of the pier), whereas under pier indicates a transect that starts at a pier edge and proceeds across the long axis of the pier.

	Percentage of Transects with Fish							
Sampling Dates	Under Pier		Pier Edge		Open Water		Near Pile Field	
	S	NS	S	NS	S	NS	S	NS
18-20 September 2007	50%	50%	60%	40%	20%	60%	60%	40%
30-31 October 2007	-	-	-	-	50%	100%	50%	100%
18-19 June 2008	100%	50%	100%	0%	75%	75%	100%	100%
Totals	75%	50%	75%	25%	46.7%	80%	63.64%	72.73%

Table 7. Distribution of small fish among transects through four habitat types during daytime sampling at Pier 57 in the Hudson River.

	Mean Number of Fish in File (CPUE)	Mean Occurrence of Schools in File (CPUE)	Mean Size of Fish in School (cm)	Mean Number of Fish in School (number)
Open water	3.5	1.1	18.5	3.5
Pile Field	4.1	0.7	22.1	6.6
Pier Edge	45.4	0.6	13.0	81.3
Pier Edge and Under Pier	13.9	0.7	16.7	20.1

Table 8. Pairwise comparison of habitat use by small fish as measured by four response metrics. Significant differences at the within family Bonferroni-corrected alpha level are marked by "x".

	Mean Number of Fish in File (CPUE)	Mean Occurrence of Schools in File (CPUE)	Mean Size of Fish in School (cm)	Mean Number of Fish in School (number)
edge-open	X			
edge-pile	X		X	X
edge-under				
open-pile				
open-under				
pile-under				

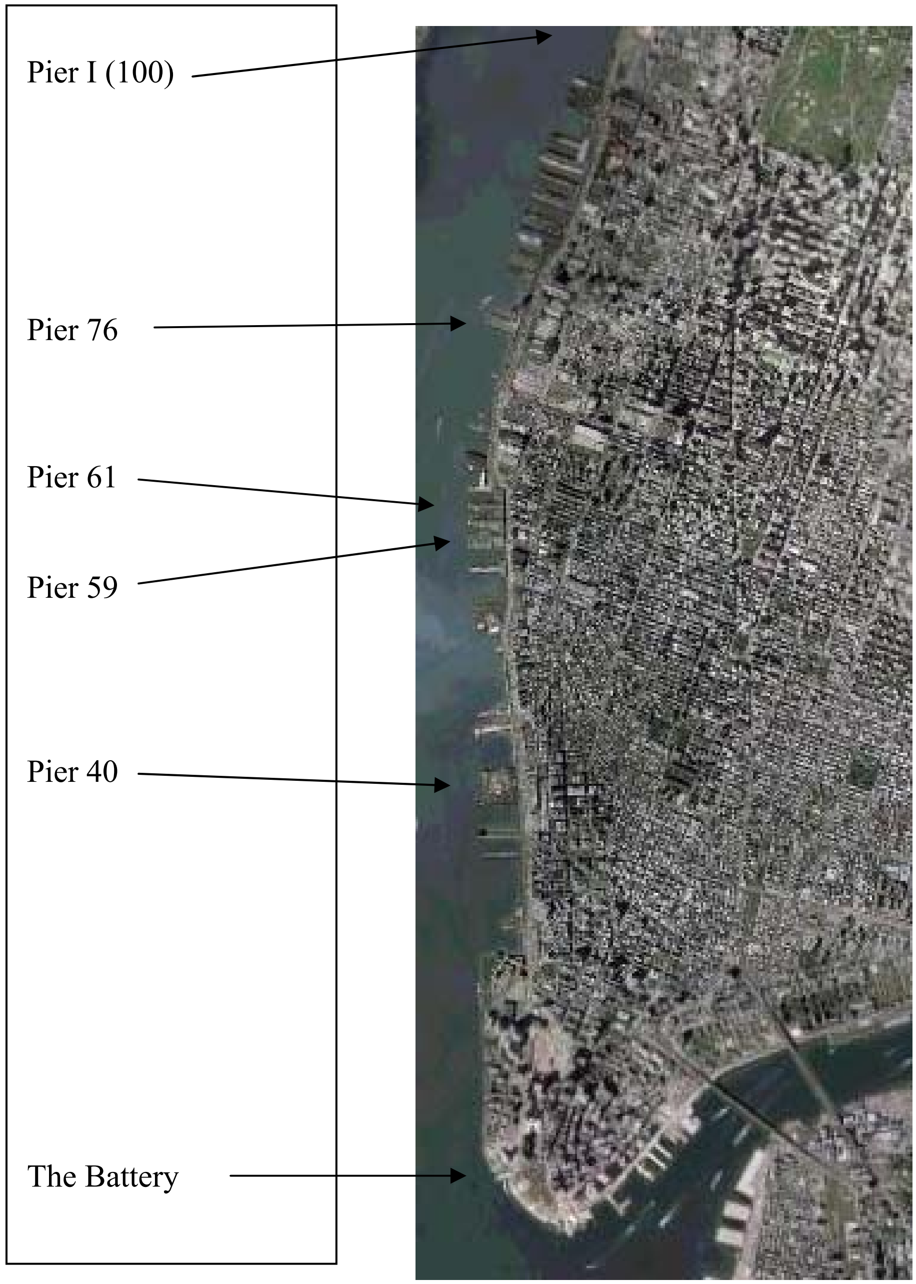

Figure 1. Study area along the eastern shore of the Hudson River Estuary and its confluence with the East River. The numerical address of several prominent piers is given as landmarks; pier numbering is generally linear but interrupted where derelict piers no longer show. The image spans about 4 nautical miles in the North-South (long) axis.

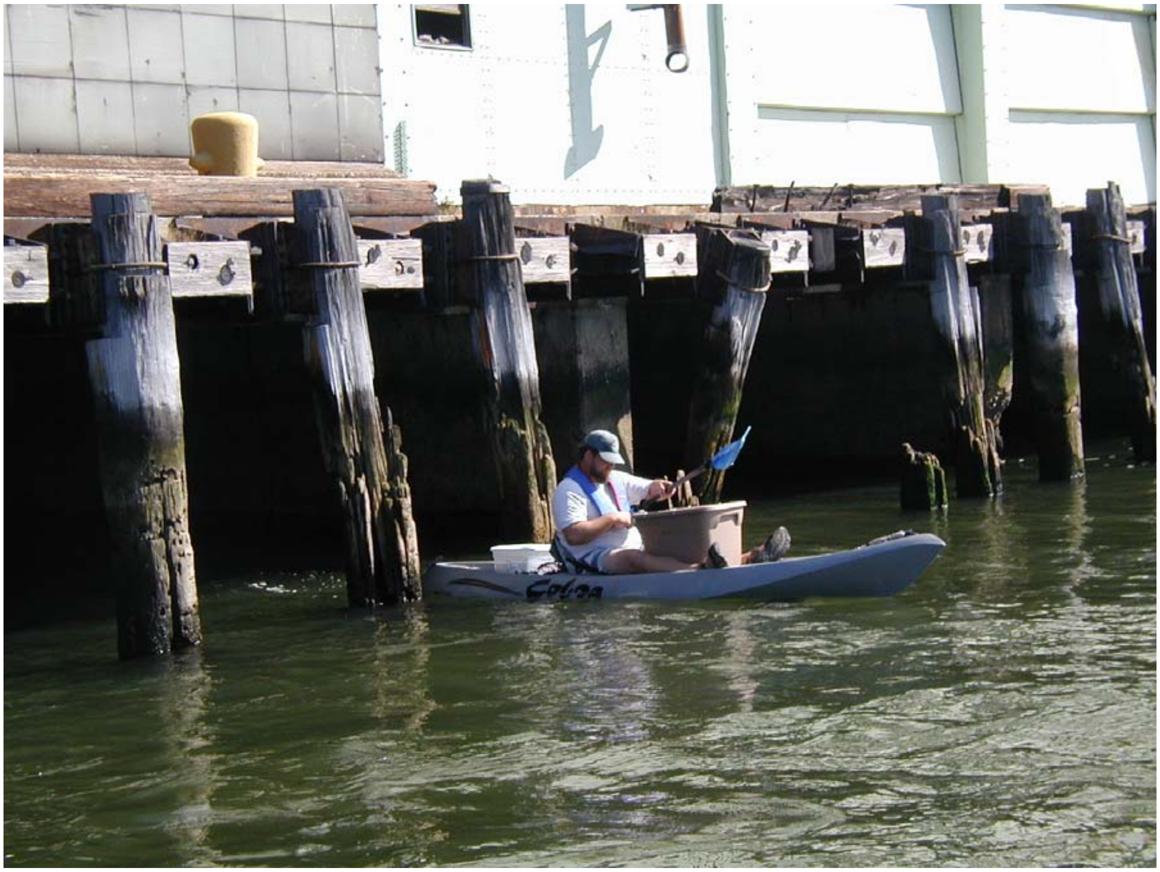

Figure 2. A Rutgers University scientist emerges from under Pier 57 during a DIDSON survey. The DIDSON is mounted under the kayak bow, batteries are behind the paddler, and the laptop is inside the spray guard/sunshade ahead of the paddler. The kayak is very quiet and able to enter shallow water without disturbing nearby fish.

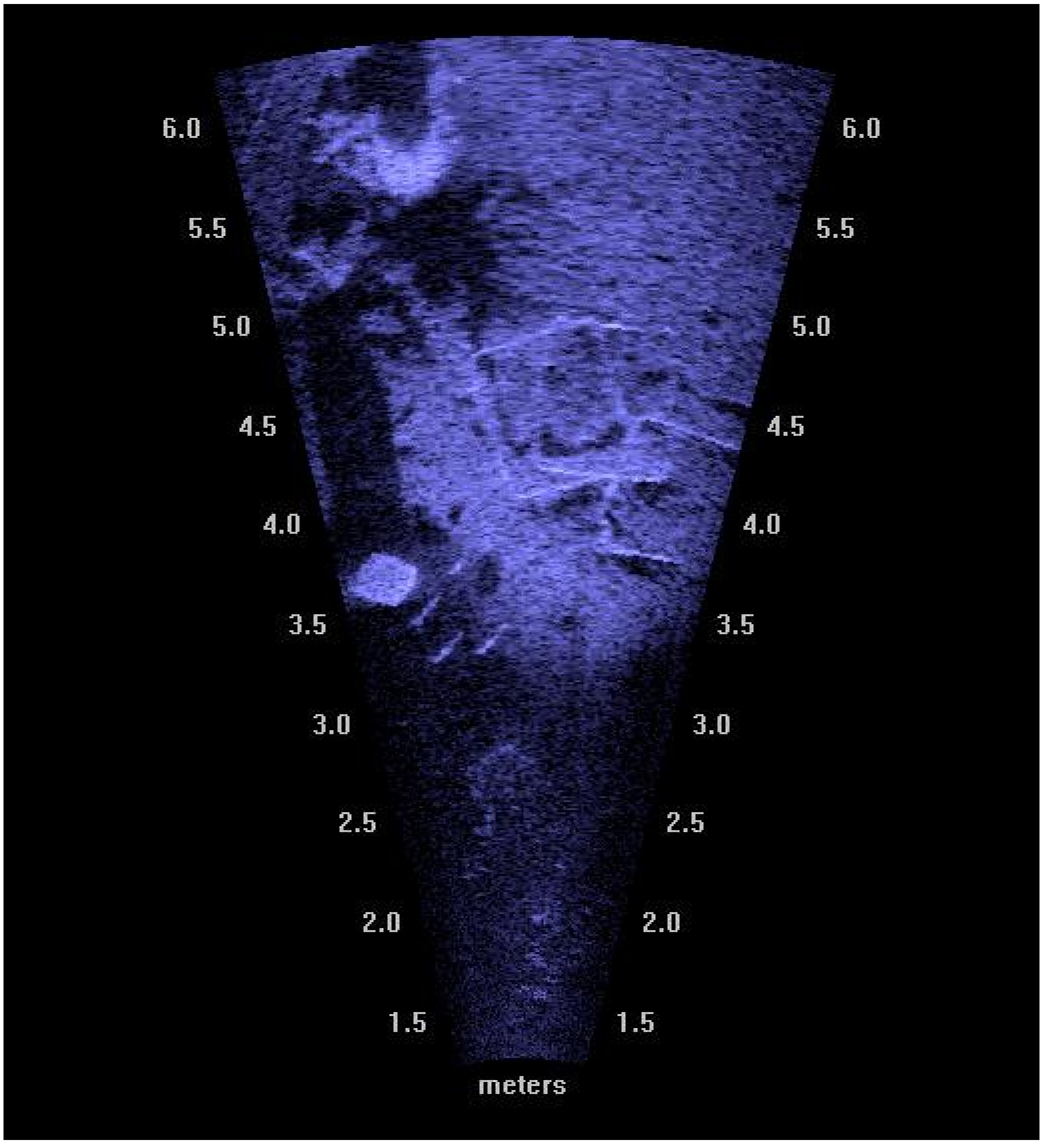

Figure 3. Four fish of about 320 mm length cross the DIDSON field of vision 3.5 m from the lens and near the bottom under a high pier with widely spaced piles. This is part of a school of 10 fish that moved in a very linear fashion across the field while maintaining even spacing, a characteristic of sub-adult striped bass. Abundant man-made debris is also evident. DIDSON field depth is set for 5 m at 23^{o} angle.

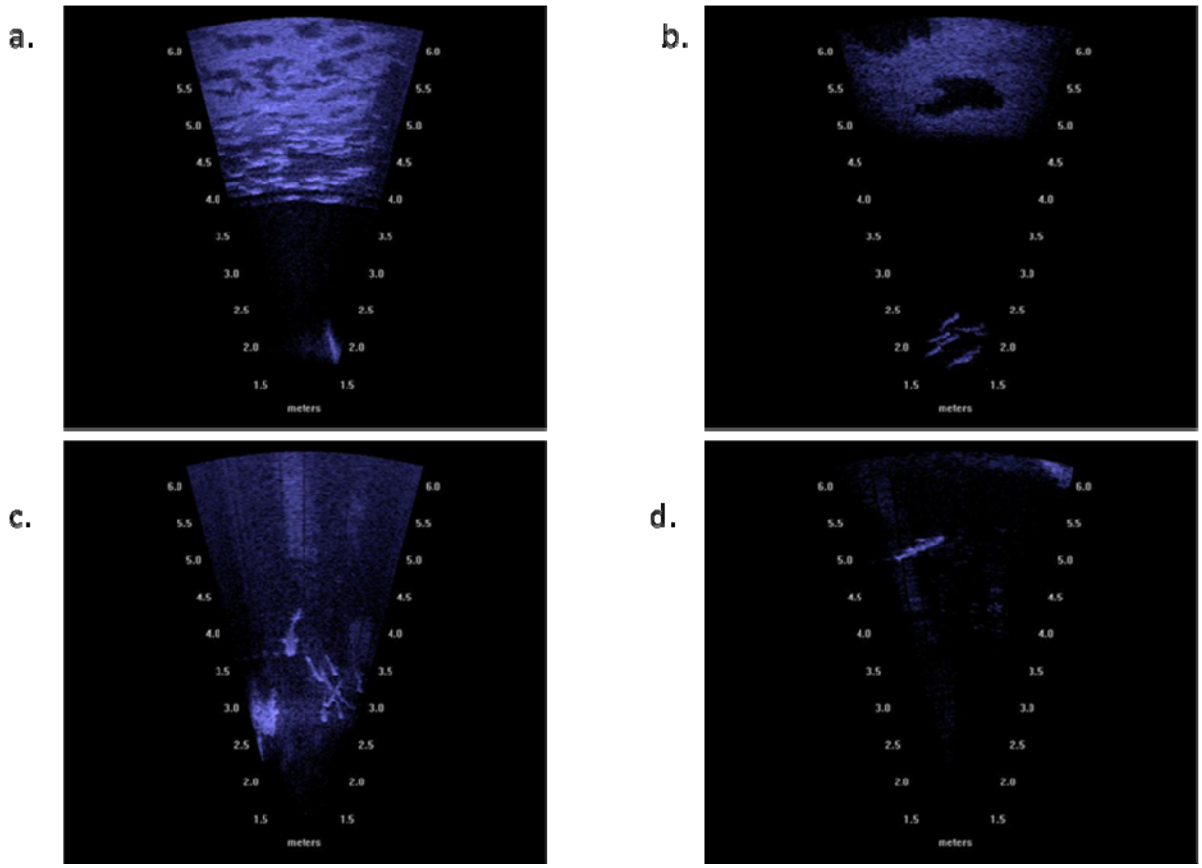

Figure 4. DIDSON images in the vicinity of piers in the Hudson River (see Fig. 1) including a) a school of unidentified large fish (25 - 30 cm in length) between 4 - 5 m from the sensor and acoustic shadows of the same fish at 5 - 6 m from the sensor, b) a small school of large (30 - 40 cm in length) fish at approximately 2 - 2.5 m from the sensor with a blurred acoustic shadow of the same fish at 5 - 6 m, c) a school of large (30 - 40 cm in length) striped bass. Note that the dorsal view of the individual (65 – 70 cm in length) at 4 m from the sensor provides a view of the pectoral fins, and d) a single large (70 - 80 cm in length) striped bass at approximately 6 m from the sensor with both dorsal fins evident.

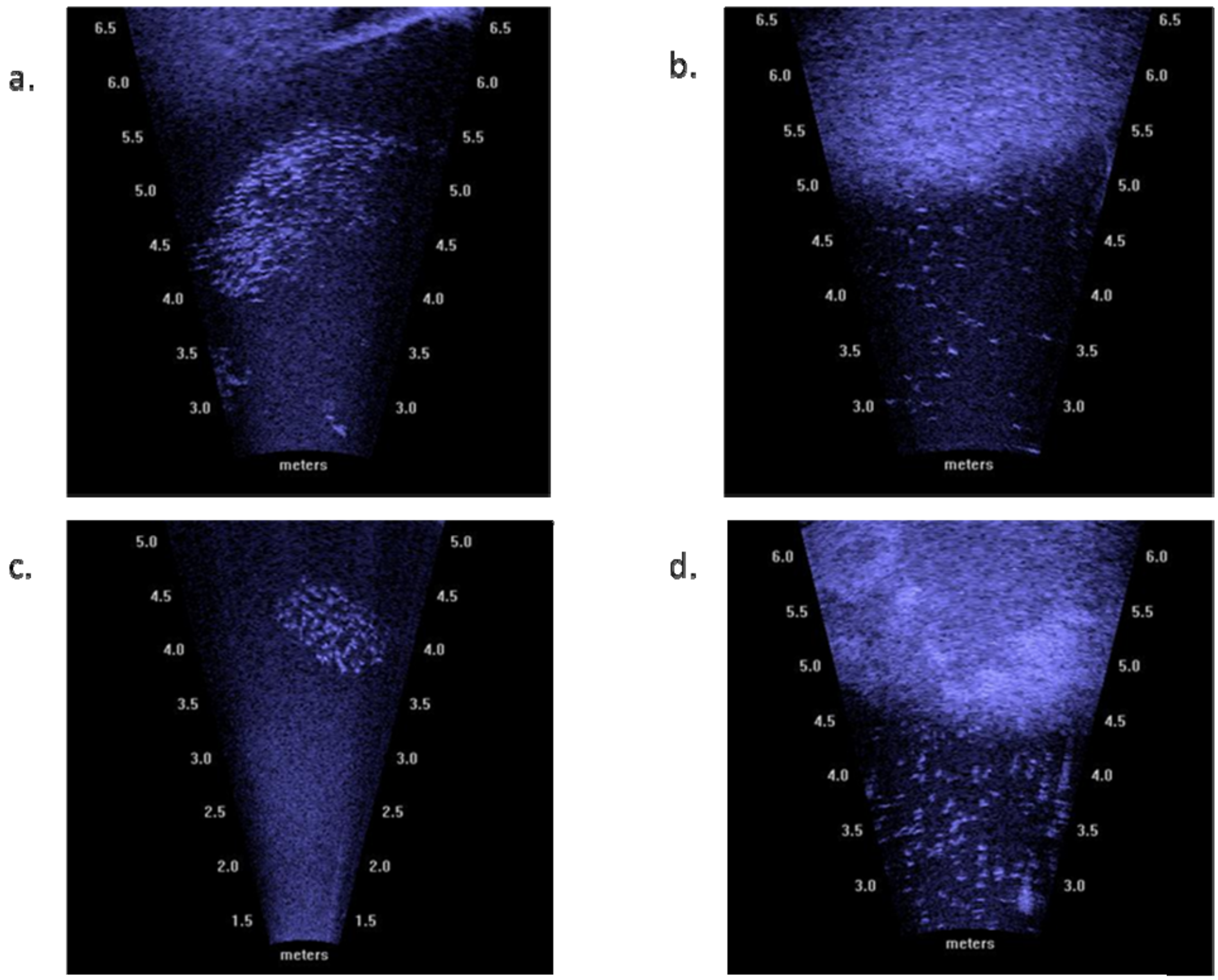

Figure 5. DIDSON images of various fish schools including a) organized school of 200+ fish (4-9 cm in length) 10 m out from Pier 40, b) large unorganized school or aggregation (6-10 cm in length) 10 m out from Pier 40, c) small organized school of 40+ fish (7-9 cm in length) by Pier 57, and d) unorganized school of 200+ fish (8-10 cm in length) at the edge of Pier 40.

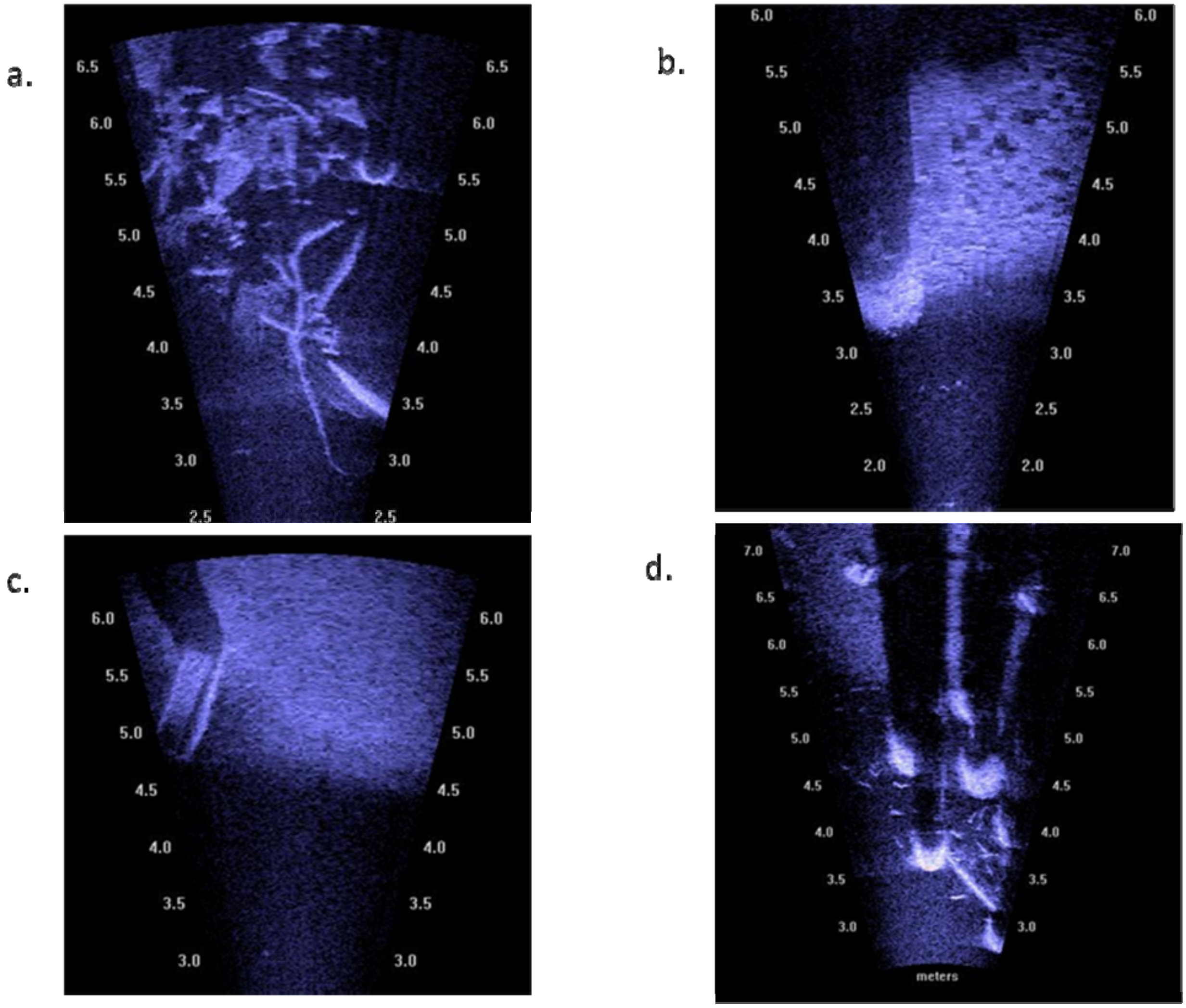

Figure 6. DIDSON images of various structural components in the Hudson River including a) debris in a piling field left of Pier 57, b) light debris at the edge of a New Jersey bridge, c) No debris by a piling under Pier 40, and d) multiple pilings under Pier 40 with fish evident near their base.

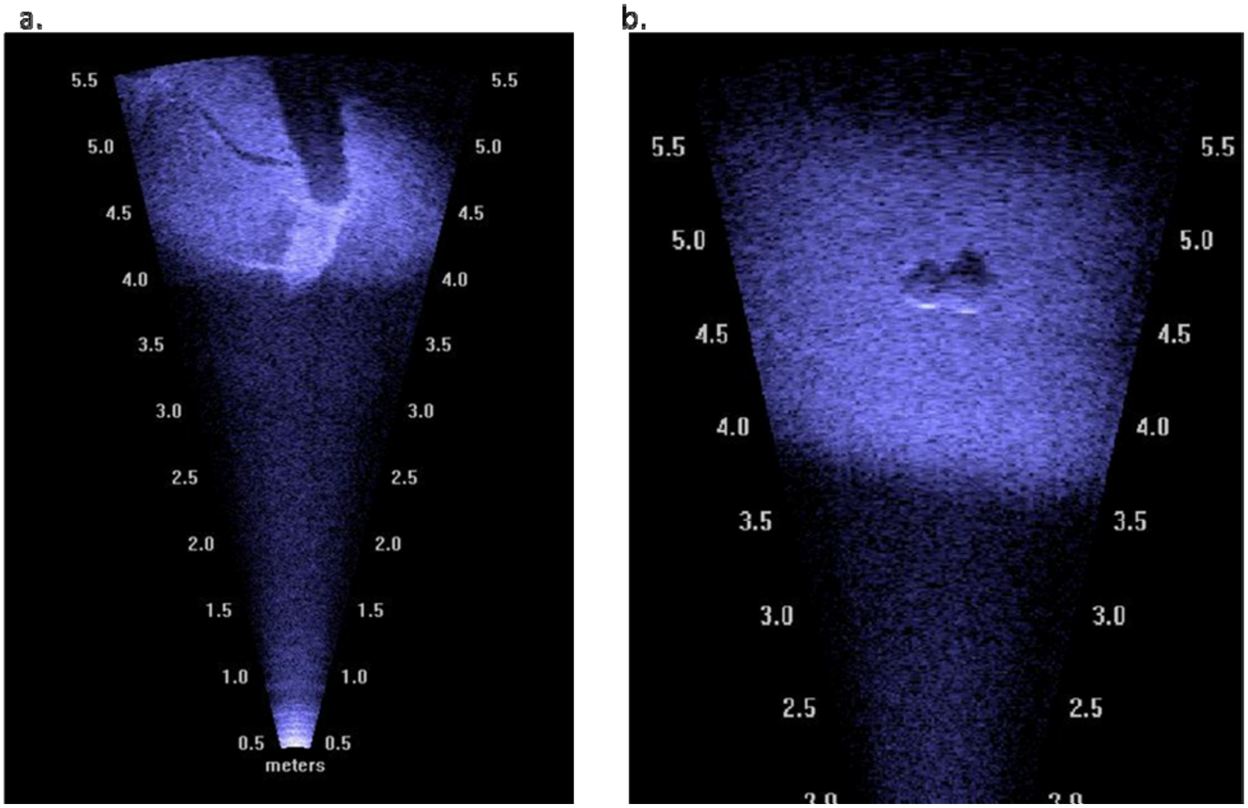

Figure 7. DIDSON images of identified species including a) American eel (*Anguilla rostrata*), 60 cm in length next to a piling under Pier 40 and b) mating pair of horseshoe crabs (22-26 cm carapace width) in a piling field near Pier 57.

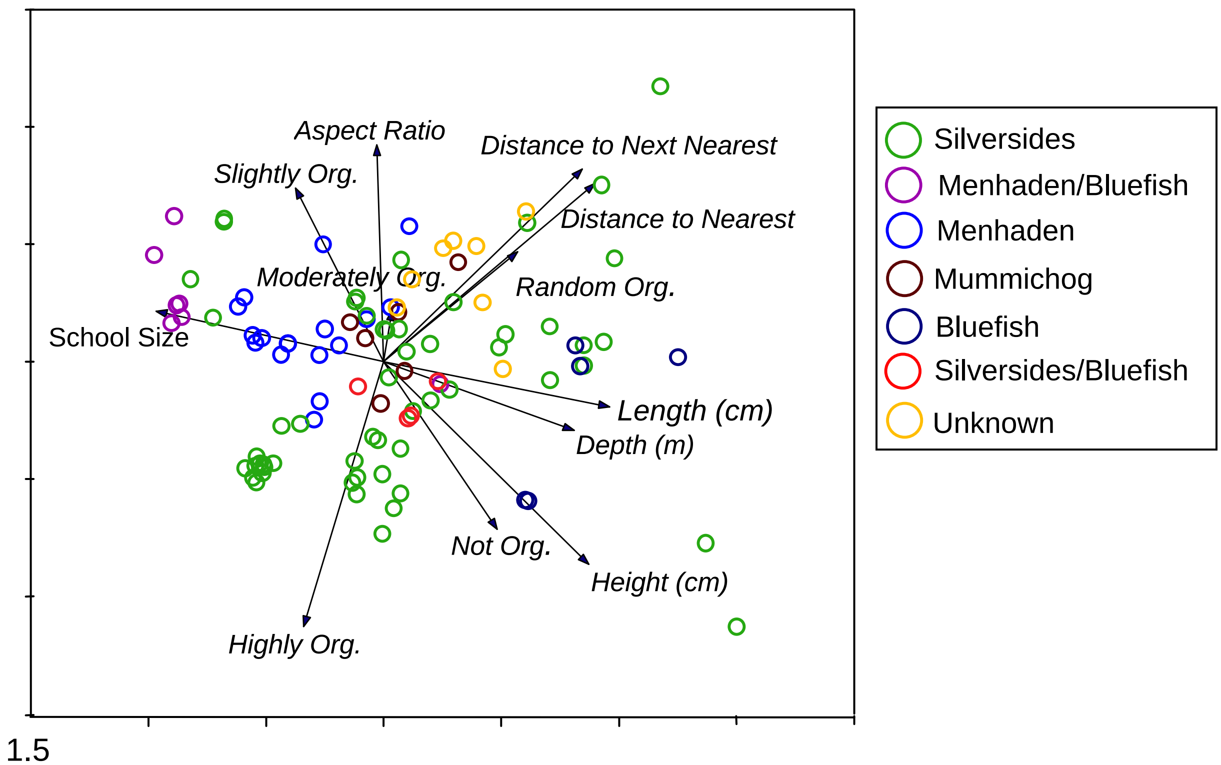

Figure 8. Principle components analysis of fish classification from DIDSON images of schooling fish as groundtruthed by net sampling at the Rutgers University Marine Field Station boat basin in Great Bay near Tuckerton, NJ. Atlantic silverside were common in groundtruth samples and exhibited a wide size range and suite of organization characteristics, but could be readily discerned from deeper bodied fish such as Atlantic menhaden and bluefish. This same variation in organization characteristics was observed visually by Atlantic silversides in response to variation in shadows from an observer passing overhead.

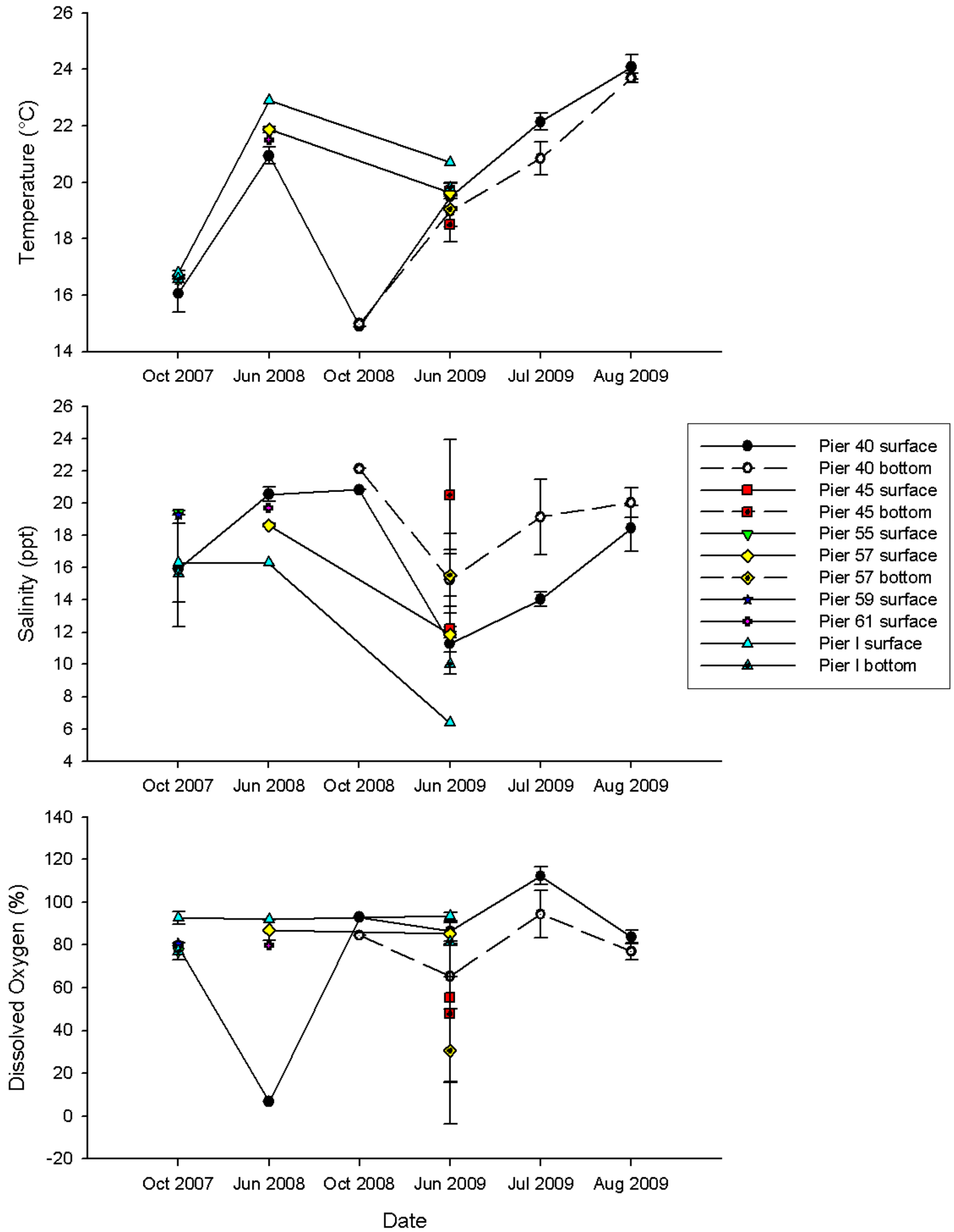

Figure 9. Temporal, spatial (latitudinal), and depth variation in salinity, temperature, and dissolved oxygen (percent saturation) at piers in the Hudson River during DIDSON sampling from October 2007 through August 2009. Many sample symbols are overlain, an indication of similarity among stations. See Fig. 1 for location of piers.

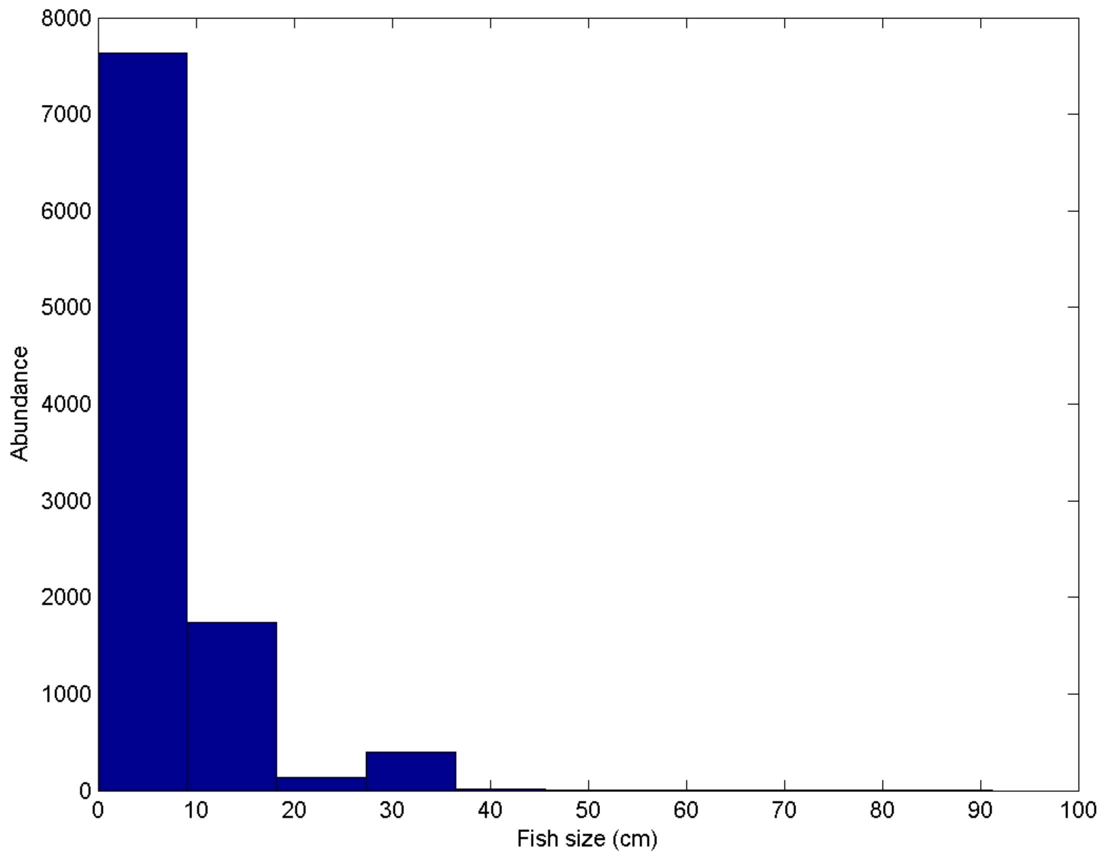

Figure 10. Size frequency distribution of all fish sampled by DIDSON in the Hudson River in among-pier habitat survey between 2007 and 2009.

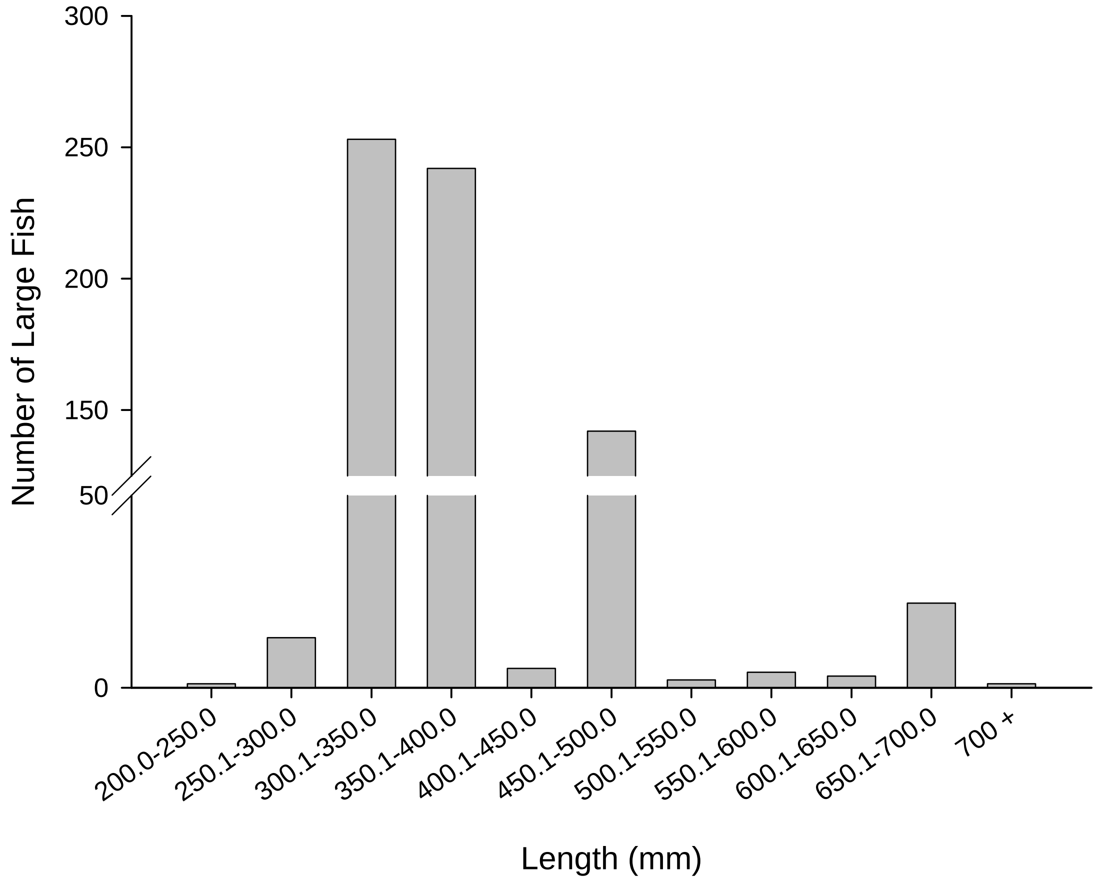

Figure 11. Distribution in the average length (mm) of the large fishes (>250 mm) sampled by DIDSON.

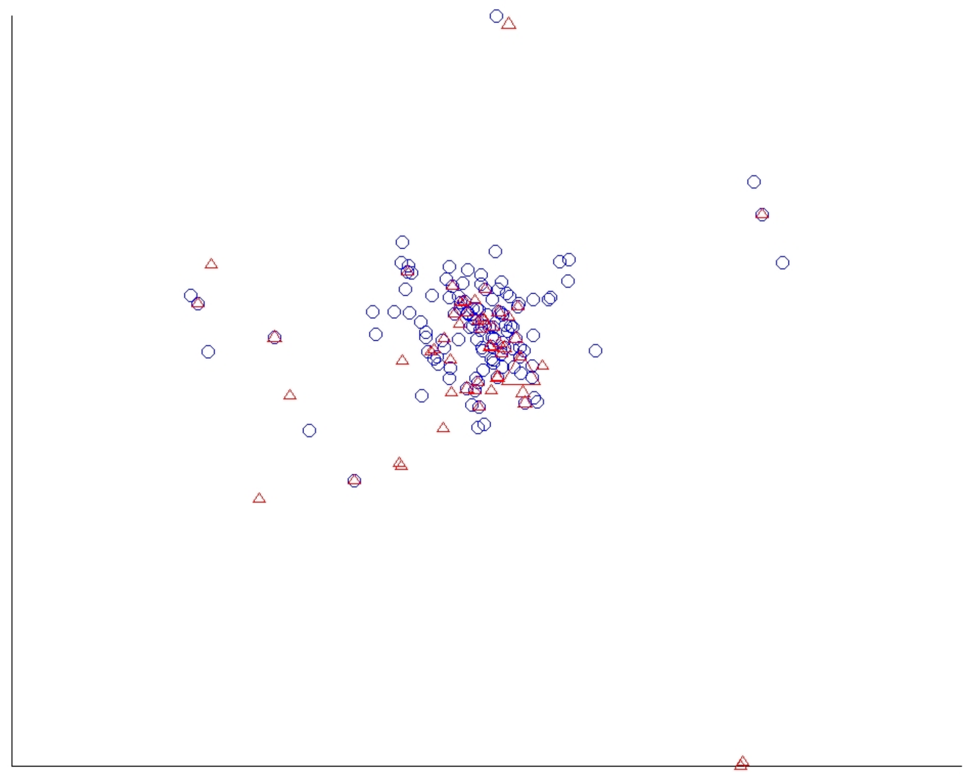

Figure 12 A. Non-metric multidimensional scaling ordination depicting relative similarity among all DIDSON sample transects. Axes do not have units because they depict only relative rank order. Samples depicted as blue circles contain no large fish. Samples depicted as red triangles contain large fish, and symbol size (area) is scaled as a square of the number of events in that sample (maximum was 5 in one transect). The spread of samples that contain large fish is even and similar to the spread of empty samples along both of the two most important axes depicting the general lack of structure to the distribution relative to multivariate space.

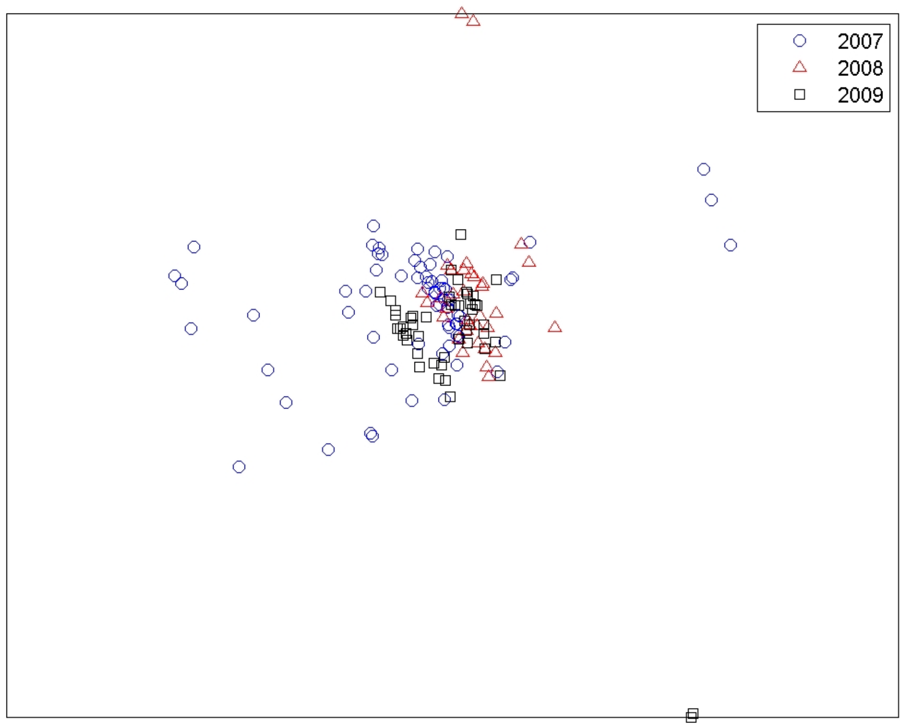

Figure 12 B. Non-metric multidimensional scaling ordination depicting relative similarity among all DIDSON sample transects. This is the same sample ordination as Fig 12 A, but samples are coded by year to show how interannual differences correlated with total variation. A more diverse sample set was taken in 2007 but was inclusive of samples similar to those taken in 2008 and 2009.

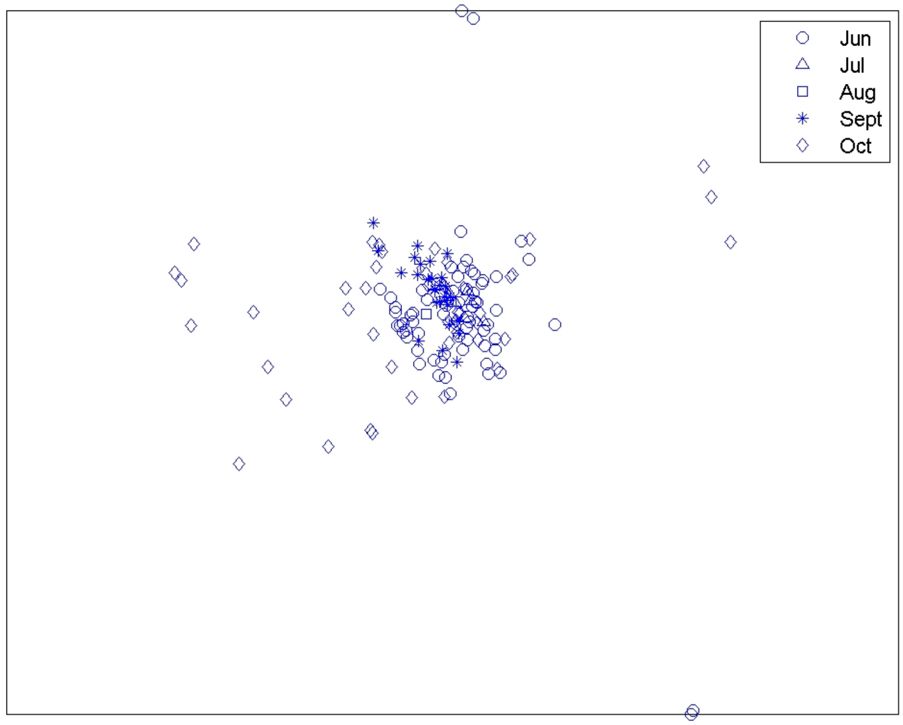

Figure 12 C. Non-metric multidimensional scaling ordination depicting relative similarity among all DIDSON sample transects. This is the same sample ordination as Fig 12 A and B, but samples are coded by month to show how seasonal differences correlated with total variation. This shows that October sampling accounted for much of the difference between sample structure in 2007 relative to 2008 and 2009 along the first (x) axis, and June sampling in June 2008 and 2009 for differences along the second (y axis), but even samples among these contained large fish (see Fig 10).

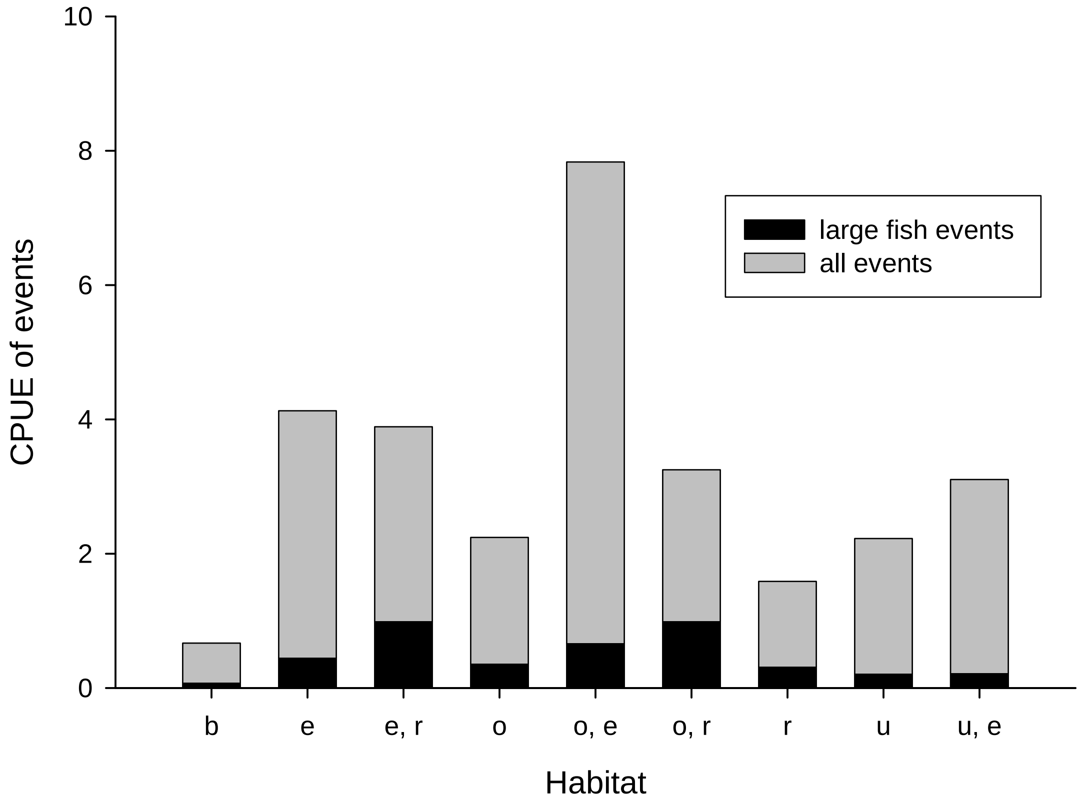

Figure 13. The CPUE (abundance expressed as catch-per-unit-effort) of large (>250 mm) fish events as well as all fish events within each designated habitat from 2007 to 2009. “b” denotes bulkhead, “e” denotes pier edge, “r” denotes relict pile fields, “o” denotes open water, and “u” denotes under-pier habitat. In some instances, these habitat types are treated together because DIDSON transects crossed habitat boundaries.

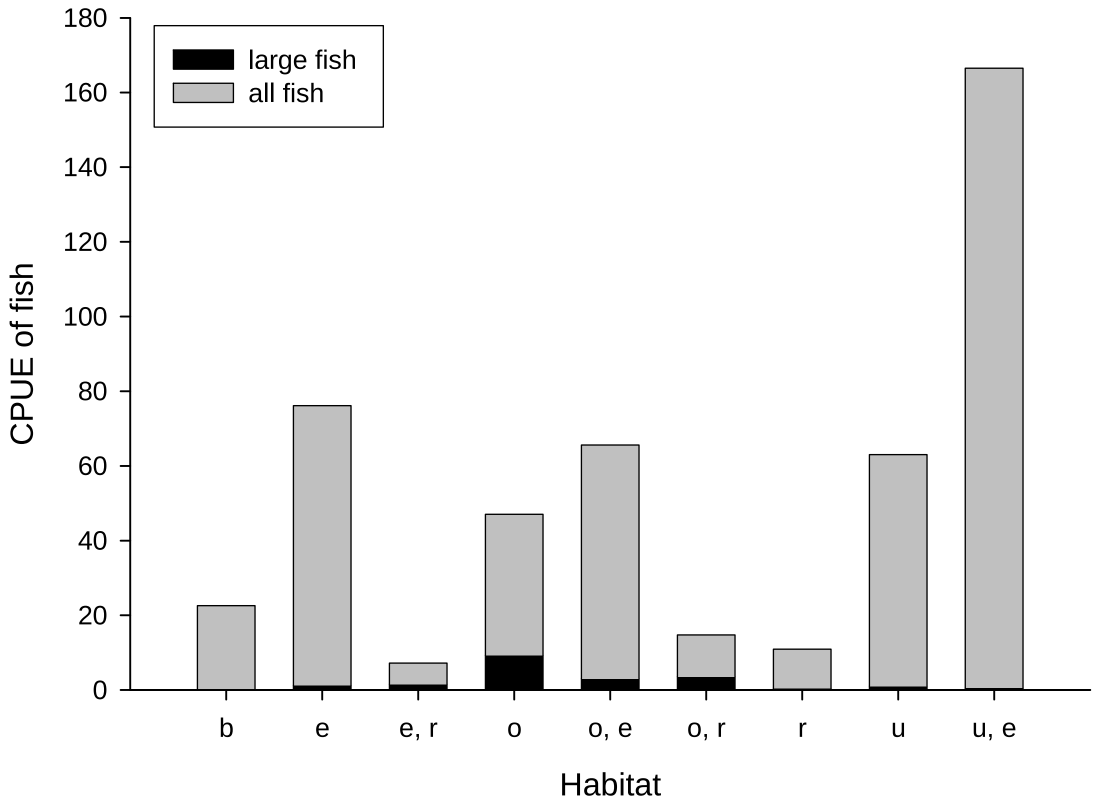

Figure 14. The CPUE (abundance expressed as catch-per-unit-effort) of the total number of large (>250 mm) fishes and all fishes within a designated habitat through 2007 to 2009. “b” denotes bulkhead, “e” denotes pier edge, “r” denotes relict pile fields, “o” denotes open water, and “u” denotes under-pier habitat. In some instances, these habitat types are treated together because DIDSON transects crossed habitat boundaries.

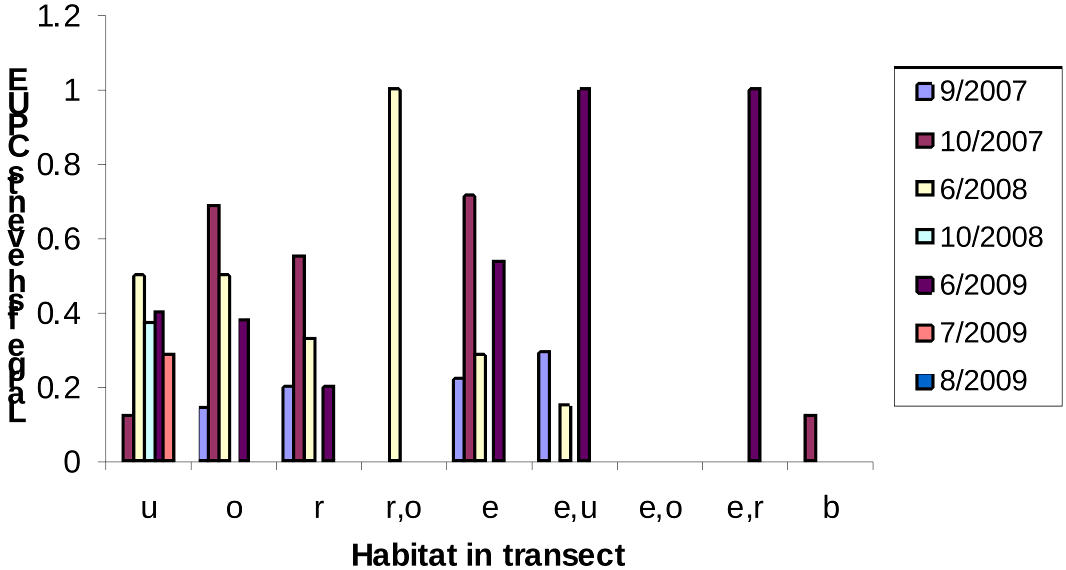

Figure 15. The seasonal distribution and abundance (CPUE, catch-per-unit-effort) (by date) of large (>250 mm) fish events in the Hudson River by designated habitat through 2007 to 2009. “b” denotes bulkhead, “e” denotes pier edge, “r” denotes relict pile fields, “o” denotes open water, and “u” denotes under-pier habitat. In some instances, these habitat types are treated together because DIDSON transects crossed habitat boundaries.

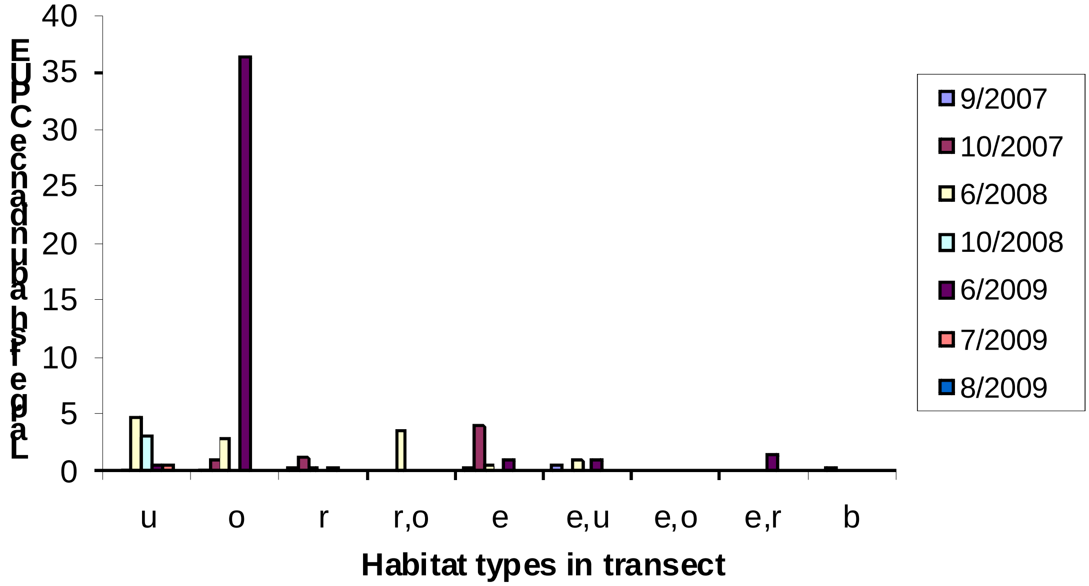

Figure 16. Seasonal abundance (CPUE, catch-per-unit-effort) of large (>250 mm) fish among habitat in the Hudson River from 2007 to 2009. "b" denotes bulkhead, "e" denotes pier edge, "r" denotes relict pile fields, "o" denotes open water, and "u" denotes under-pier habitat. In some instances, these habitat types are treated together because DIDSON transects crossed habitat boundaries.

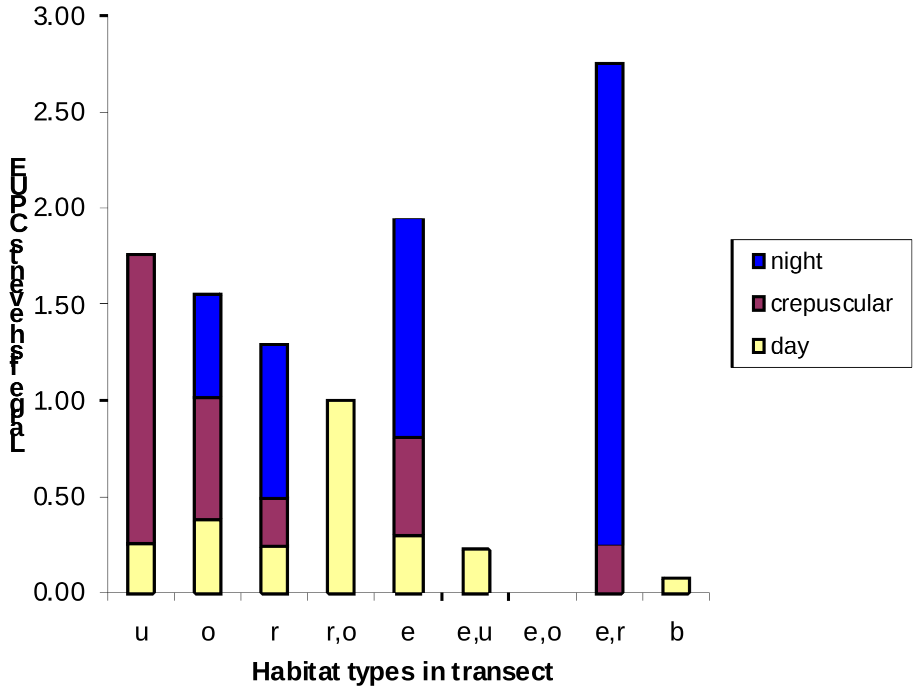

Figure 17. The diurnal distribution and abundance (CPUE, catch-per-unit-effort) of large (>250 mm) fish events by designated habitats through 2007 to 2009. “b” denotes bulkhead, “e” denotes pier edge, “r” denotes relict pile fields, “o” denotes open water, and “u” denotes under-pier habitat. In some instances, these habitat types are treated together because DIDSON transects crossed habitat boundaries.

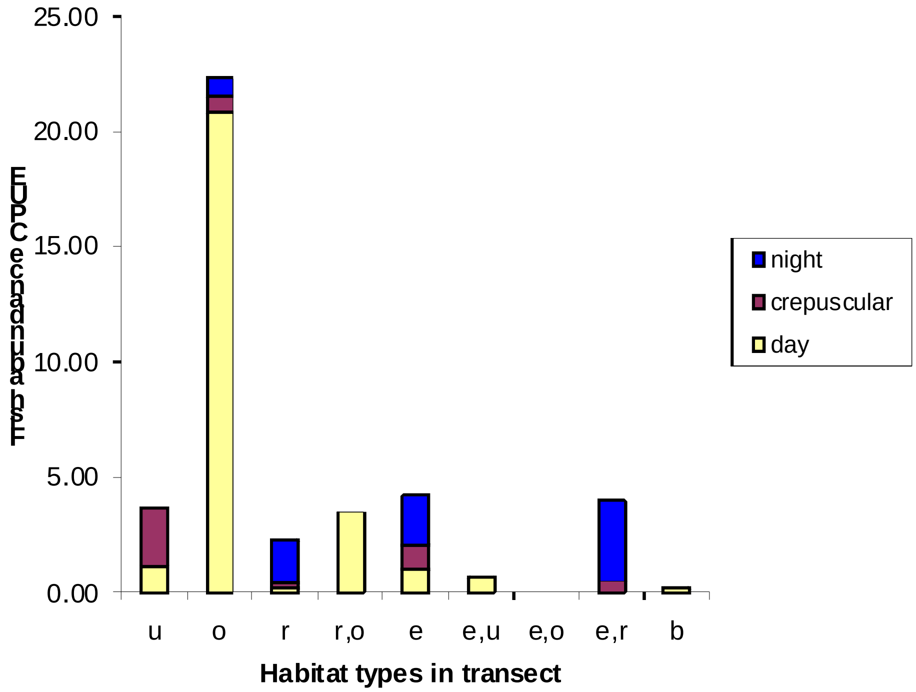

Figure 18. The diurnal distribution and abundance (CPUE, catch-per-unit-effort) of large (>250 mm) fish events by designated habitats in the Hudson River through 2007 to 2009. "b" denotes bulkhead, "e" denotes pier edge, "r" denotes relict pile fields, "o" denotes open water, and "u" denotes under-pier habitat. In some instances, these habitat types are treated together because DIDSON transects crossed habitat boundaries.

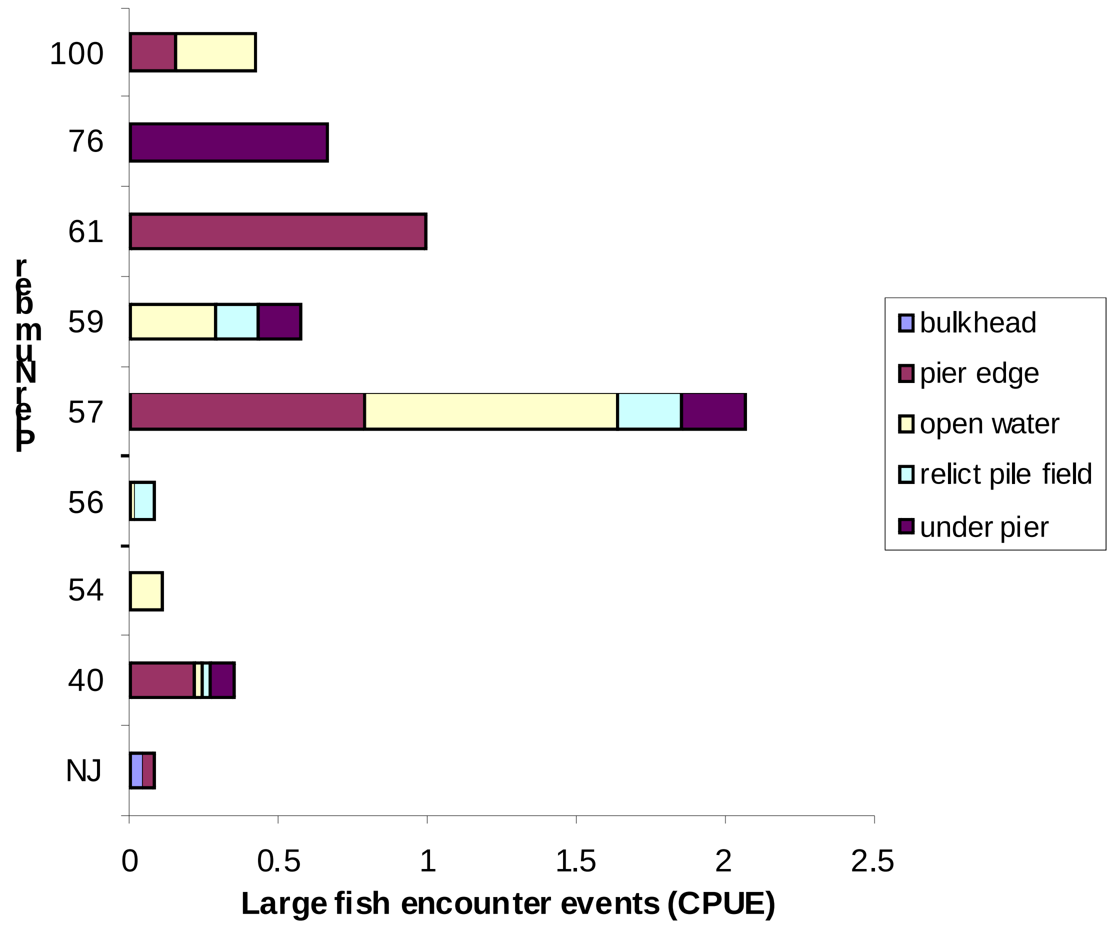

Figure 19. The distribution of large (>250 mm) fish encounter events in DIDSON transects among individual piers in the Hudson River, inclusive of adjacent open water and relict pile fields, from 2007 to 2009. See Fig. 1 for pier locations.

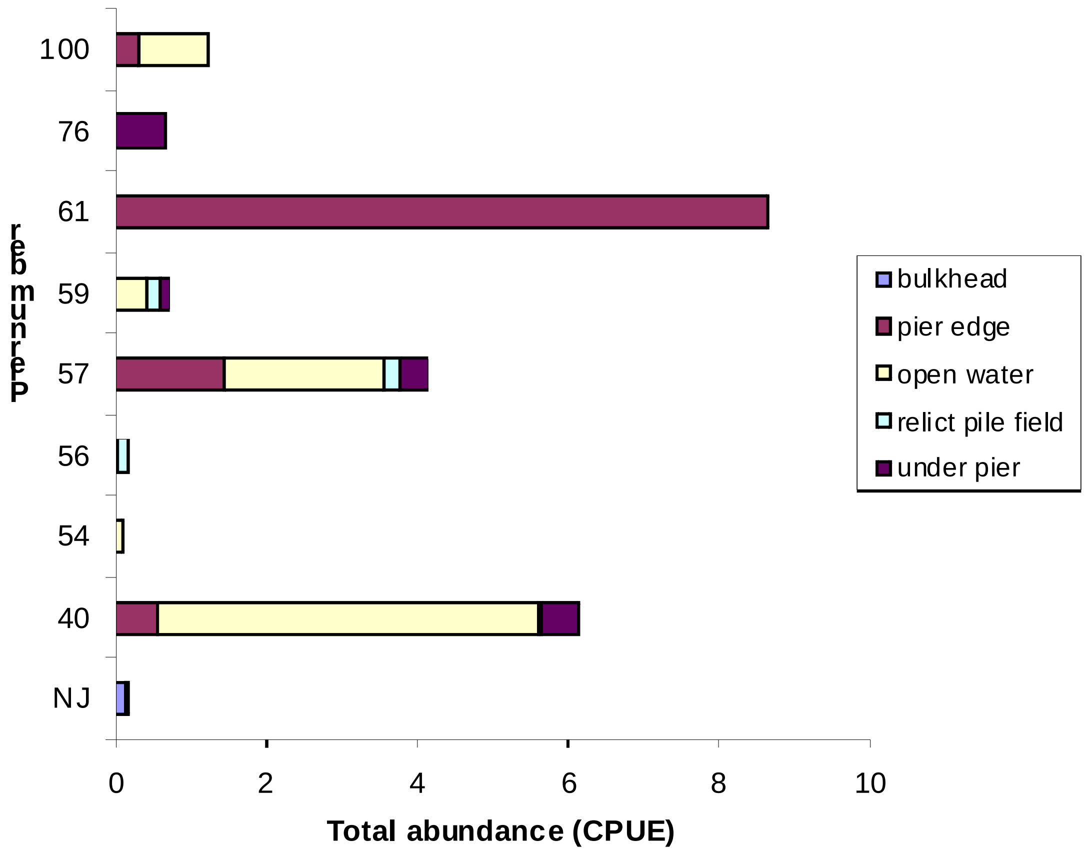

Figure 20. The distribution of large (>250 mm) fish abundance in DIDSON transects among individual piers in the Hudson River, inclusive of adjacent open water and relict pile fields, from 2007 to 2009.

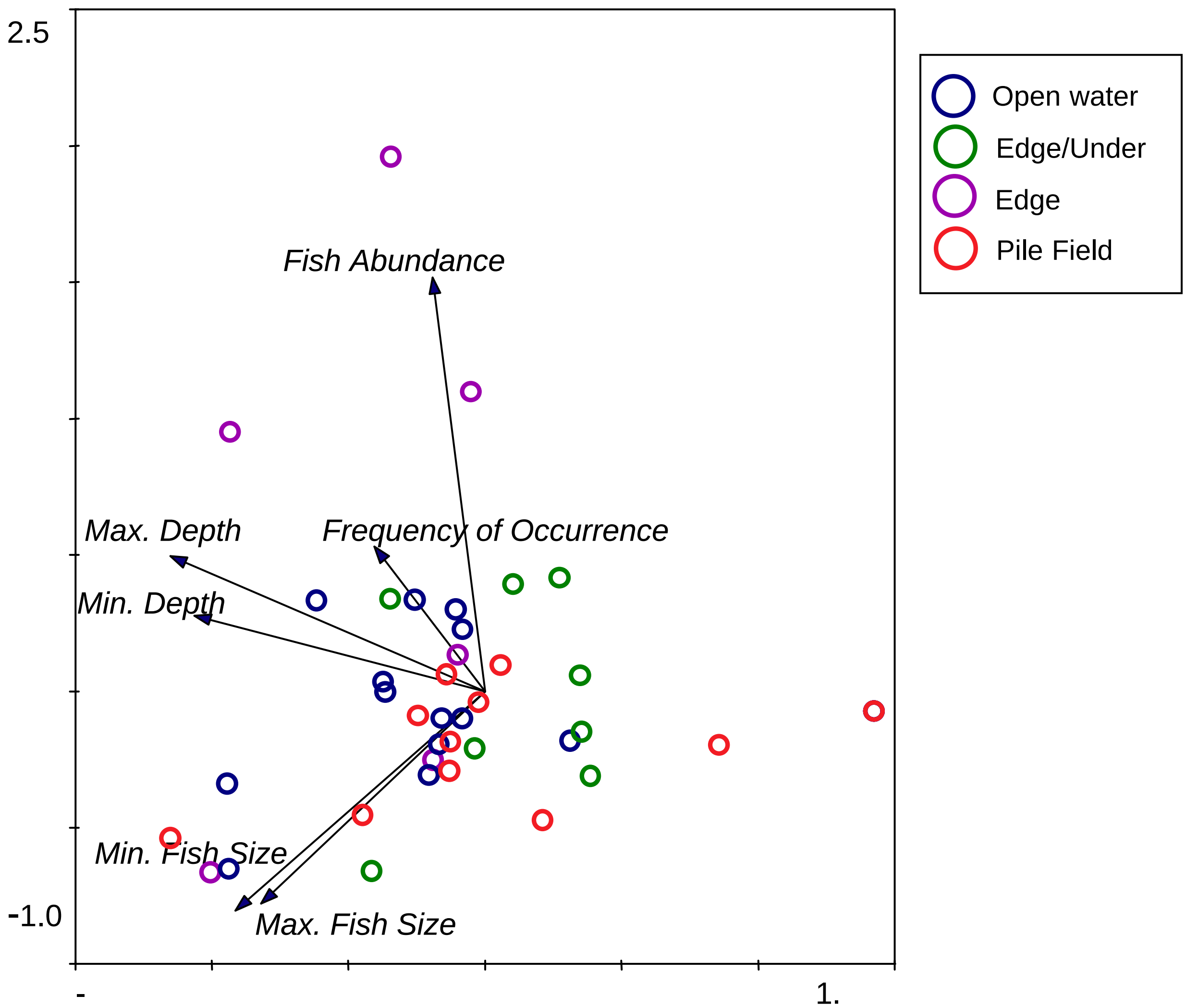

Figure 21. Principal components analysis ordination of all transects during intensive sampling of different habitats in the vicinity of Hudson River Pier 57 during 2007 and 2008. Axis 1 Eigenvalue = 0.43. Axis 2 Eigenvalue 2 =0.23. Inclusive of schooling small fish, "edge" transects encountered more and contained more fish, and "open water" transects contained both larger and smaller fish than "edge" or "edge/under" transects.