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Essential Fish Habitat for Nearshore Sentinel Species of Fishes and Crabs in Heavily Urbanized New York Harbor

Kenneth W. Able and Thomas M. Grothues



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Cover Photograph: A representative seine sampling site for an evaluation of sentinel fish and crab species in Upper New York Harbor. Photograph © Kenneth Able.

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Essential Fish Habitat for Nearshore Sentinel Species of Fishes and Crabs in Heavily Urbanized New York Harbor

Kenneth W. Able^{1,*} and Thomas M. Grothues¹

Abstract - Our objective was to evaluate nearshore fish and crab habitat use and quality in New York Harbor, a heavily urbanized area. We determined Essential Fish Habitat at several levels (abundance, reproduction, growth, survival, and habitat fidelity) for specific sentinel species of estuarine fishes (*Fundulus heteroclitus* [Mummichog], *Fundulus majalis* [Striped Killifish], *Menidia menidia* [Atlantic Silverside]) and *Callinectes sapidus* (Blue Crab). “Heavily altered” and “altered” shorelines at different sites typically had a steep slope and fabricated break on the upland side with very little or no vegetation; other “naturalized” shallow shorelines had gradually sloping mudflats or beaches with some intertidal and supratidal vegetation. Resident species (Mummichog, Striped Killifish) completed their life cycle along these shallow beaches and marsh shorelines, as evidenced by collections that included all size classes from newly hatched larvae to gravid adults. Mark–recapture efforts involving Mummichog demonstrated minimal dispersal, suggesting that all habitat needs were met in these limited shallow areas. The non-resident, but frequent users of these shorelines either migrated in to reproduce, grow, and survive (e.g., Atlantic Silverside) or grew from settlement from the plankton and survived to juveniles (e.g., Blue Crab). Given these findings, even small and potentially fractured restoration projects that seek to restore shallow, naturalized habitat with marsh features should be encouraged in this and other heavily urbanized estuaries.

Introduction

Estuaries, and the fishes and crabs that live there, have been subjected to numerous anthropogenic impacts (Rochette et al. 2010, Seitz et al. 2014, Whitfield and Elliott 2002). Shallow areas (Blaber et al. 2000, Islam and Tanaka 2004) of estuaries, in particular (Ruiz et al. 1993, Rypel et al. 2007, Vincent 2011), are habitats that function as Essential Fish Habitat (defined as those waters and substrate necessary for spawning, breeding, feeding, or growth to maturity [Baird 1999, Schmitten 1999]) for many species of economically and ecologically important fishes and their prey (Able and Fahay 2010, Levin and Stunz 2005). Essential Fish Habitat is typically applied to managed species, but has been applied to non-managed species as well (Able 1999, Able and Hagan 2003, Able et al. 2008) including some sentinel species (Weinstein et al. 2009). Its application has several levels of increasing complexity including presence/absence (Level 1), abundance/density (Level 2), reproduction, growth, and survival (Level 3), and production (Level 4) (Able 1999, Weinstein et al. 2009). Thus, evaluation of Essential Fish Habitat across an array of

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highly altered to naturalized shorelines will provide a baseline for managing shallow shorelines in urbanized estuaries.

Prior sampling efforts in the New York Harbor area (Festa 1975, Friedman and Hamilton 1980) and elsewhere in the region, suggest that 2 year-round residents (*Fundulus heteroclitus* (L.) [Mummichog] and *Fundulus majalis* (Walbaum) [Striped Killifish]), and a seasonal resident (*Menidia menidia* (L.) [Atlantic Silverside]) fish, as well as *Callinectes sapidus* M.J. Rathbun (Blue Crab), are among the most abundant and thus useful sentinel species (Able and Fahay 2010, Finley et al. 2009, Teather et al. 2012). Mummichog is among the most numerous fish along shallow, temperate estuarine systems of the US east coast. (Able and Fahay 2010). Further, the value of these natural habitats is evident because this resident species spawns, undergoes embryonic and larval development, feeds, and grows there. In addition, the secondary production due to Mummichog in natural estuarine habitats is among the highest measured for any fish species (Hagan et al. 2007, Meredith and Lotrich 1979, Teo and Able 2003a). Most of this production results from the high abundance and growth of the young-of-the-year; thus, they are of particular importance. All life-history stages are also critical to trophic pathways because they are important predators and prey (Able and Fahay 2010, Able et al. 2007, Griffin and Valiela 2001, Nemerson and Able 2003).

Striped Killifish is a common inhabitant of high salinity, sandy intertidal areas in natural, temperate estuaries from New Hampshire to Florida (Able and Fahay 2010). Adults of this species (Able and Fahay 1998) spawn on sandy intertidal areas and deposit eggs as deep as 7.6–10.2 cm within the sediment (Newman 1909, Sumner et al. 1913) on spring tides (Able and Fahay 1998). Larvae occur in intertidal sand-bottomed pools (Able and Fahay 1998). Individuals of this species are important as both predator and prey along sandy beaches (Able and Fahay 2010).

Another sentinel species, Atlantic Silverside, is among the most abundant forage fish species in US temperate estuaries during the spring through fall, after which individuals move offshore for the winter (Able and Fahay 2010, Griffin and Valiela 2001). The importance of this species as a food source for piscivores such as *Morone saxatilis* (Walbaum) (Striped Bass), *Cynoscion regalis* Bloch and Schneider (Weakfish), *Pomatomus saltatrix* (L.) (Bluefish), and other fishes is well documented (Able and Fahay 2010). Spawning of Atlantic Silverside occurs between April and July in the Mid-Atlantic (Middaugh et al. 1981) in the intertidal zone, where fish lay demersal, adhesive eggs at high tide (Middaugh 1981). The eggs are laid ~1.2–2.4 m above mean low water to reduce exposure to aquatic predators (Middaugh et al. 1981, Tewksbury and Conover 1987). Filamentous algae are the preferred attachment substrate even in the presence of many other substrates (Conover and Kynard 1984) such as rip-rap and bulkheads (Balouskus and Targett 2012).

Blue Crab is both abundant and widely distributed in the Hudson River estuary and New York Harbor (Wilson and Able 1992). The recently hatched larvae are carried away from estuaries onto the continental shelf (Epifanio and Garvine 2001) where they continue to develop until they recruit back to the estuary as megalopae and then settle to the bottom as small juveniles. The juveniles typically occupy a

number of habitats along the estuarine salinity gradient where they feed and grow through several molt stages until they attain adulthood and mate (Rakocinski and McCall 2005 and literature cited therein).

Materials and Methods

Habitat characterization

We selected our study sites in Upper New York Harbor based on the availability of accessible shorelines between Liberty State Park Marsh Cove and the Arthur Kill (Table 1, Fig. 1). This portion of Upper New York Harbor has been heavily altered over time by human activities (Fig. 2). The degree of alteration varied between sites as a function of their differing history of commercial or recreational use, maintenance or neglect, intentional restoration efforts, and exposure resulting from differences in shape and bathymetry. All, however, were in close proximity to each other in southeast-facing embayments. We examined these sites by land and boat during several reconnaissance trips in 2013 to determine final site selection and begin site characterization and sampling for the 8 sites examined in detail. We classified these locations as heavily altered (i.e., steeply sloping shoreline of construction rubble or boulders with no marsh, marsh pools, culverts/creek, or beach), altered (i.e., shallower, sloping shoreline of varying amounts of rubble with small amounts of marsh, no marsh pools, and varying amounts of culverts/creeks), and naturalized (i.e., shared some characteristics of natural marsh such as fringing marsh, marsh pools, creeks, and beaches) (Table 1).

We determined the details of each site using a variety of approaches. Shoreline slope data was measured along transects using a Leica Viva CS15 unit on 15 December 2014. The length of transects varied between sites because of site-specific variation in shoreline width. The number of transects increased with the diversity and span of shoreline types at each site. Two transects were taken at Coast Guard Embayment–North, Coast Guard Embayment–South, SIMS Recycling Embayment, and Liberty State Park Marsh Cove; 4 transects were completed at Bayonne Golf Club, Alexan CityView, and Army Corps of Engineers Embayment; and 3 transects were established at Embayment North of Global Marine. We recorded elevation whenever a change in slope was present along transects perpendicular to the beach. The number of such measurements varied from 13 total points at SIMS Recycling Embayment to 81 total at Alexan CityView. We calculated the slope for each transect along with the within-site mean slope and standard deviation.

We collected sediment samples at each site on 23 and 24 October 2014, at locations where the sediment was exposed, to further characterize each site. We did not include SIMS Recycling Embayment, the heavily altered site, in sediment sampling because of the steeply sloping large boulders with little interstitial sediments. Number and location of each sample varied somewhat among these sites. We used a 6.3-cm diameter core to collect samples, each 4 cm deep. For each sample, we dried 100 grams of each core in an oven at 53 °C, recorded the mass again, and then sorted each sample using a sediment shaker to determine the composition and sorting following Folk (1954). We used sieve sizes of 2 mm to 0.0625 mm and weighed sorted grain-

Table 1. Characteristics of sampling sites in Upper New York Harbor in New Jersey during 2013 and 2014. + indicates presence, 0 indicates absence. See Figure 1 for locations. The degree of alteration (1 = heavily altered, 2 = altered, 3 = naturalized) are described in more detail in Materials and Methods.

Embayment location/site	Embayment width at head (m)				Habitats			Shoreline type	
	Marsh	Marsh pools	Culvert/ creek	Beach	Marsh	Culvert/ creek	Beach	Intertidal	Supratidal
Liberty State Park Cove	80	+	+	+	+	+	+	Narrow rip-rap and fringing <i>Spartina alterniflora</i>	<i>Iva frutescens</i> , <i>Baccharis halimifolia</i>
Army Corps of Engineers Embayment	360	+	+	+	+	+	+	Broad with <i>S. alterniflora</i> , <i>Phragmites</i> , <i>I. frutescens</i> , <i>B. halimifolia</i> , <i>I. frutescens</i> and pools in marsh peat	<i>P. australis</i>
SIMS Recycling Embayment	49	0	0	0	0	0	0	Very narrow, steep with rubble boulders, no vegetation	Rubble boulders, no vegetation
Embayment North of Global Marine	118	+	+	+	+	+	+	Broad, sandy beach with some <i>S. alterniflora</i> , pool, some rip-rap	Bulkhead
Coast Guard Embayment (North)	400	0	+	+	+	+	+	Broad, sandy beach with some <i>S. alterniflora</i>	<i>P. australis</i> , <i>I. frutescens</i> , <i>B. halimifolia</i>
Coast Guard Embayment (South)	400	0	0	0	+	+	+	Steep beach with rubble, small patches of <i>S. alterniflora</i>	<i>P. australis</i> , <i>I. frutescens</i> , <i>B. halimifolia</i>
Alexan CityView	240	0	+	+	+	+	+	Broad, beach with rip-rap and <i>S. alterniflora</i> , <i>I. frutescens</i>	Bulkhead
Bayonne Golf Club	240	0	0	0	+	+	+	Rubble with <i>S. alterniflora</i>	Golf course



Figure 1. Study sites (closed circles) in New Jersey along the Upper New York Harbor. See Table 1 for description of shoreline characteristics.

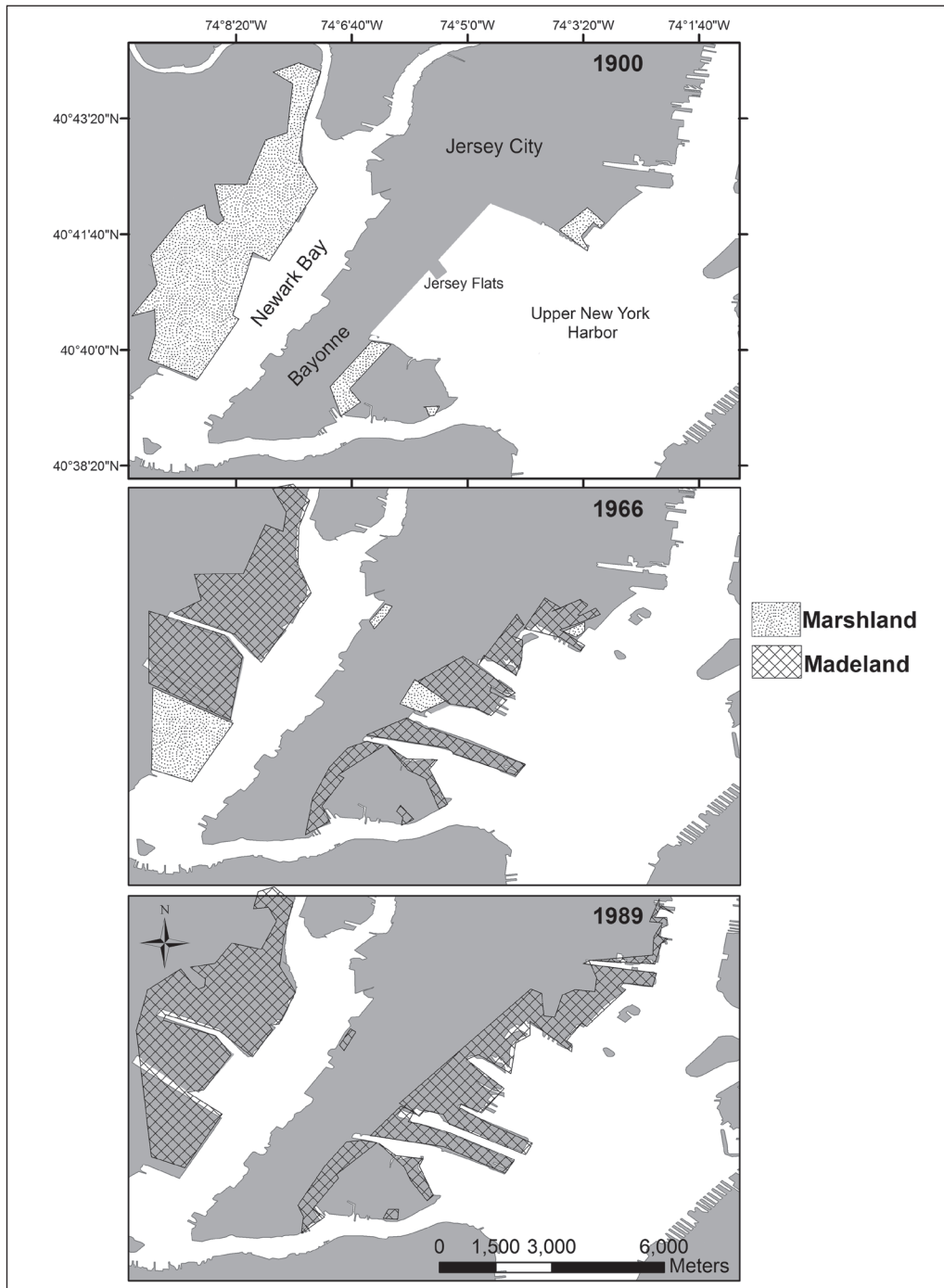


Figure 2. Diagrammatic representation of two major habitat types over time (1900–1989) in Upper New York Harbor shorelines (after Squires 1992). “Marshland” indicate areas of emergent aquatic vegetation. “Madeland” indicate areas where marshlands and shallow shorelines were filled with spoil disposal, railroad construction, industrial development, and other sources as the result of human activity.

size fractions to determine the percentage of sediment grain size components following Wentworth (1922). Analysis of sorting was performed in the script SANDY_C v.1.75 (Ruiz-Martinez et al. 2016) running in the MATLAB environment.

We sampled above-ground salt marsh vegetation, where it occurred, in September at the peak of the growing season. At each sample position at each site, we clipped all vegetation within 2 replicate 0.25-m quadrats, counted the live and dead plant stems, measured the length of live stems, and dried all stems to a constant weight (at 60 °C) prior to recording their mass.

We used a handheld YSI Professional Plus (Yellow Springs Instruments, Yellow Springs OH) to collect water quality data (temperature, salinity, dissolved oxygen, pH) on 12 occasions from a total of 16 sampling dates between 28 August 2013 and 14 July 2015. Salinity values were calculated from conductivity at temperature and are unitless following UNESCO (1981).

Fish and crab distribution by habitat

Reconnaissance sampling began in fall 2013. We conducted regular seine sampling to characterize the target fishes and crabs at each site from spring 2014 to summer 2015 (Table 2). Sampling events at each site were influenced by local topography. Additionally, we conducted irregular sampling with dip nets where shallow marsh pools and depressions occurred at Liberty State Park Marsh Cove, Army Corps of Engineers Embayment, and the Embayment North of Global Marine. SIMS Recycling Embayment site was not sampled by seine because this heavily altered site consists of a steeply sloping shoreline of large boulders.

Mummichog tag and recapture

We used tag–recapture to determine residency and the possibility of dispersal among and within sites for Mummichog, whose populations at the study sites are intermediate forms between a northern and southern subspecies (Able and Felley 1986, Bell et al. 2014, Mogue and Weis 1995). Tag–recapture addressed the extent of ranging among sites (space covered to meet demands of life including foraging, refuge, and reproduction, all metrics of habitat quality).

The tagged (Alexan CityView = 36–101 mm, Army Corps of Engineers Embayment = 36–100 mm) and recaptured fish at both of the study sites were representative in size for large juveniles and adults of Mummichog. At Alexan CityView, we tagged 396 Mummichog on 17 September 2013 and an additional 76 on 1 July of the following year, after first checking for any that had been tagged previously. At the Army Corps of Engineers Embayment, we tagged 319 Mummichog in September 2013 and another 401 on 2 June 2014, again first checking for and removing previously tagged individuals.

We used coded wire tags (1.1 mm long x 0.28 mm diameter; Northwest Marine Technology, Inc., Shaw Island, WA) to mark individuals >36 mm TL from both gears. We tagged fish on the left side of the dorsal musculature with a handheld coded wire tag injector (Northwest Marine Technology, Inc.) or an MKIV tag injector (Northwest Marine Technology Inc.). Subsequently, tagged fish were then checked for tag retention using a magnetic detector specific to the purpose (Wand Detector,

Northwest Marine Technology Inc.), hereafter simply referred to as the “wand” (Teo and Able 2003). After all the fish were tagged and measured (total length), we released them in the same location in which they were caught. During the first tagging session, coded wire tags were erroneously batch marked. Thus, they could be identified to date but not individual. The error was discovered and rectified with

Table 2. Overall rank based on total abundance by site and month of sentinel fish species and Blue Crabs in Upper New York Harbor seine sampling pooled across all dates during June, July, September, and October 2014 and July 2015. Dashes indicate no seine samples occurred.

Site	Year	Month	Atlantic Silverside	Mummichog	Striped Killifish	Blue Crab
Liberty State Park Marsh Cove	2014	Jun	-	5	-	3
		Jul	805	210	128	32
		Sep	1798	1	1	17
		Oct	28	21	18	6
	2015	Jul	1142	5671	2445	-
Army Corps of Engineers Embayment	2014	Jun	-	95	6	9
		Jul	1403	329	187	86
		Sep	268	-	28	8
		Oct	121	154	119	11
	2015	Jul	806	1	2	-
SIMS Recycling Embayment			-	-	-	-
Embayment North of Global Marine	2014	Jun	-	36	-	24
		Jul	40	236	287	26
		Sep	310	612	103	8
		Oct	24	188	132	86
	2015	Jul	406	116	358	-
Coast Guard Embayment (North)	2014	Jun	2	-	94	6
		Jul	1170	28	97	68
		Sep	225	-	30	1
		Oct	559	15	106	8
	2015	Jul	1465	100	69	-
Coast Guard Embayment (South)	2014	Jun	-	-	-	27
		Jul	54	15	3	34
		Sep	31	169	-	17
		Oct	7	124	-	66
	2015	Jul	216	315	-	-
Alexan CityView	2014	Jun	-	1	-	44
		Jul	4285	1972	916	105
		Sep	448	348	65	52
		Oct	51	291	122	11
	2015	Jul	2119	817	453	-
Bayonne Golf Club	2014	Oct	916	5	23	-
	2015	Jul	36	3	6	-
Overall number			18,735	11,878	5798	755
Overall rank			1	2	3	6

individually marked tags for subsequent events. Calculation of recaptures did not include fish that were too small to have been previously tagged.

Tagging and recapture with seines (15.2 m, 4.8-mm mesh) and wire mesh traps (41 cm long by 22 cm diameter, 6-mm mesh) were focused at 2 different sites (Alexan CityView, Army Corps of Engineers Embayment) near Bayonne, between the Arthur Kill and Jersey City, NJ, but we attempted recaptures at all 8 regularly sampled sites (Table 1, Fig. 1). Recapture sampling took place at Army Corps of Engineers Embayment and Alexan CityView on 24 October 2013, 2 June 2014, 1 July 2014, 22 July 2014, 2 September 2014, 23 October 2014, and 13 July 2015. We kept the fish from both seine and traps separated by location. Buckets of fish were batch sampled with the wand and divided into aliquots if any tags were detected; we then repeated the procedure with further aliquot reduction until all tagged fish were isolated. We measured and recorded all of the tagged fish as well as a random subset of 20 untagged fish. After all the samples were processed, all the untagged fish were released in their capture location.

Reproduction, growth, and survival

Evidence for successful reproduction at each study site was based on the occurrence of young-of-the-year (YOY) of the 3 sentinel fish species (Mummichog ≤ 40 mm TL, Striped Killifish ≤ 50 mm TL, Atlantic Silverside ≤ 70 mm TL; Able and Fahay 2010) in seine, trap, and dip-net samples, all with meshes small enough to capture YOY. This interpretation is based on composite length-frequencies across all sites. Evidence for successful post-settlement recruitment of Blue Crab was based on their occurrence in seine samples.

We based estimates of growth and size attained at the end of the year for fishes and Blue Crabs on analysis in modal length frequencies (after Able and Fahay 2010) from seine collection at each site. Survival, on a sampling site specific basis, was implied based on continued occurrence and growth of young-of-the-year fishes and Blue Crabs during the spring through fall, and on the recapture of marked fish.

Results

Habitat characterization

The study sites in Upper New York Harbor were all impacted by human activity. We characterized them as heavily altered (SIMS Recycling Embayment), altered (Coast Guard Embayment [North and South]), and naturalized (Bayonne Golf Club, Alexan CityView, Embayment North of Global Marine, Army Corps of Engineers Embayment, and Liberty State Park Marsh Cove) (Table 1). These indices are somewhat arbitrary because the shoreline varied even within the same site. Thus, we quantitatively describe each site individually in this section. The heavily altered shoreline of New York Harbor, such as at SIMS Recycling Embayment (mean among-transect slope $b = 0.57 \pm 0.028$), was steeply sloped. Other steep shorelines were most evident at Coast Guard Embayment–South ($b = 0.16 \pm 0.018$), Bayonne Golf Club ($b = 0.12 \pm 0.057$), Alexan CityView ($b = 0.08 \pm 0.026$), Embayment North of Global Marine ($b = 0.06 \pm 0.028$), and Coast Guard Embayment–North

($b = 0.05 \pm 0.019$). The least sloping shoreline in New York Harbor was at Liberty State Park Marsh Cove, which had much less slope ($b = 0.02 \pm 0.003$) and a flat, fringing marsh.

Some of the sites had construction rubble or boulders exposed along the shoreline and were impossible to core. Where sediment samples could be taken, they were dominated by medium sand and were “very well sorted” with some differences in skew and kurtosis (Fig. 3). In particular, the coarser sediments were poorly represented at Bayonne Golf Club, but better represented at Coast Guard Embayment–North than at other sites. At SIMS Recycling Embayment, gravel and sand could be seen between the boulders, but could not be sampled.

The dominant intertidal vegetation at all sites, except the SIMS Recycling Embayment, which had no intertidal vegetation, was *Spartina alterniflora* Loisel (Smooth Cordgrass; 67.1–100% of quadrats sampled; Table 1). At sites where this intertidal species did occur, the growth was robust, with 22–144 live stems, biomass of 132–604 g, and stem height of 7–118 cm per 0.25 m² quadrat. Other, species that were less abundant included *Spartina patens* (Aiton) Muhl (Saltmeadow Cordgrass), *Phragmites australis* (Cav.) Trin. Ex Steud. (Common Reed), and *Salicornia* spp. (saltworts). Supratidal vegetation included *Baccharis halimifolia* L. (Eastern Baccharis), *Iva frutescens* L. (Jesuit’s Bark), and *Schoenoplectus pungens* (Vahl) Palla (Common Threesquare).

The range of salinity, dissolved oxygen, and pH were relatively similar across all sites. During regular sampling, salinity varied from 16 to 25 with a mean \pm standard deviation of 20.5 ± 2.9 . Daytime dissolved oxygen rarely fell below stress

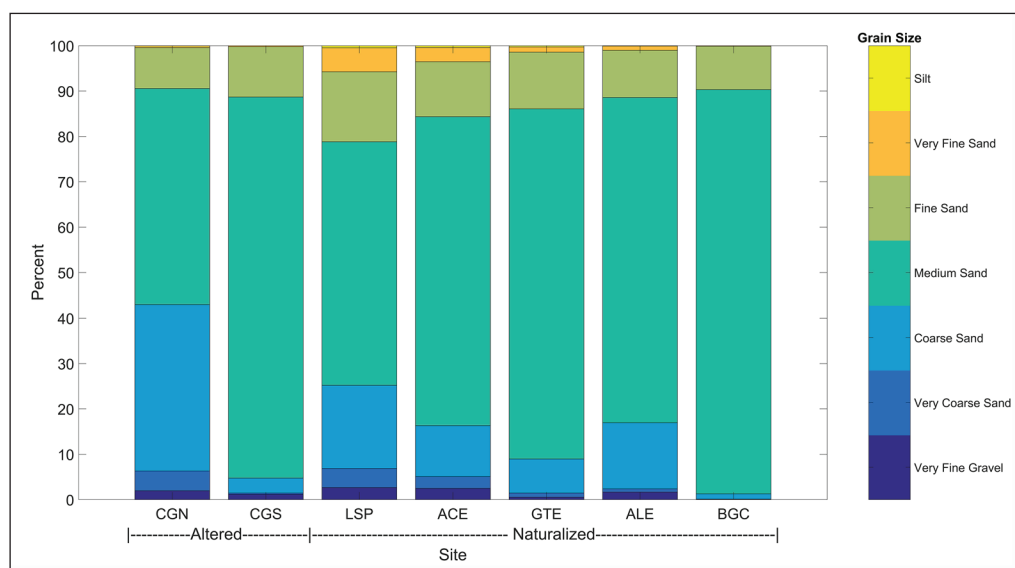


Figure 3. Sediment grain size distribution among sample sites in New Jersey along the Upper New York Harbor at CGN (Coast Guard Embayment–North), CGS (Coast Guard Embayment–South), LSP (Liberty State Park Marsh Cove), ACE (Army Corps of Engineers Embayment), GTE (Embayment North of Global Marine), ALE (Alexan CityView), and BGC (Bayonne Golf Club).

levels and was often near or well above saturation, generally 4.45–16.0 mg/L and averaging 8.2 ± 2.6 mg/L across all sites for all times, but with a single standout minimum value of 3.2 mg/L at SIMS Recycling Embayment on 22 July 2014. pH was variable across most sites with a mean of 7.8 ± 0.35 , but varied from 7.0 to 8.8. The highest and lowest values occurred at Liberty State Park Marsh Cove. Temperatures were far more variable across sites due to the seasonal insolation cycle, with a mean of 22.0 ± 4.6 °C, a minimum of 11.8 °C in October 2013, and a maximum of 28.7 °C in July 2014.

Fish and crab distribution and abundance

Atlantic Silverside, Mummichog, and Striped Killifish had similar overall ranking in abundance in composite samples, representing over 36,000 individuals, across all New York Harbor seine sampling sites (Table 2). The overall abundance of Atlantic Silverside was greatest, followed by Mummichog with a similar order of magnitude. Striped Killifish was one order of magnitude lower in abundance. Blue Crab abundance was another order of magnitude less.

The species-specific abundance, when expressed as catch per unit effort (CPUE), varied between and within alteration types based on seine collections during

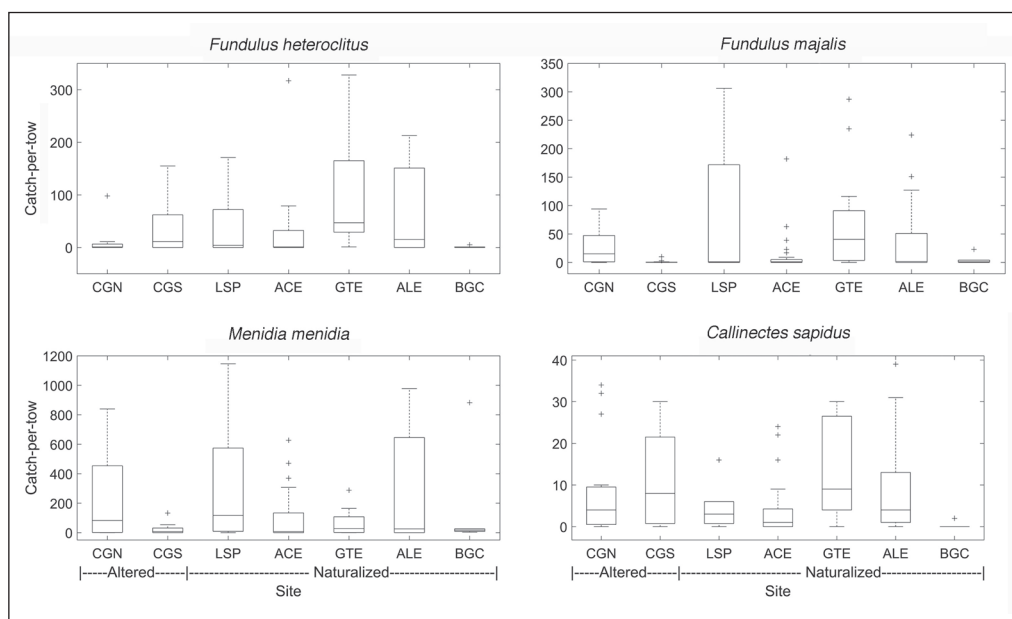


Figure 4. Abundance of sentinel species collected with a seine and pooled across all sampling dates at LSP (Liberty State Park Marsh Cove), ACE (Army Corps of Engineers Embayment), GTE (Embayment North of Global Marine), CGN (Coast Guard Embayment–North), CGS (Coast Guard Embayment–South), ALE (Alexan CityView), and BGC (Bayonne Golf Club) during 2013–2015. The SIMS Recycling Embayment (a heavily altered site) was not included because seine samples were not possible. Several outlier points were left off of the figures to make overall spatial patterns more easily visible (*Fundulus heteroclitus*: 717/tow at ACE and 2576 and 3095/tow at LSP; *Fundulus majalis*: 765 /tow at ALE, 1040 and 1099/tow at LSP; *Menidia menidia*: 1911/tow at ACE).

2013–2015 (Fig. 4). Mummichog was most abundant at some of the naturalized sites (Alexan CityView, Embayment North of Global Marine, Liberty State Park Marsh Cove) and 1 altered site (Coast Guard Embayment–South), whereas some of the lowest values for that species occurred at 2 naturalized sites (Army Corps of Engineers Embayment, Bayonne Golf Club). Striped Killifish were most abundant at a naturalized site (Embayment North of Global Marine) and an altered site (Coast Guard Embayment–North), but both types of sites had low values as well. Atlantic Silverside were most abundant at naturalized sites (Liberty State Park Marsh Cove, Alexan CityView) and an altered site (Coast Guard Embayment–North), but again both types of sites also had low values. Blue Crab were most abundant at naturalized sites (Embayment North of Global Marine, Alexan CityView) and at altered sites (Coast Guard Embayment–North and Coast Guard Embayment–South).

Reproduction

Many aspects of the early life history of the sentinel species were consistent across sites based on composite length-frequencies for each of the 4 species (Figs. 5, 6, 7, 8). Maturing adults (~40 – 80 mm TL) of Mummichog were evident in September and October 2013, June and July 2014, and July 2015 (Fig. 5). Their larvae and small juveniles (<20 mm) were detected in dip-net collections from shallow marsh pools or depressions in July 2014 where they occurred at naturalized sites (Alexan CityView, Embayment North of Global Marine, Army Corps of Engineers Embayment, and Liberty State Park Marsh Cove) and an altered site (Coast Guard Embayment–North). The larger (at ~10–40 mm TL) YOY were also evident in seine collections in July 2014 and 2015, as well as age 1+ individuals (at >60–100 mm TL) in July 2014 and 2015. By September and October 2014, the length frequencies were dominated by YOY at sizes of ~20–60 mm TL and ~30–70 mm TL, respectively. The size of YOY individuals in October 2014 was similar to that from October 2013.

Adult-sized Striped Killifish (most >40–100 mm TL) were collected in fall of 2013 and in all collections during 2014, as well as July 2015 (80–120 mm TL) (Fig. 6). Based on the occurrence of YOY (10–60 mm TL) in July 2014 and 2015, it appears this species was reproducing at many of the embayments during 2013–2014 (Fig. 6). The lack of representative collections in other months at several sites (Coast Guard Embayment–South, Embayment North of Global Marine, Liberty State Park Marsh Cove) may be the result of reduced vulnerability to the sampling gear due to burial in the substrate. The YOY were evident in July 2014 and 2015 (at ~15–45 mm TL) as well as a few adults at ~75–100 mm TL. By September and October 2014, the length-frequencies were dominated by YOY and presumed 1+ age adults over the combined size range of 45–100 mm TL. The size of individuals in September and October of 2014 overlap in size with those from the same months in 2013 from Alexan CityView and Army Corps of Engineers Embayment.

Maturing adult Atlantic Silverside (~50–100 mm TL) were abundant in fall 2013, but few were found in June 2014 (Fig. 7). YOY were caught in July 2014 and 2015 (at ~30–60 mm TL) with perhaps some age 1+ individuals (>60 mm TL) also present at most sites. By September and October of 2013 and 2014, the length-

frequencies were dominated by presumed YOY at 40–100 mm TL. These sizes are similar to those from September and October in 2013.

For Blue Crab, the recruitment of small YOY (<15 mm) occurred in September of 2013 and June, September, and October of 2014 (Fig. 8). These smaller

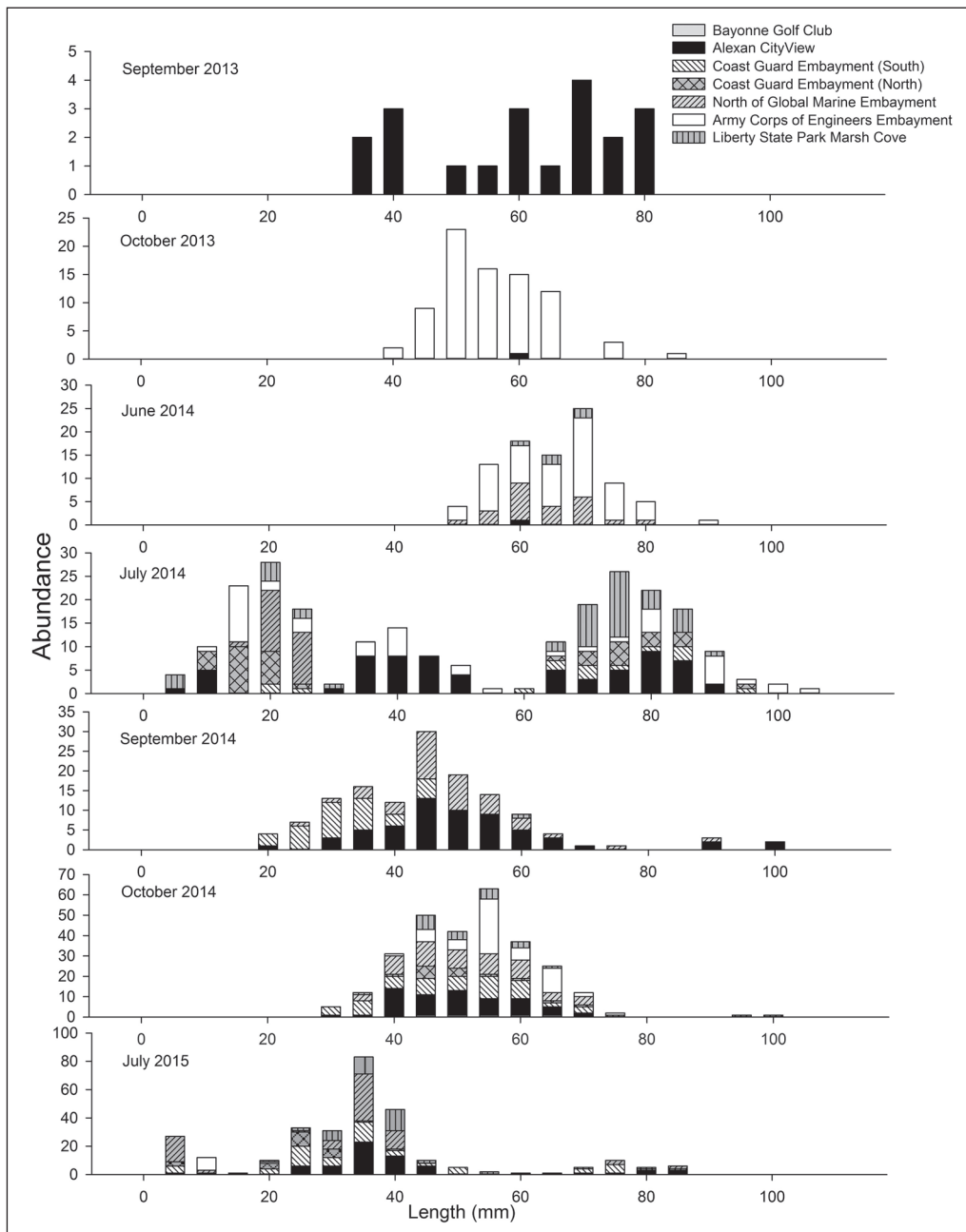


Figure 5. Composite monthly length frequencies of *Fundulus heteroclitus* (Mummichog) from seine and dip-net samples across all study sites during 2013–2015. Note differences in y-axis scales.

individuals were evident at most naturalized sites but not at the altered sites (Bayonne Golf Club [infrequently sampled] and Coast Guard Embayment–North) and the heavily altered site (SIMS Recycling Embayment).

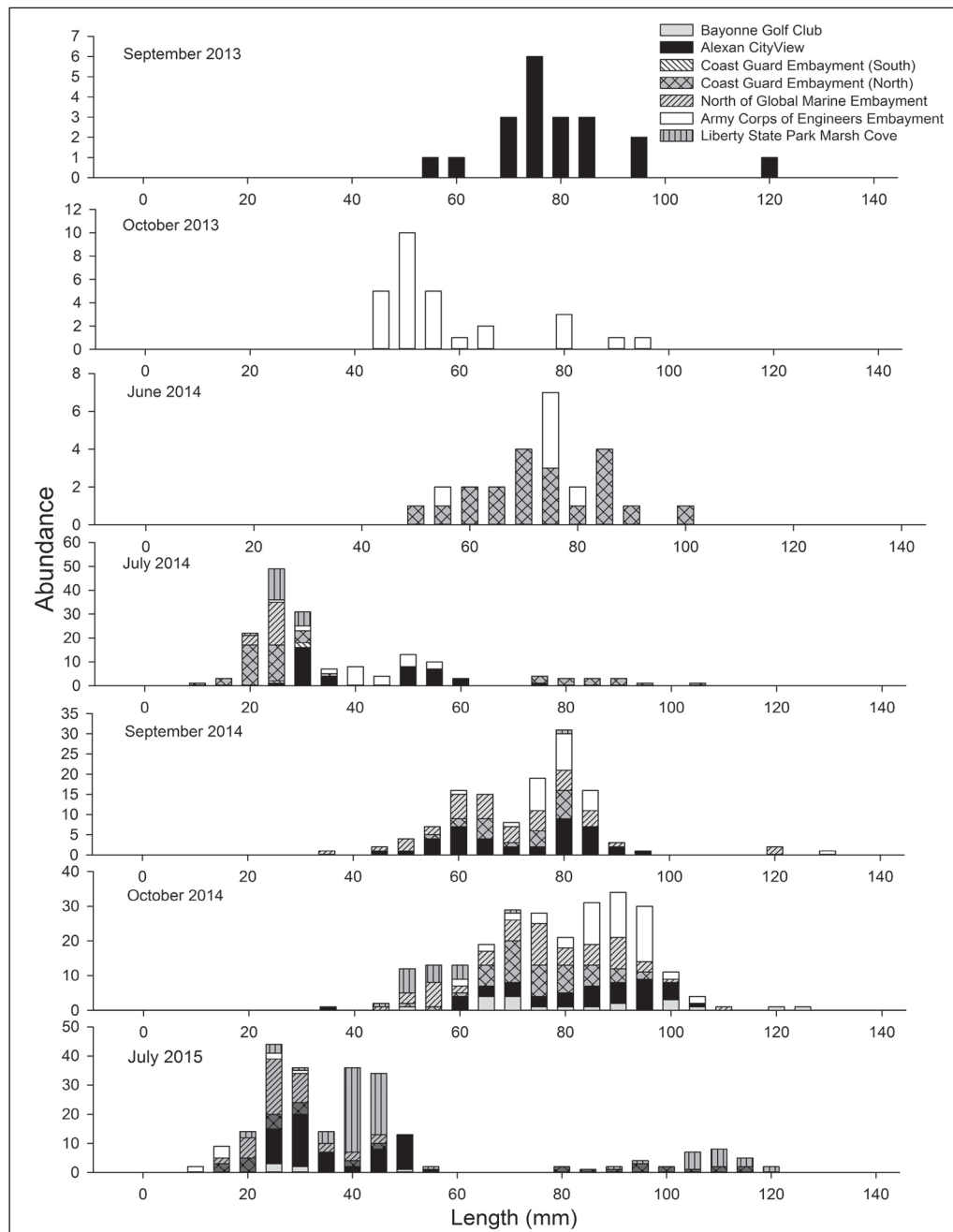


Figure 6. Composite monthly length frequencies of *Fundulus majalis* (Striped Killifish) from seine and dip-net samples across all study sites during 2013–2015. Note differences in y-axis scales.

Growth and survival

Estimates of growth, based on modal length-frequency progression, suggested that it was similar across most sites and across years for each species as indicated by the shared sizes in the above treatment (Figs. 5, 6, 7, 8). In addition, survival of all

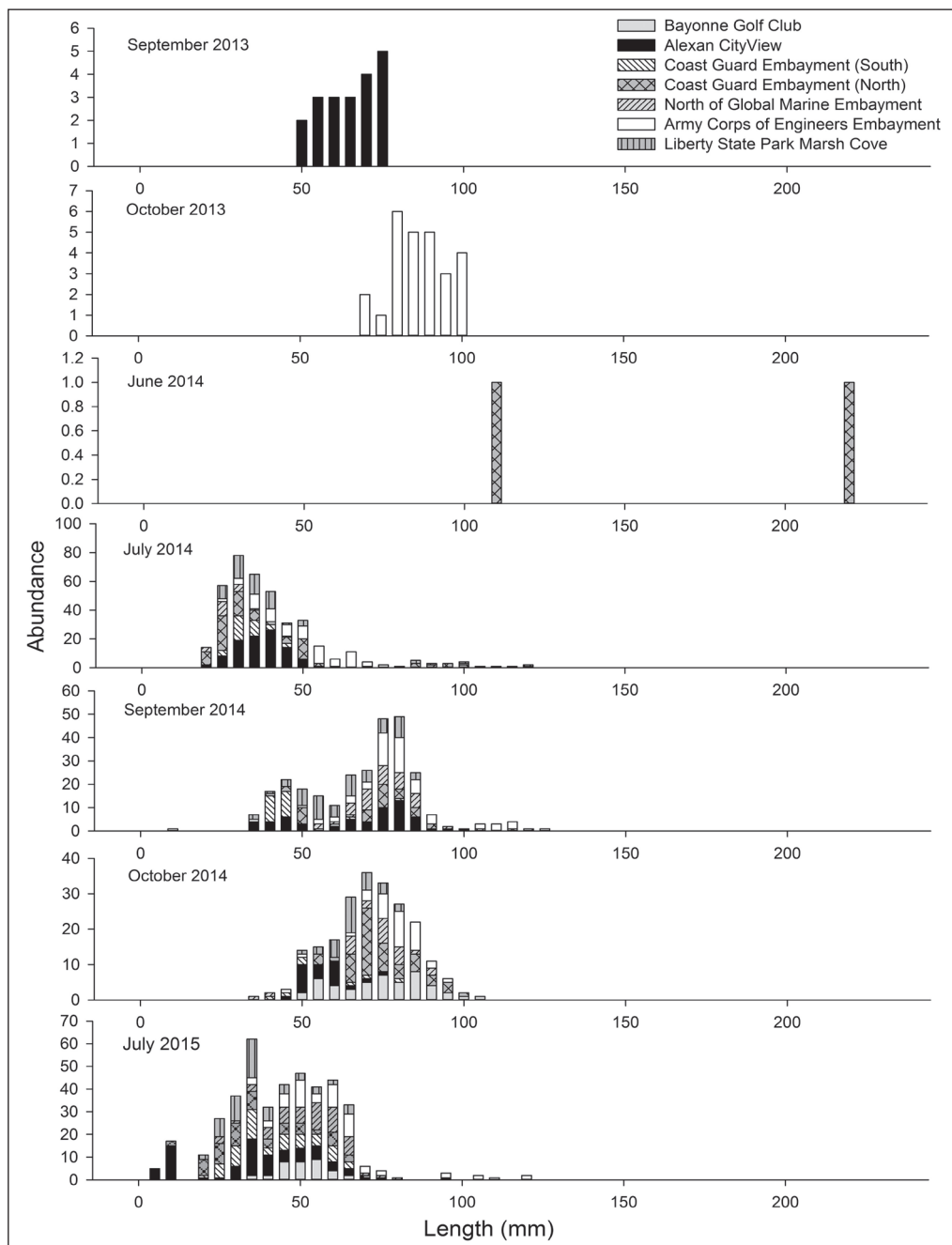


Figure 7. Composite monthly length frequencies of *Menidia menidia* (Atlantic Silverside) from seine samples across all study sites during 2013–2015. Note differences in y-axis scales.

3 of the target fish species at most sites was supported by the continued occurrence of increasingly larger individuals from July, when the YOY first become apparent,

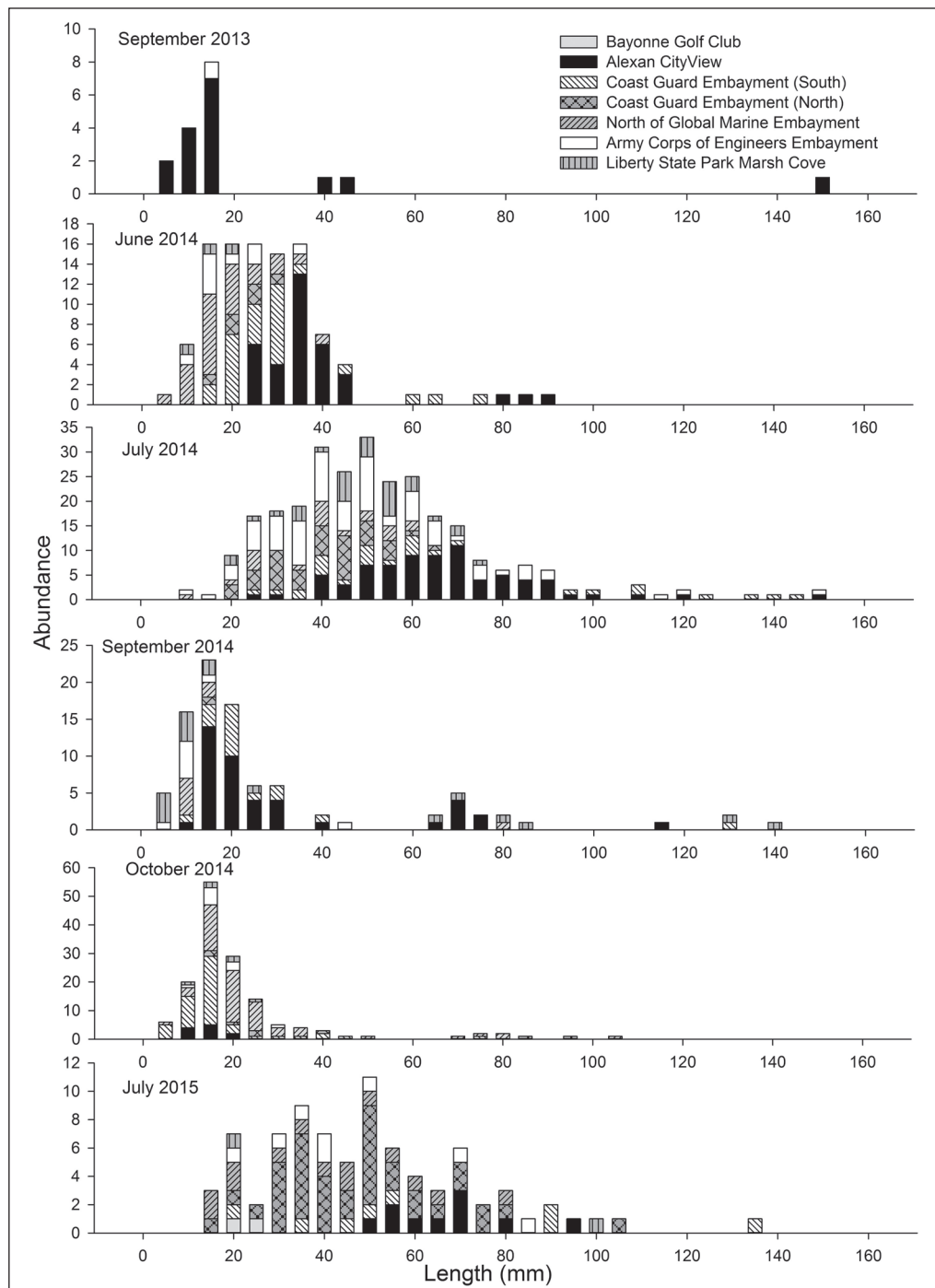


Figure 8. Composite monthly length frequencies of *Callinectes sapidus* (Blue Crab) from seine samples across all study sites during 2013–2015. Note differences in y-axis scales.

into the fall when sampling was discontinued (Figs. 5, 6, 7, 8). Survival of Blue Crabs during 2014 was evident from the progression of sizes from June through July at most sites with the exception of the Bayonne Golf Club and SIMS Recycling Embayment (both infrequently sampled).

Movements/residency

There was no evidence of Mummichog movement from the 2 naturalized tagging sites to other sampled locations. No tagged fish, either batch-marked or individually marked were re-captured at any of the other re-sampled study sites, although 4 of these are between the 2 tagging sites. Therefore, we assume there was no dispersal beyond an individual embayment. In addition, recaptures within a tagging site demonstrated site fidelity over time. Recaptures at Alexan CityView were highest soon after tagging (4%) and lower later (0.3%), with no returns occurring in the final sampling in fall 2014 and summer 2015.

At Army Corps of Engineers Embayment, recaptures were again highest (17.5%) after initial tagging and later varied from 0.3% to 10%, with no recapturing in late fall 2014 and summer 2015.

Discussion

The separate components of an Essential Fish Habitat evaluation examined in this study—i.e., distribution and abundance, reproduction, growth, and survival—implied that these structural and functional components were satisfied across all of the selected sentinel species and across most of the shallow portions at the head of these embayments. The clear exception was the heavily altered SIMS Recycling Embayment site with its steeply sloping shorelines composed of large boulders and the lack of shallow water. Of the indices measured, abundance was the most variable, both between and within types of sites. This finding may be due, in part, to the large within-site variation across many of the sites. A separate analysis, based on the same sampling approaches at the same sites, but for the distribution and abundance of the total fish and crab fauna, indicated that the shallow portion of the embayments supported a fauna with many components intact (T.M. Grothues and K.W. Able, unpubl. data). The patterns of reproduction for all 3 of the fish species are consistent with other studies in New Jersey estuaries (Able 1990, Able and Fahay 2010). Growth, another important indicator, is an important measure of habitat quality (Able 1990, Houde 1989). For example, continued growth throughout the important summer season, when most growth occurs for Middle Atlantic Bight fishes, including these sentinel species (Able and Fahay 1998), implies that continued survival has occurred and makes survival during the overwinter period more likely (Hales and Able 2001, Sogard 1997). Growth rates, based on size attained at the end of the year, were similar in all study sites in New York Harbor in which the sentinel species occurred. In most instances, sentinel fish growth during the summer and fall allowed the target species to attain size for reproduction. As a result, fishes in the general study area attained an adult size at these sites, an important criterion for the shallow sites to be considered as nursery locations (Beck et al. 2003).

The fidelity of Mummichog to the 2 tagging sites confirmed that these embayments allow for populations to reproduce, grow, and survive. The small-scale site fidelity observed in this study is typical for other populations of this species, but is the first for such a highly urbanized estuary. In many prior studies in natural and restored marsh creeks, there is almost complete fidelity to a single creek watershed (Able et al. 2006, 2012; Fritz et al. 1975; Hagan et al. 2007; Teo and Able 2003a, b). While Mummichog occur in natural marshes primarily in creeks, as pointed out, they also occur in pools (Able et al. 2005, Hunter et al. 2009, Smith and Able 1994), basins (Able and Fahay 1998, Able et al. 2010), and occasionally along unvegetated shorelines (Able et al. 1996, 2002; Ruiz et al. 1993). This flexibility in habitat use is consistent with the observations for shallow waters in the heavily urbanized study site.

Since tagged fish were only recaptured at tagging sites, it can be concluded that the embayments, which are separated generally by deep bulk-headed habitat, are closed regarding population dynamics (i.e., vary independently in population size, habitat use, growth, and reproduction). This finding does not suggest that they are genetically isolated, since it takes very little exchange to spread genes. Rather, it provides some confidence that metrics associated with a sample site are in fact representative of that site and, in this case, supports that the sites from urbanized Upper New York Harbor are capable of sustaining populations of these fish.

Essential fish habitat

This examination supports the concept that the limited shallow-water habitats in most of the studied embayments in Upper New York Harbor provide Essential Fish Habitat for many of the sentinel species that are the focus of this study (Table 3). For Mummichog, many embayments, both naturalized and altered, provided critical biological and ecological attributes necessary for growth and development. Most studied embayments had juveniles and adults of sentinel fishes and juvenile Blue Crabs present. Overall abundance varied between sites with many showing high levels. The exceptions were a heavily altered site at SIMS Recycling Embayment (which lacked shallow shorelines and associated habitats), Bayonne Golf Club (which had limited habitat at the specific site we sampled), and Liberty State Park Marsh Cove (which was difficult to sample at high tide where the fringing marsh was flooded, making Mummichogs unavailable). There was a high degree of residency for this species at the 2 naturalized sites (Army Corps of Engineers Embayment, Alexan CityView) where tag/recapture experiments took place. Evidence of reproduction occurred at all sites, except the heavily altered site at SIMS Recycling Embayment. Evidence for YOY growth and survival occurred at all sites, except at SIMS Recycling Embayment where this species did not occur or was rare. As a result of these characteristics, functional attributes of Essential Fish Habitat for this species were similar across most sites.

For Striped Killifish, the occurrence of life-history stages were generally consistent with most sites having juveniles and adults, though with some exceptions at those classified as heavily altered and altered. These patterns were similar for abundance, with the occurrence of both juveniles and adults consistent with high overall

Table 3. Response of shallow-water sentinel fish species to Essential Fish Habitat structural and functional components for multiple sites in New York Harbor during 2013–2015. - indicates no assessment, ? indicates insufficient sampling to assess clearly, J = juveniles, A = adults. ++ = high, + = low, and 0 = absent or, in the case of survival, not measured. M = Mummichog, SK = Striped Killifish, AS = Atlantic Silverside, and BC = Blue Crab.

Site	Structural attributes												Functional attributes													
	Life-history composition (J, A)						Abundance			Residency			Reproduction			Growth			Survival							
	M	SK	AS	BC	J	A	M	SK	AS	BC	M	BC	AS	M	SK	AS	M	SK	AS	BC	M	SK	AS	BC		
Liberty State Park Marsh Cove	J, A	J	J, A	J	J, A	J	+	+	++	+	-			+	+	+	0	?	+	++	0	?	0	?	++	++
Army Corps of Engineers Embayment	J, A	J, A	J, A	J	J, A	J	++	++	++	++	+			+	+	+	++	++	++	+	++	++	++	++	++	++
SIMS Recycling Embayment	J, A	-	-	J	J	J	+	+	0	0	+			0	0	0	0	+	0	0	-	0	0	0	0	0
Embayment North of Global Marine	J, A	J, A	J, A	J	J, A	J	++	++	+	++	-			+	+	+	++	++	++	++	++	++	++	++	+	++
Coast Guard Embayment (North)	J, A	J, A	J, A	J	J, A	J	++	++	++	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+
Coast Guard Embayment (South)	J, A	J	J, A	J	J, A	J	++	+	+	++	-			+	+	+	++	++	?	?	++	++	?	?	?	++
Alexan CityView	J, A	J, A	J, A	J	J, A	J	++	++	++	++	+			+	+	+	++	++	++	++	++	++	++	++	++	++
Bayonne Golf Club	J, A	A	J, A	J	J, A	J	+	?	++	+	-			+	+	?	0	?	?	?	?	0	?	?	?	?

abundance. Some sites lacked evidence of Striped Killifish reproduction and had low or unmeasured growth and survival. These embayments were likely inadequate for this species because they lacked shallow water (SIMS Recycling Embayment) or sandy or protected shorelines (Liberty State Park Marsh Cove, Coast Guard Embayment–South, Bayonne Golf Club).

For Atlantic Silverside, many embayments provided habitat for abundant juveniles and adults. The exceptions were the heavily altered site at SIMS Recycling Embayment, where seine sampling could not occur because of the deeper water and large boulders, and at the altered site at Coast Guard–South and the naturalized site at Embayment North of Global Marine, where they were less abundant. Thus, with these exceptions, the heads of many shallow embayments demonstrated the functional attributes of Essential Fish Habitat for this species including reproduction, growth, and survival.

For Blue Crab, many embayments provided habitat and thus critical structural and functional attributes. Juveniles were present in all embayments, with very high abundance, growth, and survival of juveniles at several naturalized sites (Army Corps of Engineers Embayment, Embayment North of Global Marine, Alexan CityView) and an altered site (Coast Guard Embayment–South), and lower abundances at another naturalized site (Liberty State Park Marsh Cove). Thus, shallow water is important to this species as well (Dittel et al. 1995).

The occurrence of a few other species, namely juvenile *Limulus polyphemus* (L.) (Horseshoe Crab), *Uca* spp. (fiddler crabs), *Geukensia demissa* (Dilwyn) (Ribbed Mussel), that are common or abundant in estuaries was also assessed based on qualitative observations. All these species occurred at Liberty State Park Marsh Cove and Army Corps of Engineers Embayment, whereas both Horseshoe Crab and Ribbed Mussel occurred at Alexan CityView, and Horseshoe Crab and *Uca* spp. occurred at Embayment North of Global Marine. Horseshoe Crab juveniles also occurred at Coast Guard Embayment–North and Coast Guard Embayment–South. The heavily altered site at SIMS Recycling Embayment did not have any of these species due to steeply sloping, rocky edges with deeper water. The occurrence of these species in an urbanized estuary provides the opportunity for further studies of Essential Fish Habitat.

Given these findings, it seems clear that the limited shallow, upper portions of embayments in New York Harbor provide Essential Fish Habitat for the sentinel species studied here. In a sense, this finding is not surprising since all of these species spend much of their time in shallow water throughout their life history or at least as juveniles and, for some species, as eggs and larvae (Able and Fahay 2010). As a result, these portions of a heavily urbanized estuary may still contribute as nurseries (see also Courrat et al. 2009, Hajisamae and Chou 2003) although the degree to which this happens is likely influenced by the reduced spatial availability of shallow waters in heavily modified habitats, as in New York Harbor (Squires 1992).

Recommendations for restoring habitat value and increasing resilience

These findings indicate that any future restoration or naturalization of New York Harbor ought to include the restoration or preservation of intertidal and shallow

subtidal habitats. In order to conserve existing habitats, the edges of the harbor should not be further bulkheaded or hardened. Any activity to fill in the shallow waters, such as is taking place in the upper margin of the Army Corps of Engineers Embayment by the Liberty National Golf Course, should be stopped. Where possible, the margins of the embayments should mimic those of Alexan CityView and the Bayonne Golf Club, which have extensive fringing salt marsh and shallow subtidal areas. At these sites and elsewhere, it appears that creeks draining from culverts, as at the head of Army Corps of Engineers Embayment and at Coast Guard Embayment–North, may function similarly to marsh creeks based on the abundance of Mummichog at these sites. Elsewhere, sandy beaches could be restored or created to provide habitat for such species as Striped Killifish and Horseshoe Crab. The creation of both of these types of habitats around the periphery of these artificial embayments would provide additional habitats as well as habitat islands to provide for the dispersal of these and other species such as Atlantic Silverside and Blue Crab.

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