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Use of gill nets and telemetry in tracking movements and feeding of striped bass (*Morone saxatilis*), bluefish (*Pomatomus saltatrix*), and weakfish (*Cynoscion regalis*) at a salinity front in a small estuary

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Abstract—The hypothesis that striped bass (*Morone saxatilis*), bluefish (*Pomatomus saltatrix*), weakfish (*Cynoscion regalis*), and species of forage fish would be associated closely with a salinity transition front was tested through sampling and tagging efforts. In a small New Jersey estuary, a station at a salinity front and another in a nearby channel were sampled weekly with gill nets. Abundance of bluefish was significantly greater at the front, and abundance of weakfish was significantly greater at the channel. Forage fish were collected at both stations, and the diets of bluefish and weakfish overlapped in all seasons. Ultrasonically tagged striped bass, weakfish, and bluefish were tracked concurrently, and their home ranges, or the 95% probability of their occurrences were computed. Home ranges of tagged striped bass occurred upriver and also near river kilometer 1. Home ranges of weakfish were located in the midriver channels, and those of bluefish were located midriver and upriver at river kilometers 5–12. Home ranges for these 3 species were not limited to the area of the salinity front, contrary to the initial hypothesis.

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Small tributaries of temperate-zone estuaries have vital but incompletely understood roles as sources of energy for growth of many sought-after commercial and recreational fish species. In flood-dominated estuaries, tidal movements and freshwater discharges create a salinity transition zone or front, where saline and riverine waters mix, with a salinity gradient forming both horizontally and vertically. Turbulent mixing in this zone may produce a turbidity maximum, where inorganic and organic particulates are suspended. The frontal boundary allows retention of nutrients, phytoplankton, microbes, and zooplankton (Grimes and Kingsford, 1996; Epifanio and Garvine, 2001). High freshwater discharges stabilize the duration and volume of such a nutrient-rich habitat (Morgan et al., 1997; Roman et al., 2001). It has been hypothesized that, with such mixing, food is concentrated for consumers, including larval and small-size fish, which in turn attract larger predators (North and Houde, 2001; Martino and Houde, 2010).

The Navesink River, a flood-dominated small tributary of the Hudson–Raritan Estuary in New Jersey that borders the Mid-Atlantic Bight, is used by predatory fish, forage fish, and invertebrate species (Shaheen et al., 2001; Stoner et al., 2001; Meise and Stehlik, 2003; Scharf et al., 2004; Manderson et al., 2006; Manderson et al.[1]). Previous hydrographic studies have delineated a convergence zone or salinity transition zone in the upper river (Chant and Stoner, 2001; Fugate and Chant, 2005). In this river system, 3 of the dominant pelagic predators are bluefish (*Pomatomus saltatrix*), striped bass

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[1] Manderson, J. P., J. Pessutti, J. Rosendale, and B. Phelan. 2007. Estuarine habitat dynamics and telemetered movements of three pelagic fishes: scale, complexity, behavioral flexibility and the development of an ecophysiological framework. ICES Council Meeting (C.M.) Documents 2007/G:02, 36 p.

(*Morone saxatilis*), and weakfish (*Cynoscion regalis*). In estuaries, these 3 species are predators of fish and invertebrate species in varying proportions depending on season and availability (Lankford and Targett, 1994; Buckel and Conover, 1997; Collette and Klein-MacPhee, 2002; Nemerson and Able, 2004; Rudershausen et al., 2005; Ferry and Mather, 2012). They are frequently sympatric and are competitors for the same prey (Hartman and Brandt, 1995; Uphoff, 2003). In a study in which gill nets were used in the Navesink River in 1998 and 1999 (Scharf et al., 2004), abundance of bluefish was greatest at a station in the upper river in the Red Bank basin and was significantly correlated with areas of fine sediment.

From May through October in 2006 and 2007, Manderson et al. (2014) conducted a weekly hydrographic study of the Navesink River from river kilometers 1–12. On 12 of those weeks, they also conducted a hydrographic study limited to the area around the salinity front in the upper or western end of the river, together with fish collection and diet analysis. Concurrently, acoustically tagged bluefish (age 0 and age 1+), weakfish, and striped bass were monitored by using receivers throughout the river to determine days of continuous occupation and movements by individuals of these 3 species (Manderson et al., 2014). Median residence times in 2007 were 8 d for striped bass, 29 d for age-1+ bluefish, 29 d for age-0 bluefish, and 47 d for weakfish. Manderson et al. (2014) concluded that the seasonal residencies of these predators in the Navesink River were affected by 2 direct factors: variation in day length and temperature. Freshwater discharge also affected predator residence times indirectly, possibly through prey availability (Manderson et al., 2014).

On the basis of the analyses reported in Manderson et al. (2014), we hypothesized that, when freshwater discharge was moderate to high, biophysical mechanisms supporting the salinity transition zone and concentrating food resources would be maintained and predators would chiefly reside there. We hypothesized that, when discharge was low, the salinity transition zone would be disrupted, resulting in a reduction in food resources and emigration of predators from the zone or the entire estuary. Manderson et al. (2014) did not examine evidence extensively for testing this hypothesis, including examining within-estuary movements of predators, occurrence and distributions of prey, and diets, or the potential relationship of the biota to hydrographic features in the estuary.

The objective for this study was to test the hypothesis that striped bass, bluefish, and weakfish are more abundant in the vicinity of the main salinity transition zone or front of the Navesink River than away from it. We used data from hydrographic surveys, gill net collections, predator diets, and telemetry to evaluate the available evidence that supports or disproves our hypothesis. The telemetry data were used to generate daily and composite home ranges of the 3 predator species in this river.

Materials and methods

Study area

The Navesink River is approximately 12 km long, ≤1.5 km wide, and around 10 km^2 in area (Fig. 1); it flows eastward into the Shrewsbury River, then north to Sandy Hook Bay and Raritan Bay. It is a flood-dominated estuary, with a 1.4-m average tidal range (Chant and Stoner, 2001). The salinity front is near this upper or western end of the river (Fugate and Chant, 2005), and practical salinity ranges from ~1 in the upper Navesink River during spring freshets to ~28 at the mouth of this river (senior author and J. Manderson, unpubl. data). To the west, the Swimming River is the primary freshwater source. The upper river depth for the Navesink River averages ~2 m at high tide, and substrates are fine sand and silt with high organic content (Chant and Stoner, 2001; Stoner et al., 2001; Meise and Stehlik, 2003). The lower Navesink River is characterized by shallow sandbars and channels (depths up to 4 m). High-velocity tidal currents and coarse to medium sands are found in the channels. Shallows and embayments in the summer and fall are vegetated with sea lettuce (*Ulva lactuca*) and other macroalgae. For our studies, we designated the confluence of the Navesink and the Shrewsbury rivers as river kilometer 0.

Hydrographic measurements and station locations

Weekly hydrographic surveys were made the length of the river from April through October, in 2007, along transects that intersected with an array of ultrasonic receivers (see *Telemetry* section). An SBE 25 Sealogger[2] conductivity, temperature, and depth recorder (Sea-Bird Electronics Inc., Bellevue, WA) was cast at the location of each receiver, to measure temperature, conductivity, pressure, dissolved oxygen, photosynthetically active radiation, turbidity, and concentration of chlorophyll-*a*. Similar work was completed in 2006 with the same equipment and methods (see Manderson et al.[1]).

Hydrographic mapping and gill net sampling at the upstream end of the Navesink River, near the salinity front, were conducted during 12 weeks in May through October 2007. Hydrographic mapping took place twice a day during daylight hours at the end of flood and at the end of ebb tides, once a week on 4 consecutive weeks during each of 3 periods: spring (May), summer (late July–early August), and fall (late September–early October). We integrated data from a global positioning system (GPS), the SBE 25 Sealogger, and a Hydrolab datasonde (OTT Hydromet, Kempten, Germany) that measured temperature and salinity at 1-s intervals 0.5 m below the surface. After the salinity front was located by using the SBE 25 Sealogger, the site of

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[2] Mention of trade names or commercial companies is for identification purposes only and does not imply endorsement by the National Marine Fisheries Service, NOAA.

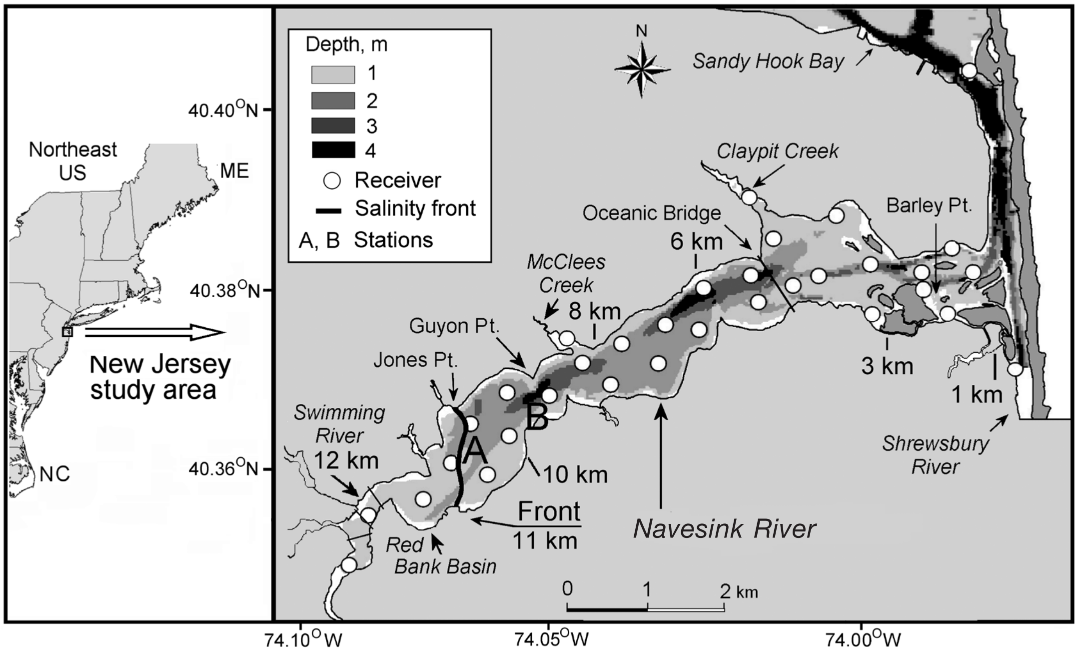

Figure 1

Map of the Navesink River, showing the location of the river on the northeastern coast of the United States, depths at mean low low water, locations of receivers used to track ultrasonically tagged bluefish (*Pomatomus saltatrix*), striped bass (*Morone saxatilis*), and weakfish (*Cynoscion regalis*) in 2007 (indicated with circles), approximate location of the salinity transition front at flood tide (indicated by the black line) in 2007, and locations of station A at the front at flood tide and station B at a nearby channel, where gill net sampling was conducted in 2007 (indicated with the letter A or B).

that cast of the SBE 25 where the front was found was designated as station A (depth: 1–2 m at low tide) for gill net sampling. The location of station A changed depending on the hydrodynamics. When the tide changed that day, station A was relocated. Station B for gill net sampling was located approximately 2 km downriver in a nearby channel (depth: 3–7 m at low tide) and was always in the same location (Fig. 1).

Freshwater discharge records were obtained from U.S. Geological Survey streamflow station 01407500 in the Swimming River west of Red Bank, New Jersey (data available at website; Manderson et al., 2014).

Fish collections and diets

To investigate predator diets and prey distributions, we used targeted gill net sampling during the 12 weeks of hydrographic surveys. Three replicate nets were deployed at each of the stations A and B, at peak of flood tide and at peak of ebb tide, twice daily. They were anchored close to the river bottom, and were soaked for 2 h in the morning and again in the afternoon of that same day. The gear and soak times were chosen to be the same as those employed in 1998 and 1999 by Scharf et al. (2004). Gill nets were 45.7 m in length by 2.4 m depth, had 6 panels of equal length (7.6 m) and various mesh sizes (1.3–7.6 cm^2). After fishing for 2 h, gill nets were retrieved. Fish and macroinvertebrates captured in each net were sorted, counted, and measured. Striped bass and weakfish were measured in total length (TL), and measurements of bluefish were taken in fork length and converted to TL. Weakfish and bluefish were assigned to either age-0 or age-1+ (age 1 or older) cohorts on the basis of analysis of length frequencies in the earlier study (Scharf et al., 2004). Weakfish and bluefish <300 mm TL in spring and fall and <250 mm TL in summer were classified as age-0. Relative abundances of fish species from the front and channel stations were compared by using Mann-Whitney tests ($P<0.05$).

Stomachs of the targeted predators were removed and preserved in 70% ethanol. Stomachs <5% full and those containing only unidentified matter were counted as empty. Fish and invertebrate prey were identified to the lowest possible taxonomic level, weighed wet (to the nearest 0.01 g), and lengths (in millimeters) of intact prey items were recorded. The most important prey taxa by percent weight of all predators were pooled into 10 categories, including a category for unidentified fish or other organisms. Cluster analysis was performed by the least squares method on percentages of prey taxa by predator, age class, and season. However, too few striped bass were collected to conduct any diet analysis.

Gill net collections were used to identify typical distributions of dominant prey taxa. We chose the size limit for predator-vulnerable fish as ≤150 mm TL, on the basis of lengths of prey in stomach contents from

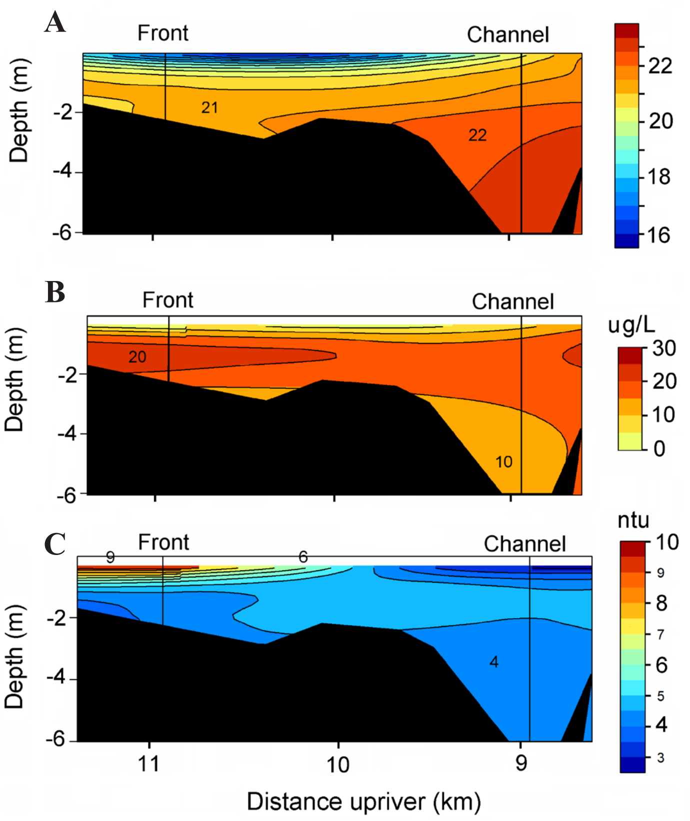

Figure 2

Hydrographic profiles of (**A**) salinity, (**B**) chlorophyll-*a* concentration (µg/L), and (**C**) turbidity (ntu) in the upper Navesink River, in New Jersey, at flood tide on 2 August 2007. Locations of station A at the salinity transition front and station B at a nearby channel that were sampled with gill nets are marked.

the study in 1998 and 1999 (senior author and J. Manderson, unpubl. data). In the field of potential prey, we included bay anchovy (*Anchoa mitchilli*, 50–110 mm TL), Atlantic silverside (*Menidia menidia,* 60–130 mm TL), and Atlantic menhaden (*Brevoortia tyrannus*, 50–150 mm TL), as well as bluefish and weakfish ≤150 mm TL.

Telemetry

Ultrasonic telemetry was used in 2006 and 2007 to monitor the movements of bluefish, weakfish, and striped bass by using methods described in detail by Manderson et al. (2014). Briefly, we moored an array of omnidirectional receivers (model VR2, Vemco, Bedford, Nova Scotia, Canada) ~80 cm above the bottom throughout the Navesink River from 15 May through 3 October 2006 and from 18 April through 31 October 2007. In 2006, the array consisted of 27 receivers. In 2007, 5 additional receivers were moored in marsh creeks and coves. Nearest neighbor distances between receivers in the river averaged 493 m (standard deviation 141 m), within a range of 216–788 m. Receivers moored in the middle and upper river had detection ranges of 350–600 m, whereas detection ranges were smaller and more variable in the topographically complex lower river (details of range tests are provided in Manderson et al., 2014).

From 14 May through 8 September 2006 and from 1 May through 2 October 2007, striped bass, bluefish, and weakfish were caught by hook and line when seasonally available. They were placed in coolers with cooled water from the laboratory and with battery-operated airstones and were transported within 1 h to the laboratory. Fish were anaesthetized with AquiS (AquiS New Zealand Ltd., Lower Hutt, New Zealand) at a concentration of 54 mg/L. A sterilized, uniquely coded ultrasonic transmitter (V9-6L, Vemco), with a frequency of 69 kHz and a repetition rate of 40–120 s, was then inserted into the body cavity of each fish. Fish were held in the laboratory 2–48 h afterward so that we could be certain of their recovery and were

Table 1

Total catch of striped bass (*Morone saxatilis*), bluefish (*Pomatomus saltatrix*), and weakfish (*Cynoscion regalis*) by season, age class, and station (located at a channel [B] or salinity transition front [A]) for gill net sampling conducted in the Navesink River, New Jersey, in 2007.

Species and age class	Spring Channel	Spring Front	Summer Channel	Summer Front	Fall Channel	Fall Front
Age-1+ striped bass	1	6	0	0	0	0
Age-0 bluefish	0	0	46	86	147	389
Age-1+ bluefish	1	5	21	0	3	0
Age-0 weakfish	0	0	94	4	261	52
Age-1+ weakfish	88	3	53	7	31	7

then released randomly throughout the river. In 2006, 34 age-1+ striped bass (359–630 mm TL), 14 age-1+ bluefish (310–390 mm TL), 15 age-0 bluefish (175–270 mm TL), and 15 age-1+ weakfish (224–535 mm TL) were released. In 2007, 12 age-1+ striped bass (342–510 mm TL), 21 age-1+ bluefish (310–610 mm TL), 30 age-0 bluefish (222–275 mm TL), and 27 age-1+ weakfish (304–480 mm TL) were released.

The home range of an animal, where it spends 95% of its time during normal activities, was calculated for each species by using the "utilization distribution" method (Anderson, 1982; Tolimieri et al., 2009). Those fish that were ultrasonically detected 3 or more times on a given day and that were detected on a minimum of 6 days were included in our analysis. The adehabitatHR package (Calenge, 2006) in R, vers. 2.13.1 (R Core Team, 2011) was used to perform the analysis on the telemetry records. Signals were binned in 10-min intervals. Records were censored in instances when signals from more than one fish overlapped in a time bin. Because the Navesink River is relatively narrow in relation to the detection range of the receivers used in this study, mean daily positions in universal transverse coordinates were converted to distances upriver (in meters). Home ranges were generated for individual fish by using an analysis grid of squares with sides 100 m×100 m, limited to areas within the coastline boundary. Composite grids for all data from each species were then generated and plotted for each species, age class (in bluefish), and year.

Results

Hydrography

When freshwater discharge was high, a well-defined salinity gradient was established in the upper Navesink River. At end of flood tide, this gradient was located at approximately river kilometers 10–11 between Jones Point and just east of the basin off Red Bank (Fig. 1). Usually, the salinity front shifted 0.5–1.5 km downstream with ebb tide. In 2007, freshwater discharge was high although variable in July and August, and discharge was low in September and October (Manderson et al., 2014), leading to a fully mixed salinity state in the river in fall.

In a hydrographic profile of the upper portion of the Navesink River on 2 August 2007, during a period of high freshwater discharge, the salinity gradient was from near 17 at the surface to >22 near the channel bottom, at both tides (Fig. 2). The salinity front at high tide was located at the steepest vertical salinity gradient at approximately river kilometer 11. The surface layer in the upper river at that time was 25.5°C and contained concentrations of chlorophyll-*a* >20 µg/L, at approximately river kilometers 7–11. West of the front near the surface was a zone of high turbidity, an area that typically extended into the Swimming River.

In contrast, at a time of low discharge in late September and October 2007, the estuary was well mixed and hydrographic profiles were much more uniform. No clearly delineated front was observed. The differences between the units of the contours of salinity and chlorophyll-*a* concentration in the upper river profiles were one-tenth the magnitude of the differences between the units in August, and turbidity was high only in the Swimming River.

Predators, predator diets, and prey field

During gill net sampling, 7 age-1+ striped bass, 30 age-1+ bluefish, 648 age-0 bluefish, 189 age-1 weakfish, and 411 age-0 weakfish were collected (Table 1). The seasonal arrival and egress of the species were discussed by Manderson et al. (2014). Catch at station A at the salinity front, as opposed to station B in the channel, was significantly different for all taxa and seasons (Mann-Whitney tests: $P<0.01$). Almost twice as many age-0 bluefish were collected at the front station than at the channel station in summer and fall. Age-1+ bluefish were collected rarely except in summer, and during

Table 2

Categories of most important prey found in stomach contents of bluefish (*Pomatomus saltatrix)* and weakfish (*Cynoscion regalis)* captured during gill net sampling in 2007 in the Navesink River, New Jersey, expressed by season and age class as a percentage of total weight.

Species	Bluefish	Bluefish	Bluefish	Weakfish	Weakfish	Weakfish	Weakfish	Weakfish
Season	Summer	Summer	Fall	Spring	Summer	Summer	Fall	Fall
Age class	Age-0	Age-l+	Age-0	Age-1+	Age-0	Age-1+	Age-0	Age-l+
N	73	18	259	70	17	42	127	22
Amphipoda	0.11	0.00	0.00	0.02	28.27	0.00	4.27	0.00
Mysidacea	0.00	0.00	0.00	41.00	0.13	0.01	0.00	0.00
Caridea	4.29	0.77	0.03	56.67	17.38	3.56	3.89	0.00
Brachyura	15.83	72.75	0.29	2.02	0.00	22.27	2.64	0.47
Anchoa mitchilli	1.41	0.00	0.57	0.00	4.54	0.00	0.65	0.00
Brevoortia tyrannus	47.41	1.18	94.67	0.00	40.99	32.04	83.39	95.85
Cynoscion regalis	5.02	0.00	0.00	0.00	0.00	6.70	0.00	0.00
Menidia menidia	8.31	2.51	1.34	0.00	0.00	3.86	1.04	0.00
Pomatomus saltatrix	0.00	12.75	0.00	0.00	0.00	2.55	0.00	0.00
Fish, unid. and other organisms	17.62	10.04	3.09	0.30	8.69	29.01	4.13	3.72

that season they were captured largely in the channel. Age-0 and age-1+ weakfish were more abundant at the channel station than at the front station in all seasons.

Overall, the most important prey by percent weight was Atlantic menhaden (Table 2). By cluster analysis (at 30% similarity), the greatest differences in diet resulted with season and age class, and with predator species of lesser importance. In spring, age-1+ weakfish consumed mainly sand shrimp (*Crangon septemspinosa*) and mysids (*Neomysis americana*). In summer, age-0 bluefish, median length 150 mm TL, ate age-0 Atlantic menhaden, species of the infraorder Brachyura, Atlantic silverside (*Menidia menidia*), age-0 weakfish, and other fish species. In that season, age-1 bluefish ate species of Brachyura (mainly blue crabs [*Callinectes sapidus*]) and smaller bluefish. In summer, weakfish consumed Atlantic menhaden, other fish species, and blue crabs, and the age-0 weakfish also consumed amphipods and species of the infraorder Caridea (sand shrimp and grass shrimp [*Palaemonetes* spp.]). The other fish species in both seasons included winter flounder (*Pleuronectes americanus*) and striped searobin (*Prionotus evolans*). In fall, Atlantic menhaden constituted 91.9% of the stomach contents of all predators at both stations.

Differences in stomach contents between stations A (front) and B (channel) were found only for bluefish in summer. At that time, bluefish consumed more crabs at station B than at station A and more Atlantic menhaden at station A than at station B (Mann-Whitney tests: $P<0.01$).

Potential prey fish were captured in the fine mesh panels of the gill nets at both Stations A and B (Fig. 3). Summer was the only season in which the catch at the 2 stations was different. At that time, significantly more Atlantic silverside were caught at the front than at the channel, and significantly more Atlantic menhaden were captured at the channel than at the front (Mann-Whitney tests: $P<0.01$). In summer, age-0 bluefish and weakfish were also potential prey, the former at the front and the latter at the channel. In fall, nearly all the potential prey collected at both stations were age-0 Atlantic menhaden. Although bay anchovy were common in predator diets, they were rarely collected in the gear during sampling.

Telemetry

Home ranges for ultrasonically tracked striped bass, bluefish, and weakfish in the Navesink River in 2006 and 2007 averaged 73–133 m^2 in area, depending on species (Table 3). There was great variation among individuals of each taxon. Striped bass had the smallest home ranges by area. Home ranges of age-1+ bluefish were larger than those of weakfish and age-0 bluefish, although not significantly different.

From 2006 through 2007, 89 tracked fish met the criteria for mapping, and the centers of their home ranges were located mainly in one or more of 4 defined reaches of the estuary (Figs. 4 and 5). Detections were relatively few in number at river kilometers 3–5 and 7–8.

Reach 1	Shoals and islands in the lower river near the confluence of the Navesink and Shrewsbury rivers (river kilometers 1–3).
Reach 2	Channel on both sides of the Oceanic Bridge (river kilometers 5–7).
Reach 3	From McClees Creek to the channels off Guyon Point, including Station B (river kilometers 8–10).
Reach 4	Upper river, from the Red Bank basin to Jones Point, including the salinity front and Station A (river kilometers 10.0–11.5).

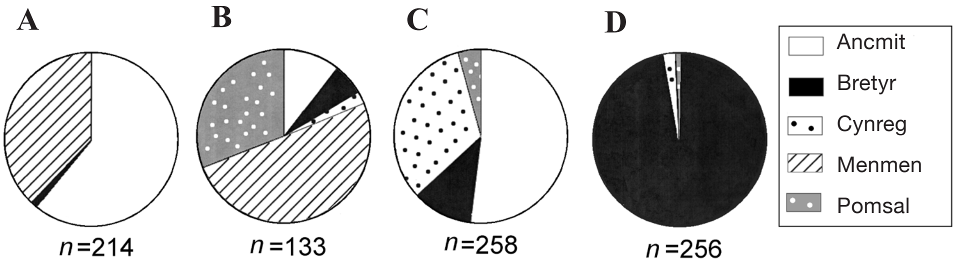

Figure 3

Most abundant forage fish (<150 mm) caught by gill nets in the Navesink River in New Jersey in 2007 and the total number of fish captured per season: (**A**) spring catch, (**B**) summer catch from station A at salinity front, (**C**) summer catch from station B at channel, and (**D**) fall catch. Forage fish species include the bay anchovy (*Anchoa mitchilli*, [Ancmit in the key]), Atlantic menhaden (*Brevoortia tyrannus*, [Bretyr]), weakfish (*Cynoscion regalis*, [Cynreg]), Atlantic silverside (*Menidia menidia*, [Menmen]), and bluefish (*Pomatomus saltatrix*, [Pomsal]).

Table 3

Species, age class, year, number of fish, length range of fish (TL), mean home range (m^2), standard deviation (SD), and reaches (1–4) of the Navesink River, New Jersey, most frequented by striped bass (*Morone saxatilis*), bluefish (*Pomatomus saltatrix*), and weakfish (*Cynoscion regalis*) tagged ultrasonically in 2006 and 2007.

Species and age class	Year	Number of fish	Length range (TL)	Mean home range (m^2)	SD	Reaches
Striped bass	2006	17	359–597	81.7	56.97	1, 2, 3, 4
Striped bass	2007	3	445–510	72.7	39.88	1, 3, 4
Age-0 bluefish	2006	9	194–270	101.4	76.56	3, 4
Age-0 bluefish	2007	11	222–275	101.9	68.55	3, 4
Age-1+ bluefish	2006	6	320–345	132.9	85.31	2, 3, 4
Age-1+ bluefish	2007	14	310–690	126.7	67.20	1, 2, 3, 4
Weakfish	2006	8	224–535	95.1	86.78	2, 3
Weakfish	2007	21	304–480	101.1	67.29	2, 3

Home ranges of striped bass were located in reaches 3 and 4, with a few detections in reach 1 near the river mouth, in 2006 and 2007. The home ranges of weakfish (all but 2 fish were age 1+) were centered in the channels in reaches 2 and 3, at river kilometers 5–10, in both years. For bluefish, ontogenetic differences in home ranges were observed in both years. The home ranges of age-1+ bluefish were more extensive, from reaches 2 through 4, at river kilometers 4–11. The home ranges of age-0 bluefish were centered mostly in reaches 3 and 4, at river kilometers 8–12, across the front and upriver to the Red Bank basin and Swimming River. Detections of bluefish were not as specific to channel habitats as were detections of weakfish.

Some fish shifted from a primary home range to a secondary home range during their period of residence. For example (Fig. 6), an age-1+ bluefish released on year day 122 was detected in reaches 3 to 4 at receivers located from the Red Bank basin to the Oceanic Bridge. Then, beginning on year day 142, it was detected downriver in reaches 1 and 2, at receivers from Claypit Creek to Barley Point, until it passed the last receiver and out of the river on year day 152.

The signals from some fish ceased and were detected again later in the season. Some striped bass were tagged in spring, subsequently detected in reach 1, apparently exited the river, and were detected again as they returned in fall. Some striped bass and age-1+ bluefish were detected at the farthest west receiver, disappeared, and then were detected again, apparently having made excursions into Swimming River.

Discussion

Salinity fronts, prey fields, and diets

We hypothesized that striped bass, bluefish, and weakfish would be found most often in the Navesink River in the vicinity of the main salinity transition front in the

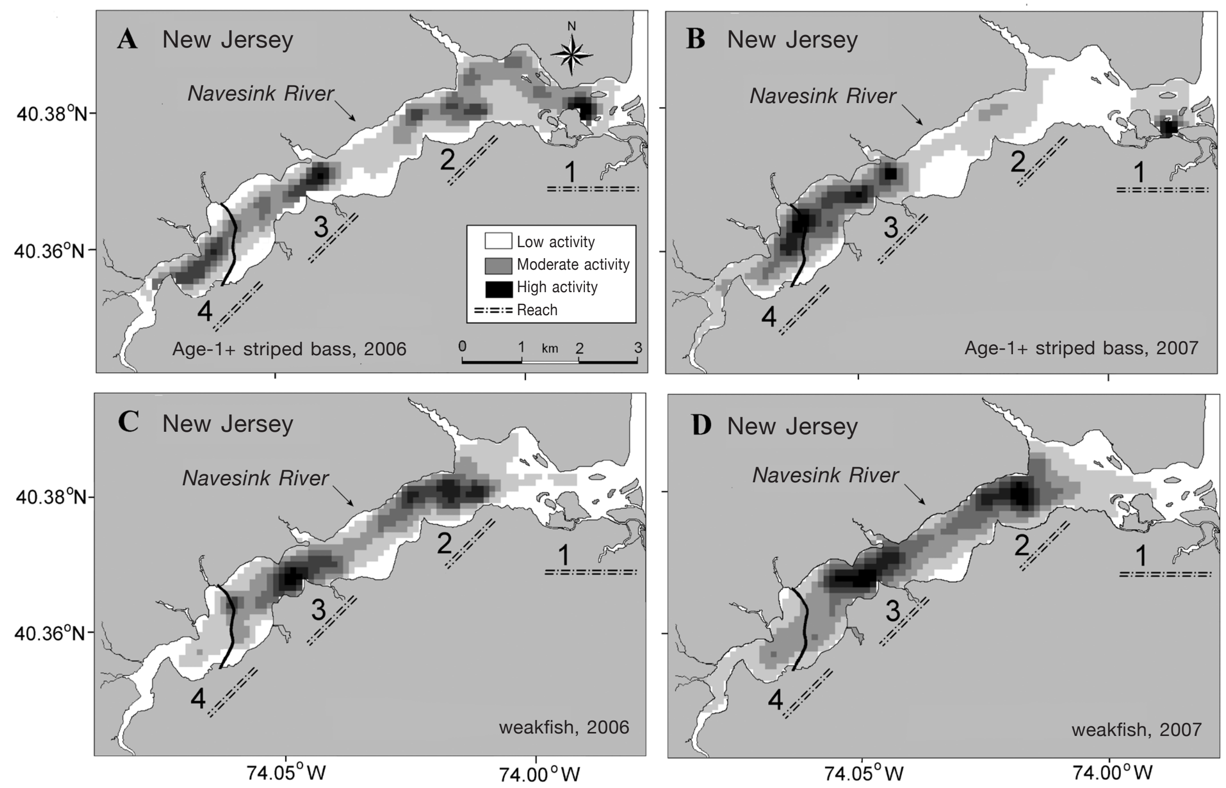

Figure 4

Plots of home ranges derived from acoustic detections of ultrasonically tagged fish in the Navesink River in New Jersey: age-1+ striped bass (*Morone saxatilis*) in (**A**) 2006 and (**B**) 2007 and weakfish (*Cynoscion regalis*) in (**C**) 2006 and (**D**) 2007. Parallel dashed lines denote reaches 1–4 of the estuary.

upper river rather than in a nearby channel. The front was well developed in summer 2007, and we were able to test the hypothesis. The data for age-0 and age-1+ bluefish conformed to the hypothesis at that time, but data for weakfish did not. Among forage fish, only Atlantic silverside was caught exclusively at the salinity front; other species were caught at both the front station and the channel station. Atlantic silverside feed on zooplankton, such as copepods, ostracods, mysids, and the young stages of many estuarine organisms (Collette and Klein-MacPhee, 2002), and zooplankton productivity is known to be concentrated at salinity fronts (Morgan et al., 1997; Martino and Houde, 2010). More Atlantic silverside were found in stomachs of fish collected at the salinity front than in stomachs of fish captured at the channel. In and around the front, chlorophyll-*a* concentration was highest as expected, and high turbidity was limited to locations upriver from the front. The abundance of Atlantic menhaden particularly is associated with patches of high chlorophyll-*a* concentration that result from phytoplankton blooms (Friedland et al., 1996; Collette and Klein-MacPhee, 2002); however, Atlantic menhaden were collected at both the front and channel stations in summer. In fall, in the absence of a defined hydrographic front, Atlantic menhaden were abundant at both stations.

The estuarine turbidity maximum does not control the availability of all prey resources that support the 3 predator species that we investigated. Atlantic menhaden and the majority of other forage fish were not limited to the area of the estuarine turbidity maximum. Invertebrate prey, particularly blue crabs and sand shrimp, were almost as important as Atlantic menhaden by percent weight in the predator diets in spring and summer. These 2 invertebrate prey species are abundant throughout the Navesink River (Meise and Stehlik, 2003; senior author, unpubl. data). We believe that, in addition to the main salinity front, other areas in the Navesink River have hydrodynamics and benthic habitats that are suitable for supporting the 3 predator species.

We found that the diets of bluefish and weakfish in 2007 generally contained the same major prey taxa. Other researchers have recognized dietary overlap with these 2 species and with striped bass (Hartman and Brandt, 1995; Wuenschel et al., 2013). The fish species that are the major prey customarily consumed by bluefish, weakfish, and striped bass in mid-Atlantic estuaries and nearshore areas are bay anchovy, Atlantic menhaden, and Atlantic silverside (Juanes and Conover, 1994; Buckel and Conover, 1997; Taylor et al., 2007).

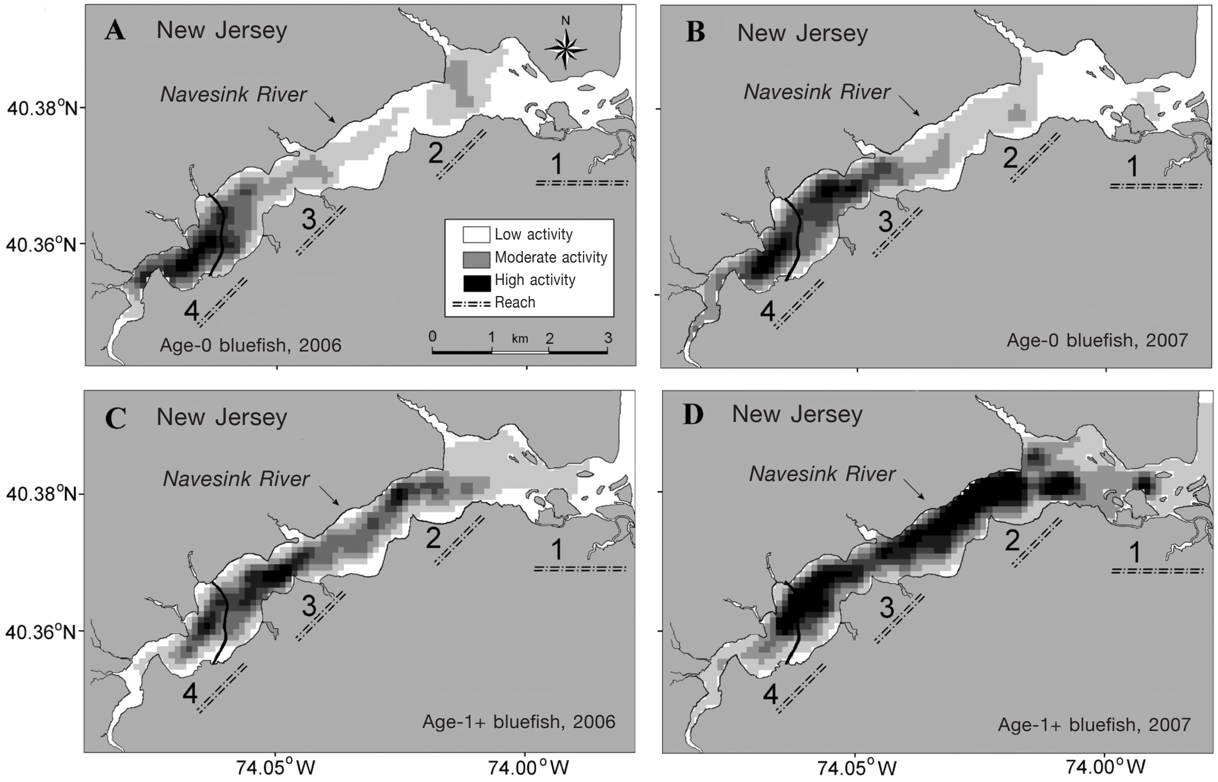

Figure 5

Plots of home ranges derived from acoustic detections of ultrasonically tagged fish in the Navesink River in New Jersey: age-0 bluefish (*Pomatomus saltatrix*) in (**A**) 2006 and (**B**) 2007 and age-1+ bluefish in (**C**) 2006 and (**D**) 2007. Parallel dashed lines denote Reaches 1–4 of the estuary.

The increased proportion of fish in the predator diets as the year progressed is attributable to 2 factors: 1) increased availability of fish prey and 2) growth of predators that allowed them to catch larger prey. The proportion of fish in relation to invertebrates in the diets of young bluefish, weakfish, and striped bass similarly has been reported to increase in other estuaries during the summer (Hartman and Brandt, 1995; Woodland et al., 2011) as forage fish grow to available size.

In mid-Atlantic estuaries, the fluctuating availability of Atlantic menhaden has had a key effect on diets of predatory fish. In the Chesapeake Bay, Atlantic menhaden dominated the diets of striped bass in the 1950s (Griffin and Margraf, 2003). They also contributed more than 60% by weight to the diet of age-2+ bluefish, striped bass, and weakfish in 1990 and 1992 (Hartman and Brandt, 1995). Although Atlantic menhaden were important in the diets of bluefish and weakfish in the Navesink River in 1998, 1999, and 2007, they were absent from the stomachs of age-0 bluefish collected in nearby Sandy Hook Bay in the 1980s (Friedland et al., 1988). The low abundance of Atlantic menhaden in the mid-Atlantic region in the 1990s and 2000s (Ferry and Mather, 2012; Pikitch et al., 2012) led to their decrease in the diets of striped bass in Chesapeake Bay and was suspected to be linked to poor physical condition of the striped bass themselves (Uphoff, 2003; Walter et al., 2003; Jacobs et al., 2009).

Home ranges and habitat associations of predators

Our study is the first to map the home ranges of 3 predators at the same location and time, to examine stomach contents, and to collect potential prey. The results of this study were consistent between 2006 and 2007, both in location and in dimension of home ranges. We found that home ranges were fairly small and similar in size among the 3 predators, indicating that the animals lock into small core areas or hotspots. The centers of home ranges were often situated in one of the deeper channels or basins directly downriver from the salinity front, particularly for weakfish. Age-0 bluefish was the only fish cohort that was detected consistently on both sides of the salinity front, in reach 4. Age-1+ bluefish had larger home ranges than age-0 bluefish, possibly because their greater body size allowed greater swimming speed (Beamish, 1978; Stehlik, 2009). Home ranges overlapped spatially, yet the occupation of those spaces was separated temporally. The overlap in the diets of predators parallels the overlap of their home ranges. The dimensions of the home ranges of these 3 predators have been found to be similar in other small

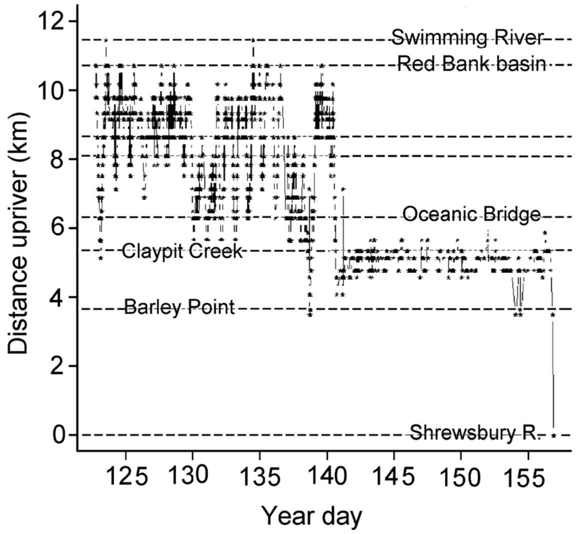

Figure 6

Acoustic detections of an age-1+ bluefish (*Pomatomus saltatrix*) that was 635 mm in total length and tracked in 2007 in the Navesink River, New Jersey. Dashed lines indicate geographical locations at the given distances from the mouth of this river.

estuaries (core areas with diameters of 0.5–1.0 km) in New Jersey (Grothues and Able, 2007; Ng et al., 2007; Able et al., 2012; Turnure et al., 2015). Striped bass in the Hudson River were tracked over many kilometers, but their movements occurred seasonally rather than daily (Wingate and Secor, 2007).

Within the home range of an individual fish, irregular diel or tide-related movements ≥1 km were noted in both 2006 and 2007 (Fig. 6). Results of general additive modeling with the 2006 telemetry data indicate that some of the variability in the daily positions was attributable to tide or time of day, but the telemetry data were complex and unclear because of extreme variability among individual fish (Manderson et al.[1]).

The results of the analysis of data from telemetric tracking augmented the results of the analysis of data from gill net sampling, showing that home ranges of the 3 predator species were not localized or limited to the area of the salinity front in the west of the Navesink River. Undoubtedly, the gill net sampling in 2007 did not provide a complete picture of the use of the Navesink River by the 3 predators because the gill nets were placed only in the upper river, separated by a distance of about 2 km. However, our study was designed on the basis of the results of the Scharf et al. (2004) study in which gill nets were used throughout the river. In that study, the greatest abundances of bluefish and weakfish in all 3 seasons occurred at their station 13 (close to the Red Bank basin, reach 4 in our study), and secondarily at station 10 (in the lower river near the mouth of Claypit Creek, reach 2 in our study) (Scharf et al., 2004; senior author, unpubl. data).

Combining hydrography, gill-net sampling, and telemetry allowed us to investigate the use of the estuarine habitat by the 3 dominant predators on a variety of temporal and spatial scales. Environmental forcing, as discussed in Manderson et al. (2014), broadly controls the residence times of fish in the Navesink River. Within the time of its estuarine residence, a fish uses a home range for a duration of days or weeks. Stomach contents are representative of the activity of about 1 d, and telemetric data shed light on hourly, daily, and seasonal activities. Hydrographic investigations detect areas where high chlorophyll-*a* concentration is favorable for zooplankton growth, and gill net sampling pinpoints concentrations of piscine prey. Tracks of individual fish show short-term diel or tide-related upriver and downriver movements of about 1 km, but further analyses of these movements would be needed to discover whether they originate from tides, light availability, prey presence, or a suite of influences. We determined that even in a small, 10-km^2 estuary, multiple reaches of the Navesink River system contain habitat of the quality needed to support the survival and growth of bluefish, weakfish, and striped bass from days to months. These advantageous habitats change in location with the seasons and are not limited to the estuarine turbidity maximum or the main salinity transition front.

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