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Movement patterns of striped bass (*Morone saxatilis*) in a tidal coastal embayment in New England

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ABSTRACT

Striped bass (*Morone saxatilis*) are important in commercial and recreational fisheries along the western Atlantic coastline. Although there is a good understanding of their seasonal migration patterns, less is known about the short-term movements of striped bass once they have reached New England coastal embayments during the summer months. Movement patterns were assessed by tagging 35 striped bass (38.5–80.5 cm TL) with acoustic transmitters and tracking them within a fixed array ($n = 34$ receivers) in Plymouth, Kingston, Duxbury (PKD) Bay, MA. The majority of tagged striped bass took up residency within PKD Bay for the summer months. Large juvenile through sub-adult (21–46 cm) and adult bass (>46 cm) remained residents of PKD Bay for periods of 6–75 days and appear to use the estuary as a vital summer foraging area before emigrating from the bay for their southward migration. Changes in activity space estimates were significant over the course of the season and increased with water temperature. There was a general increase of activity space preceding emigration where presence of striped bass was significantly related to water temperature and photoperiod. Various environmental factors influence striped bass movement, and it is important to understand individual patterns and behavioral ecology to make the most educated management decisions.

1. Introduction

Striped bass (*Morone saxatilis*) are highly targeted along the Atlantic coastline of the United States and are an important source of revenue for the commercial and recreational fishing industries (Werner, 2004). Overfishing and poor environmental conditions caused the collapse of Atlantic striped bass stocks in the late 1970's (Karas, 1993). Since then, federal protection of the species coupled with strict state management regulations have aided in the coastwide recovery of the stock and a concomitant rejuvenation of commercial and recreational fisheries for the species. Despite the relative health of the striped bass fishery over the last decade (ASMFC, 2013), continual management is necessary to maintain sustainable fisheries in the face of issues such as habitat loss, lack of prey, fishing mortality, mycobacterial infections, and pollution (Karas, 1993). A healthy fishing industry is fundamental to the nation, especially in coastal regions, bringing both social and economic benefits with its popularity (Cooke and Cowx, 2004; Arlinghaus et al., 2007).

Striped bass are anadromous and highly migratory along the Atlantic coast of North America (Clark, 1968; Boreman and Lewis, 1987; Dorazio et al., 1994; Walter et al., 2003). A large percentage of striped bass follow a seasonal migration route (Clark, 1968), traveling south in the fall and north in the spring to spawn (Boreman and Lewis, 1987; Karas, 1993; Grothues et al., 2009). Coastal migratory stocks spend much of the summer in New England estuaries as well as offshore areas with large concentrations of seasonal forage fish (Kohlenstein 1981; Waldman and Fabrizio, 1994; Nelson et al., 2006; Mather et al., 2009). Studies on the movement patterns of striped bass have predominantly used external tagging methods (reviewed in Clark, 1968; Kohlenstein 1981; Boreman and Lewis, 1987; Dorazio et al., 1994; Waldman and Fabrizio, 1994). More recent methods have addressed topics examining seasonal activity patterns (Wingate and Secor, 2007; Pautzke et al., 2010), site fidelity and habitat use (Ng et al., 2007), spawning behavior (Hocutt et al., 1990; Douglas et al., 2009), and responses to tem-

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perature and drought (Baker and Jennings, 2005). Interestingly, striped bass movement patterns while on their summer grounds in New England coastal estuaries has just recently been focused upon (see Mather et al., 2009; Pautzke et al., 2010; Kneebone et al., 2014). Estuarine dependency during early life stages is obligate and remains important throughout the life of the fish (Secor et al., 2000). It is also believed that these estuaries provide important foraging grounds for striped bass before their annual migration (Nelson et al., 2006; Pautzke et al., 2010) and that striped bass have strong site fidelity to non-natal estuaries (Ng et al., 2007; Able et al., 2012). Recent acoustic tagging studies within the natal Hudson River, New York (Wingate and Secor, 2007) and non-natal Mullica River—Great Bay, New Jersey (Able and Grothues, 2007; Ng et al., 2007; Grothues et al., 2009) and Plum Island Estuary, Massachusetts (Pautzke et al., 2010) estuaries provide the first examples of multiple-detection movement data for individual coastal striped bass.

Quantifying movement patterns of fish in space and time is important for understanding the fundamentals of their natural history, ecological interactions, and habitat requirements (Cooke et al., 2008; O'Toole et al., 2010). A collective understanding of each of these dynamics is also critical for the effective management and conservation of exploited species (Lowe et al., 2003; Cooke et al., 2004). The objective of our study was to quantify the movement and activity patterns of large juvenile and adult striped bass in a New England bay. To do so, we capitalized on the use of acoustic transmitters within a large-scale fixed array deployed across a range of habitat types and predicted that striped bass would exhibit strong fidelity to PKD Bay over the extent of the summer and that activity would correlate to temperature of the bay.

2. Materials and methods

2.1. Study site

Plymouth, Kingston, and Duxbury (PKD) Bay is a coastal embayment located approximately 50 km south of Boston, Massachusetts (centered at 42° 42′41.59″N, 70° 47′41.89″W; Fig. 1) that serves as a popular fishing destination for recreational anglers targeting striped bass during the summer months (U.S. Fish and Wildlife Service, 2008). PKD Bay is bound on its east end by two barrier beaches separated by a 1.6 km wide inlet, connecting the embayment to Cape Cod Bay. Characteristics of PKD Bay include large channels surrounded by sand and mud flats, salt marshes, tidal creeks that can be exposed at low tide (Iwanowicz et al., 1974), as well as a small residential island (Clarks Island) whose northern portion consists of rocky outcroppings and eelgrass (*Zostera marina)* bed habitat. There are also several important freshwater inflows to PKD Bay, including Jones River in Kingston, the Back River and Bluefish River in Duxbury, and the Eel River in Plymouth. Tidal exchange is semidiurnal with a mean tidal amplitude of 3.2 m. On average, the total surface area of the bay fluctuates between 22.1 and 40.7 km^2 at mean low and mean high water, respectively, resulting in a 66.1% tidal exchange in water volume (Iwanowicz et al., 1974). PKD Bay is relatively shallow with a mean depth of 2–3 m and a maximum depth of 20 m at high tide.

2.2. Receiver array

An array of 34 fixed acoustic receivers (VR2W, Vemco Division, AMIRIX Systems Inc., Halifax, Nova Scotia) was deployed from May 5, 2011 through October 30, 2011 (Fig. 1). Receivers were deployed on the substrate approximately 1 m above the estuary floor, or suspended 1–2 m below the surface on a line attached to navigational markers. Receivers were arranged to maximize coverage in the bay while creating nodes that correspond with transitions between habitat types (e.g., shallow flat to deep channel). A curtain of receivers was deployed across the mouth of PKD Bay to capture movements of tagged fish in and out of the bay. Data from receivers were downloaded and receivers cleaned monthly during the deployment period. Thirteen water temperature loggers (model HOBO Pendant, Onset Computer Corporation, Onset, Massachusetts) were deployed at several receiver locations throughout the estuary (Fig. 1). The loggers were programmed to record temperature (°C) every 30 min with an accuracy of ±0.7 °C (range −20–70 °C, Onset Computer Corporation, Onset, Massachusetts).

Receiver working detection range was tested on a subset of receivers positioned at various depths and substrates immediately following deployment or the array (e.g. tidal flats and channels; Kneebone et al., 2012). During each trial, a stationary control tag was moored at 50, 100, 200, 300, 400, and 500 m away from the receiver in all four cardinal directions for 5 min. Time and GPS location were recorded, and the number of detections was monitored by a manual hydrophone (VR-100, Vemco Division, AMIRIX Systems Inc., Halifax, Nova Scotia) at each moored location. The detection radius of receivers ranged from ~100 m in water depths <3 m to ~350 m at depths >5 m. Also, the receivers positioned in 'deep' (>3 m at low tide) channels did not show a symmetrical detection range in all cardinal directions; the range was much greater along the axis of the channel and reduced in shallower water along each side of the channel. Although the overall detection range for some receivers was reduced during low tide, striped bass were mostly restricted to deeper channels during these periods (i.e., much of the submerged area goes dry at low tide), where the detection range remained high. Thus, striped bass could be detected throughout the entire tidal cycle and data correction to account for receiver range was unnecessary.

2.3. Capture and tagging

Striped bass were caught across a range of sizes and life stages using hook and line fishing techniques and gear across a range of habitats within PKD Bay. A variety of artificial lures, including soft plugs and fly lures were used ranging in size from 5 to 15 cm with 1–3 barbed hook points. Cut bait consisting of Atlantic mackerel (*Scomber scombrus*) and Atlantic menhaden (*Brevoortia tyrannus*) was also used when available. All striped bass were angled in less than 5 m of water.

Acoustic transmitters (model V9AP-1L, 9 mm diameter, 46 mm long, 6.3 g in air, 50 m depth range, min and max delay times 60 and 180 s, 160 day battery life; Vemco Inc., Halifax, Nova Scotia) were implanted in 35 striped bass during three separate periods in 2011: early-July, mid-August, and mid-September. Once landed, each fish was removed from the water, dehooked and anesthetized in a MS-222 bath (50–100 mg/L). Once fish were anesthetized (showing signs of stage-4 anesthesia, characterized by a complete loss of equilibrium and no response to handling (Summerfelt and Smith, 1990)), they were transferred to a V-shaped surgery table lined with pre-wetted neoprene and a small plastic hose connected to a pump (Little Giant, model PES-100, 95 gal/h, adjustable flow, Fort Wayne, Indiana) was placed in their mouth to deliver continuous fresh seawater running over the gills. Transmitters were then implanted in the body cavity through a small (2–3 cm) abdominal incision on the ventral side of the fish, and the incision closed with 2–3 interrupted sutures (Ethicon 3-0 PDS II, Johnson and Johnson, New Jersey). All surgeries were performed by the same trained surgeon. Immediately following surgery, striped bass were measured (total length (TL) to the nearest cm) and released into a floating mesh holding pen (1.2 m × 1.2 m × 1.2 m, 1.5 cm mesh, Memphis Net & Twine Co., Memphis, Tennessee) alongside the boat to recover. Fish were

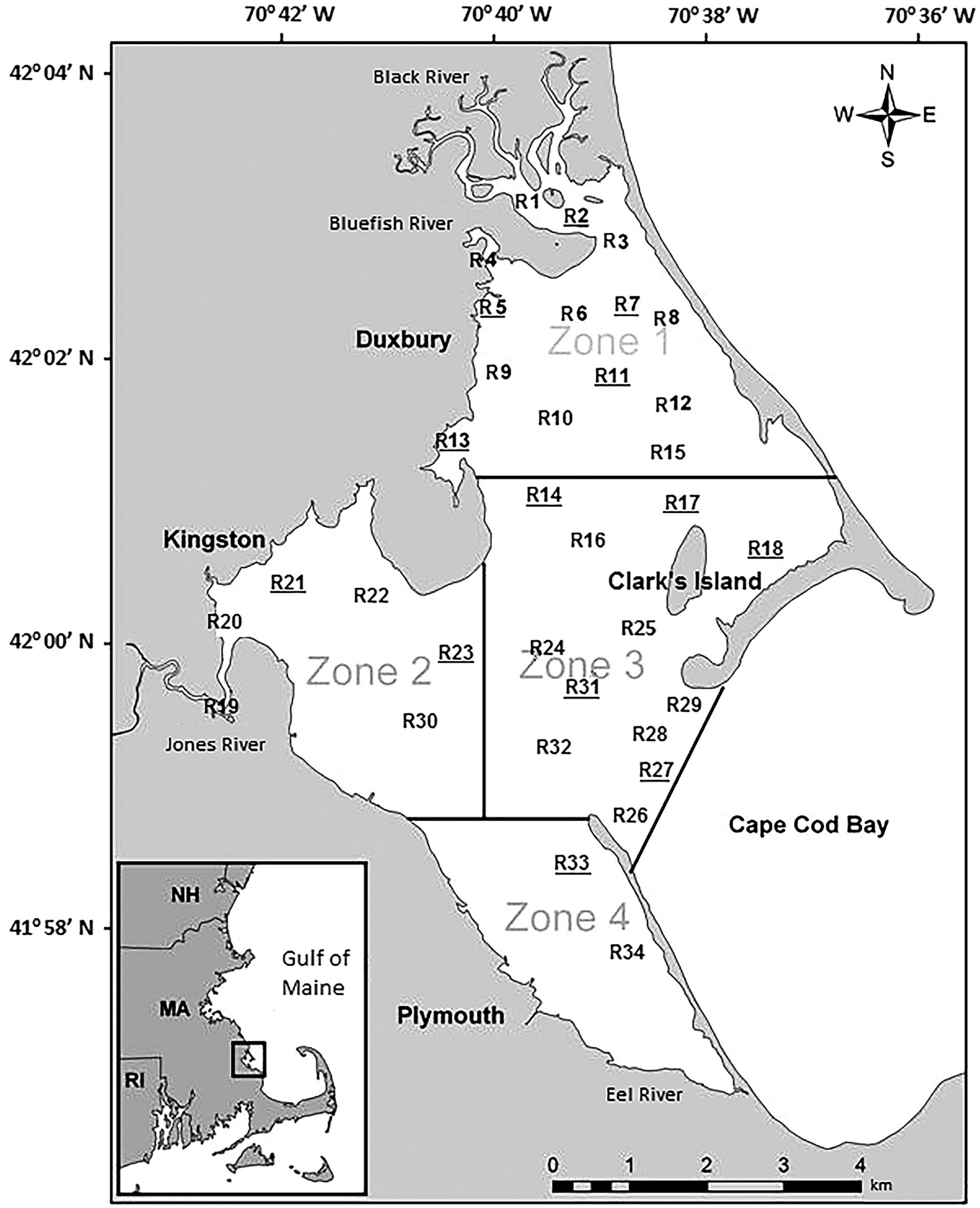

Fig. 1. Study area in the Plymouth, Kingston, Duxbury (PKD) Bay along the east coast of Massachusetts including the 34 receiver locations (receivers with temperature loggers are underlined). Separate zones were created to analyze striped bass movements and are shown in gray text divided by black lines.

released at their capture site once they regained normal orientation and were observed to be actively swimming (<20 min).

2.4. Data analysis

Prior to analysis, all transmitter data were examined for each individual fish and false detections rejected using criteria established by Vemco (Pincock, 2012). Only fish detected for more than one day, on more than one receiver, and with more than 50 detections were used in the analysis. Detections within the first 24 h of tagging were excluded to account for potential impacts from the angling event and surgery (O'Toole et al., 2010). One-way analysis of variance (ANOVA) performed in R, was used to test for differences in body size among sampling periods. In subsequent analyses, means were reported as ±1 standard deviation where appropriate and statistical significance accepted at $p \leq 0.05$ unless otherwise stated.

2.4.1. Residency

Residency was defined as any calendar day that a tagged striped bass was detected at least two consecutive times on one or more receivers in the PKD Bay array. Since there is no way to know the exact amount of time striped bass were present in PKD Bay prior to tagging, minimum residence time was calculated from time of tagging until the fish exited PKD Bay (Kneebone et al., 2012). Striped bass were determined to have exited the bay if they were detected in the PKD Bay mouth and not on any of the interior receivers in the following days. The number and proportion of transmitter-implanted striped bass exiting PKD bay was also calculated for each month (July-October) as the number of striped bass exiting the bay divided by the total number of striped bass present. In order to examine the effect of fish length on residence time, linear regression in the R statistical environment (R Development Core Team, 2011) was used.

To examine the potential influence of photoperiod (day length; DL) and water temperature as environmental triggers for striped bass emigration from PKD Bay, generalized linear mixed models (GLMMs; Zuur et al., 2009), assuming a binomial distribution and logit link function, were used to examine the effects of average weekly day length (h) and water temperature (°C) on the presence of striped bass within PKD Bay (Kneebone et al., 2012). Individual striped bass were coded as present (1) or absent (0) for the weeks between July 2 to October 30. Striped bass were recorded as present only if detected for at least 3 days of a given week (Kneebone et al., 2012). The times of sunrise and sunset were used to calculate day length data. Mean weekly temperatures were calculated from data obtained from the 13 temperature loggers deployed throughout PKD Bay. Detections from each individual fish over time were not independent; therefore, striped bass was incorporated into the model as a random effect to quantify variation of the fixed effects parameters across individuals. Separate GLMMs were run for each parameter, given that day length and temperature data were highly correlated. Parameter estimates were obtained using Laplace approximation in the 'lme4' package in R (Bates et al., 2011). Significant relationships were accepted at $p < 0.001$ (Zuur et al., 2009).

2.4.2. Space use and site fidelity

Total number of detections were tallied for each receiver deployed during the study period. To correct for uneven receiver deployment times, the number of detections per receiver per day was calculated as the total number of detections for the entire study period divided by the number of days each receiver was deployed during which at least one tagged fish was present within the array (Kneebone et al., 2012). The number of unique individual fish detected per day by each receiver was also tallied as visits per day. To examine space use and site fidelity of striped bass within PKD Bay, four zones were created by grouping the receivers into similar habitat types and field observations of striped bass activity space (Fig. 1). The distribution of striped bass across zones was calculated as the average of the total detections in each zone divided by the cumulative number of days receivers were deployed in that zone (Kneebone et al., 2012).

Site fidelity to each zone was assessed using a residency index calculated for each individual as the total number of days spent in each zone divided by the total number of days spent within the whole array (Kneebone et al., 2012). SFI values ranged from 0 (no residency) to 1 (residency only in that zone); a value of 0.5 was set as the lower limit for 'strong' site fidelity within a zone.

2.4.3. Center of activity

To understand the short-term behavior of striped bass, the center of activity (COA) for each tagged striped bass was calculated every hour (Simpfendorfer et al., 2002). The COA position represents the average geographic position of an individual within the one-hour period, and provides a more practical depiction of the habitat used by an individual than raw receiver locations (Simpfendorfer et al., 2002). COA positions were utilized to calculate the activity space of tagged striped bass within PKD Bay and the extent to which that varies over time.

Given the irregular boundaries of PKD Bay, a latticed-based estimator (Barry and McIntyre, 2011) was used to generate 2-dimentional activity space estimates for all tagged fish (Kneebone et al., 2012). Activity spaces (50% and 95%) were calculated for the entire season (total activity space) and weekly (17 weeks; July 3 to October 30) for all tagged fish. Weekly activity space was only estimated if a striped bass was detected for at least three days in a given week. Experimental estimation of the optimal smoothing parameter (k) using unbiased cross-validation was problematic due to the dispersal of the COA positions (i.e. many positions in the same location and/or in very close proximity). Instead, a fixed k value was used (Kneebone et al., 2012). All lattice-based estimates of activity space were obtained using the 'latticeDensity' package (Barry, 2011) in R.

To determine whether the body size of striped bass influenced total activity space, generalized linear models assuming Gaussian distribution and a logit link function were applied to total activity space estimates. Since weekly activity space estimates consisted of repeated measurements for an individual, the effect of body size (TL), week, and average weekly temperature on activity space was assessed using generalized additive mixed models (GAMM; Zuur et al., 2009) in the "gamm4" package in R (Wood, 2011), with striped bass incorporated as a random effect. Data exploration showed a high level of correlation between week and average weekly water temperature; thus, separate regressions were run to examine the individual effects of these factors on weekly activity space. Significant relationships were accepted at $p < 0.001$ (Zuur et al., 2009).

3. Results

The 35 striped bass implanted with transmitters ranged in size from 38.5–80.5 (Mean ± SD = 55.8 ± 12.5) cm TL. There was no difference in body size of striped bass among the three sampling periods (ANOVA: $p = 0.8$). Two fish were detected less than 50 times and were not included in the analysis (Table 1). In total, there were 70,654 reliable detections for 33 striped bass (Table 1).

3.1. Residency

Striped bass were monitored continuously in PKD Bay for extended periods throughout the seasonal monitoring period and did not routinely move in and out of the embayment (Table 2). Individual striped bass exhibited minimum residence times ranging from 6 to 75 (30 ± 19) days, and there was a significant relationship between residence time and TL ($r^2 = 0.29$, $df = 31$, $p = 0.001$) with minimum residence time decreasing with body size.

Striped bass moved out of PKD Bay predominantly in September and early October, but a small number of individuals moved out as early as July and August. Nearly all striped bass (34/35; 97%) were last detected on receivers at the mouth of PKD from July 20 to October 29, with 3% ($n = 1$) leaving in July, 3% ($n = 1$) leaving in August, 20% ($n = 7$) leaving in September and 71% ($n = 25$) being detected in October (Table 2). One individual (TL = 40.1 cm) was last detected by receiver R1 (Fig. 1) on the last day of the receiver deployment, therefore emigration could not be confirmed.

Table 1
Summary of mean daily detections per receiver and detections per total receiver days (Detections/Rday) for all receivers in each zone.

Tagging Group	Tag ID	Date tagged	Date Last Detected	TL (cm)	Total no. of detections	No. of days in array	No. of days detected	Total no. of receivers detected on
Group 1	2702	7/5/2011	9/15/2011	58.2	942	73	25	14
	2704	7/5/2011	10/27/2011	42.4	3115	115	75	18
	2706	7/5/2011	10/18/2011	46.3	747	106	24	15
	2708	7/5/2011	10/28/2011	40.3	6103	116	75	19
	2710	7/5/2011	9/17/2011	71.5	140	75	10	4
	2712	7/5/2011	10/28/2011	38.5	2468	116	56	18
	2692	7/6/2011	7/20/2011	80.5	622	15	14	3
	2694	7/6/2011	10/12/2011	56	943	99	28	13
	2696	7/6/2011	10/3/2011	59.7	1979	90	46	18
	2698	7/6/2011	10/28/2011	64.8	2516	115	43	22
	2700	7/6/2011	10/28/2011	72.3	413	115	11	9
Group 2	5820	8/12/2011	10/12/2011	50.1	7551	62	51	16
	5822[a]	8/12/2011	8/29/2011	74.9	30	18	2	2
	5824	8/12/2011	10/18/2011	48.2	1114	68	31	7
	5826	8/12/2011	10/27/2011	43.7	4397	77	52	20
	5808	8/17/2011	9/5/2011	48.2	540	20	8	3
	5810	8/17/2011	9/18/2011	80.5	351	33	14	4
	5812	8/17/2011	10/27/2011	51.7	5912	72	46	17
	5814	8/17/2011	10/27/2011	41	6464	72	49	23
	5816	8/17/2011	10/15/2011	60.5	2317	60	28	9
	5804	8/18/2011	10/29/2011	40.1	4941	73	40	13
	5806	8/18/2011	10/3/2011	61.4	1095	47	31	14
Group 3	5818[a]	9/10/2011	9/29/2011	63.9	5	20	2	2
	6368	9/10/2011	10/27/2011	45.3	309	48	11	8
	6370	9/10/2011	9/24/2011	74.4	136	15	9	4
	6374	9/10/2011	9/18/2011	77	109	9	6	2
	6378	9/10/2011	10/27/2011	51	75	32	5	6
	6380	9/10/2011	10/27/2011	56.9	3701	48	28	20
	6372	9/11/2011	10/24/2011	49	973	44	19	8
	6360	9/14/2011	10/26/2011	44.7	4811	43	41	3
	6364	9/14/2011	10/5/2011	53	257	22	7	4
	6366	9/14/2011	10/25/2011	49.4	628	42	13	15
	6358	9/15/2011	10/14/2011	65.9	791	30	27	7
	6362	9/15/2011	10/29/2011	40.7	3293	45	35	6
	6376	10/12/2011	10/27/2011	49.3	901	16	12	25

TL-total length (cm).
No.—number.
[a] Not included in analyses.

Results of GLMM analyses suggested that both DL and water temperature were significantly related to the presence/absence of striped bass ($n = 35$; $DL = 17.59$, $z = 8.64$, $p < 0.001$; $T = 2.07$, $z = 8.09$, $p < 0.001$). Upon examination of inflection points (50% probability of presence), the majority of striped bass were shown to have emigrated out of PKD Bay when DL reached 11.6 h and water temperature reached 16.8 °C.

3.2. Space use and site fidelity

Tagged striped bass were detected by 32 of 34 receivers deployed during the study period (Table 2). Individual receiver detections per day ranged from 0.3–2312 (19 ± 41) detections/day (Table 2). R16, on the northern point of Clarks Island (Fig. 1), had the most visits per day, detecting a total of 23 unique fish over the course of the study. Spatial use patterns of PKD Bay also changed monthly (Fig. 2), with the greatest proportion of detections found to be highest in zone 1 over the entire monitoring period. During the month of August, all tagged fish showed restricted movement and were detected only within zones 1 (98% of detections), zone 2 (2% of detections), and briefly on receiver R25 in zone 3. Tagged fish were detected in all four zones during June, September and October.

The lattice-based activity space analysis indicated that striped bass make use of a range of habitats within PKD Bay (Fig. 2). Although the extent of space use differed among months, striped bass consistently used core habitat in the northern region of the bay (near a large wooden bridge and tidal marshes), near the north end of Clarks Island, and within the main channel nearest to Jones River in zone 2. Total activity space varied among individuals [50%: 0.1–7.7 (2.8 ± 1.6) km^2 and 95%: 4.7–32.9 (16.5 ± 7.7) km^2], but was there was no significant relationship between body size of the fish and 50% ($df = 32$, $t = -0.488$, $p = 0.629$) or 95% ($df = 32$, $t = 1.502$, $p = 0.14$) activity space estimates (Table 3).

Mean weekly activity space varied greatly over the study period (Table 3; Fig. 3). During the week of August 7–13th, mean weekly activity space was at its lowest, and steadily increased in the following weeks. The greatest increases in mean weekly activity space occurred during the month of October, reaching a maximum in the final two weeks of the monitoring period. The results of GAMM analyses indicated that both 50% and 95% weekly activity space estimates were significantly related to mean weekly water temperature and week of study (Table 3). Lower mean water temperatures yielded higher weekly activity space estimates. A positive relationship was also evident between fish length and 50% weekly activity space estimates (Table 3).

High site fidelity was observed within zones 1 and 2 where activity space estimates identified core habitat use. Groups of individuals spent their entire residency in one or two zones, only moving to other areas in September and October. For the thirteen striped bass (41.9%) that displayed strong site fidelity to zone 1 throughout the entire monitoring period, SFI value ranged from 0.50–0.94 (0.74 ± 0.16). SFI value ranged from 0.62–0.98 (0.77 ± 0.14) for the eight fish that displayed strong site fidelity

Table 2
Summary of telemetry data from 35 striped bass tagged with acoustic accelerometers in PKD Bay.

Zone	Receiver Number	Total Detections per Day	July	August	September	October
1	R01	4	2	0	0	16
1	R02[a]	232	179	213	239	293
1	R03	57	73	0	2	160
1	R04	7	0	0	2	28
1	R05[a]	4	0	0	0	15
1	R06	7	14	0	1	14
1	R07[a]	23	0	27	33	30
1	R08	15	10	0	2	50
1	R09	0	0	0	0	0
1	R10	4	14	0	0	1
1	R11[a]	5	0	0	17	4
1	R12	9	33	0	0	7
1	R13[a]	27	2	0	2	102
1	R15	1	3	0	0	2
Detections/Rday		30	23	20	24	55
2	R19	25	0	3	4	97
2	R20	2	4	5	0	0
2	R21[a]	14	18	0	0	40
2	R22	1	4	0	0	0
2	R23[a]	4	1	0	1	15
2	R30	18	59	0	4	12
Detections/Rday		11	13	1	1	26
3	R14[a]	14	29	0	0	29
3	R16	37	41	0	8	102
3	R17[a]	6	0	0	21	4
3	R18[a]	18	16	0	5	52
3	R24	48	0	0	84	105
3	R25	11	2	5	18	19
3	R26	2	0	0	1	7
3	R27[a]	1	0	0	0	2
3	R28	2	0	0	6	3
3	R29	[b]	[b]	[b]	[b]	[b]
3	R31[a]	2	2	0	0	17
3	R32	1	0	0	0	6
Detections/Rday		13	7	0	12	27
4	R33[a]	0.4	5	0	1	1
4	R34	4	11	0	6	10
Detections/Rday		2	8	0	3	6

[a] Receiver with temperature logger.
[b] Receiver lost after deployment.

in zone 2. Four striped bass showed strong site fidelity for zone 3, with SFI ranging from 0.52–0.99 (0.71 ± 0.21) and only one striped showed high site fidelity in zone 4 (SFI = 0.53). Six of the tagged striped bass (19.4%) showed residency spread among zones 1, 2, and 3, north and west of the PKD Bay inlet. The majority of the fish exhibited a SFI < 0.1 for zone 4, indicating that striped bass did not use this area as regularly.

4. Discussion

Our study provides detailed information on the movement patterns and habitat use for striped bass using a non-natal estuary. Overall, the majority of tagged striped bass were resident within PKD Bay during the summer months (July–October) before emigrating from the bay to putatively commence their southern fall migration. Juveniles through adults were encompassed within the size range of tagged striped bass, demonstrating that the estuary is utilized by individuals in a range of sizes, ages, and life stages. The results of our study are consistent with others that have demonstrated that large juveniles (21–46 cm) and adults exhibit seasonal residency to coastal estuaries, particularly during the spring and fall (Able et al., 2012; Able and Grothues, 2007; Grothues et al., 2009).

It has been previously suggested that coastal estuaries provide important nursery habitat for juvenile fish (Able et al., 2012), but residency could also be dependent on the presence of important prey species targeted by striped bass (as suggested by Nelson et al., 2006; Pautzke et al., 2010). Other areas off the Massachusetts coast have previously been identified as summer foraging habi-

Table 3
Summary of total and weekly activity space estimates, including the results of GLM (looking at relationship between size and 50% and 90% total activity space) and GAMM (generalized additive mixed models) models (TL, average wk temp, time (wk of monitoring period on 50 and 95% weekly activity space). The table shows sample size, range, and mean ± SD of all activity space estimates for 2011. Significant relationships ($p < 0.001$) are in bold.

Tagging Group	n	Activity Space (km2̂)	TL (cm)		Temp		Week	
WAS%95	214	0.13 – 26.36 (7.78 ± 5.02)	$t = 2.89$	$p = 0.004$[*]	**$F = 58.88$**	**$p < 0.001$**	**$F = 27.25$**	**$p < 0.001$**
WAS%50	214	0.05 – 6.68 (1.70 ± 1.12)	**$t = 4.422$**	**$p < 0.001$**	**$F = 33.72$**	**$p < 0.001$**	**$F = 24.64$**	**$p < 0.001$**

TL-total length (cm).
TAS- Total activity space estimate.
WAS- mean weekly activity space estimate.
[*] Zuur et al. (2009) recommends using $p < 0.001$ to choose significant relationships.

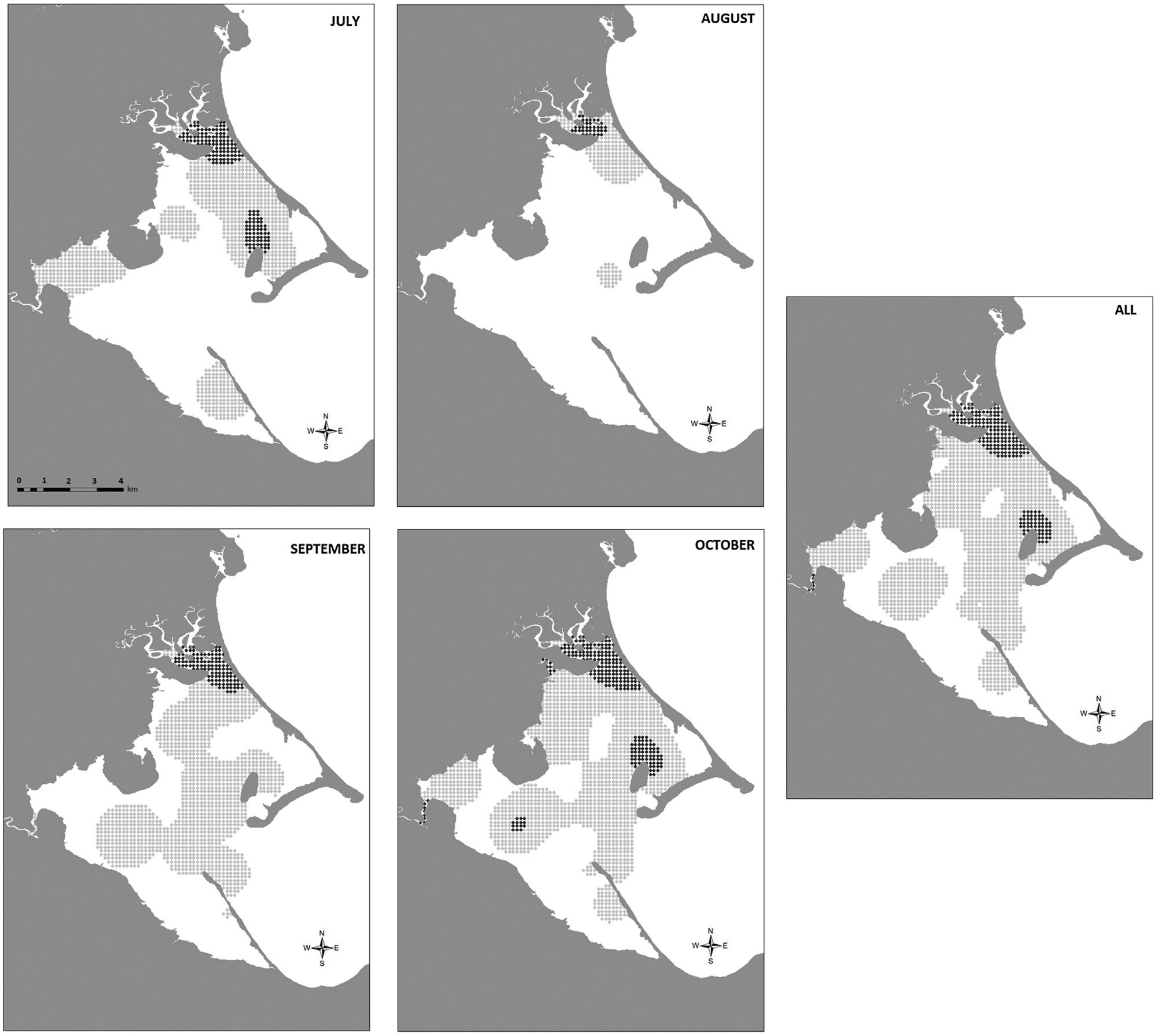

Fig. 2. Estimates of striped bass 95% and 50% activity space within PKD Bay across months of study period (July, August, September, and October) and total activity space.

tats. Pautzke et al. (2010) used telemetry to observe striped bass (n = 46) within Plum Island Estuary, Massachusetts and suggested that both short term and long term residents where using the non-natal estuary as foraging grounds. Nelson et al. (2006) reported that targeted prey species varied over the seasonal residency of striped bass species in northern Massachusetts including forage fish and several crustaceans. Therefore, PKD Bay, along with many New England coastal estuaries could provide vital habitat for juvenile through adult bass prior to their annual migration. Foraging may be an important factor in influencing moment patters of striped bass within an estuary, however further research into measuring diet as it relates to movement is warranted.

4.1. Residency

Seasonal residency periods and the timing of migratory movements have been shown to vary along the east coast of the United States (Able et al., 2012). In our study, all but one of the tagged striped bass were observed to emigrate from PKD Bay during the late summer and early fall. Many of these fish (67%, n = 22) were also detected on receiver arrays in Connecticut and New Jersey deployed as part of the Atlantic Cooperative Telemetry (ACT) Network (www.theactnetwork.com), confirming that emigration from PKD Bay was coincident with the commencement of southward migration. Prior tagging studies on striped bass have also observed coastal migration patterns during the fall months (e.g. Boreman and Lewis, 1987; Waldman et al., 1999; Kneebone et al., 2014) with migratory behavior thought to occur, in part, as a result of water temperature and photoperiod. For example, Wingate and Secor (2007) showed that tidal Hudson River striped bass emigrated from the river at a mean temperature of 15 ± 4 °C. Photoperiod has also been shown to influence emigration of other migratory species within the PKD estuary including sand tiger sharks (Kneebone et al., 2012). In the present study, most of the striped bass (69.7%) emigrated from PKD Bay when the water temperature dropped below 16.8 °C during the last two weeks of the monitoring period (October 16th – 29th) and DL reached 11.6 h.

Residency times of striped bass in coastal estuaries appear to be size-dependent. Only two individuals (74.9 and 80.5 cm TL) left the bay prior to September 5th within 18 days of being tagged (Table 1) and could have been responding to an unknown potential stressor (Cooke et al., 2004), or responding to prey availability.

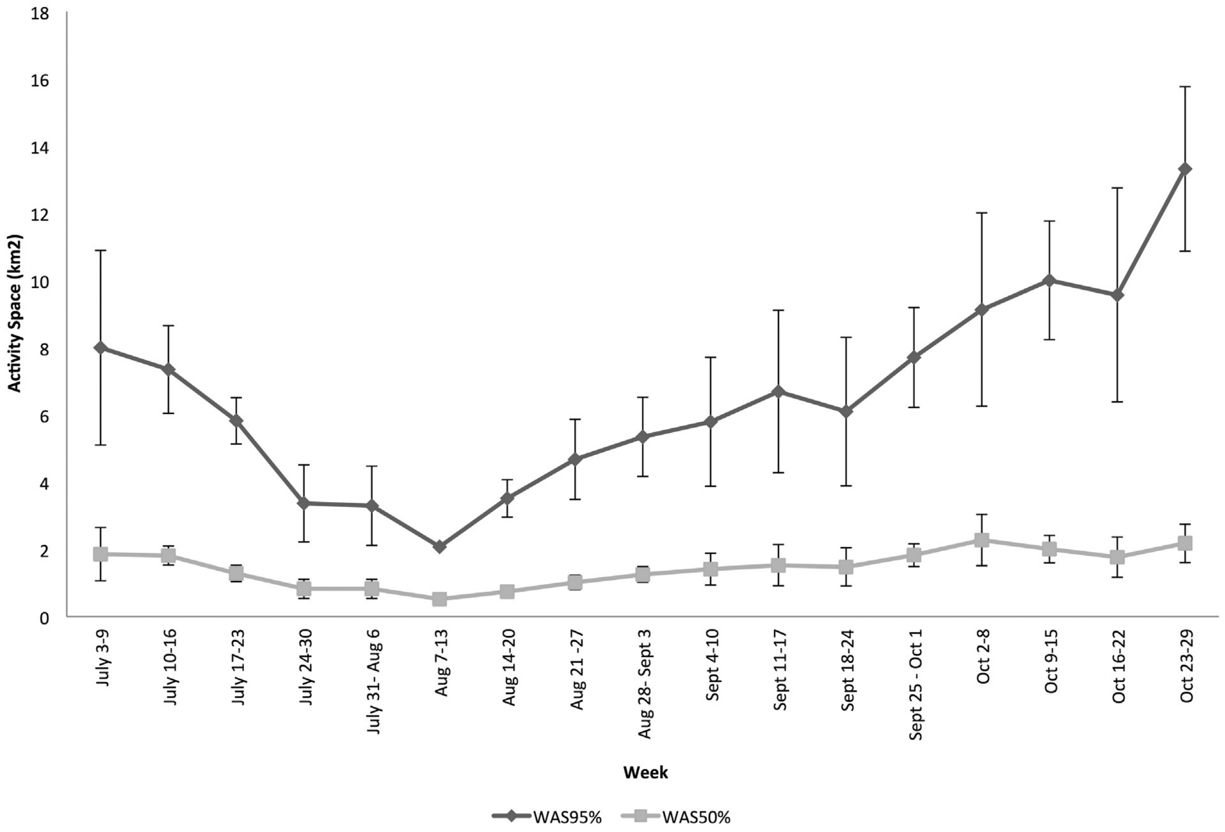

Fig. 3. Mean weekly activity spaces (95% and 50%) for 2011 (17 weeks) ±1 standard deviation.

However, as these were larger fish, it was not uncommon for them to move offshore earlier than smaller, juvenile fish (Clark, 1968). One individual fish (TL = 40.1 cm) was not confirmed to have left the bay before receivers were hauled (last detected in the northernmost marshes within PKB Bay on the last date the receivers were in) and may have been a year round resident of this estuary or could have emigrated following the removal of the receivers. Striped bass showed a negative relationship between residence time and TL suggests that smaller and likely younger individuals benefit from extended habitation of the non-natal area that could provide important foraging resources. Able et al. (2012) found that juvenile fish (<46 cm) could remain full-time residents of non-natal estuaries in New Jersey.

4.2. Activity space and site fidelity

Striped bass were observed to utilize a broad area of PKD Bay and occur in a wide range of habitats. Previous studies have shown that striped bass tend to be associated with habitat providing diverse, vertical relief (such as banks, sandbars, bridges, channel markers and other submerged structures; Harding and Mann, 2003; Ng et al., 2007). In this study, nearly half of the tagged striped bass were detected by receivers deployed in areas with a mosaic of habitat types such as those indicated in previous studies (Harding and Mann, 2003; Ng et al., 2007; Mather et al., 2009). The striped bass spent the majority of their time within zones 1 and 2 (Fig. 1), accounting for 88.8% of all detections. Zone 1 includes a variety of submerged structures including suspended oyster aquaculture grow-out platforms, a large wooden bridge (Powder Point Bridge), freshwater input, and many sandbars and eelgrass (*Zostera marina)* beds. Zone 2 contains a complex network of deep channels, large rock formations that extend above the surface, and also shares similar natural features to zone 1, including eelgrass flats and freshwater inflow. Zone 3 did demonstrate important habitat near the north end of Clarks island where deeper boat moorings boarders a shallow flat. Throughout the study, zone 4 consistently had the lowest proportion of detections and activity space estimates, however the number of detections in Zone 4 was likely due to the fact that only two receivers were deployed there and may not actually be indicative of limited use.

Overall, high site fidelity was evident within zones 1 and 2, where activity space estimates showed core habitat use. Given the high degree of site fidelity one would expect that the number of detections would be directly related to release location. Tagging efforts were concentrated around the presence of striped bass schools and as a result, more fish were tagged in zone 1 and 2 during July and August and shifted to zones 2 and 3 in September. This shift may have occurred as a result many environmental factors such as temperature fluctuation (Graves et al., 2009; Mather et al., 2009), forage fish distribution and variation in prey species throughout the study period (Harding and Mann, 2003; Ferry and Mather, 2012). Although further research and data to quantify diet is necessary, other studies have observed trends in movement related to prey selection and distribution (Ferry and Mather, 2012). While the majority of striped bass were tagged and released in zones 1 and 2 areas, striped bass did migrate between zones throughout the study and many individuals were residents of a different zone than the one in which they were originally captured. Only two individuals were tagged in zone 4, though neither remained residents.

Weekly activity space estimates suggest that fish were distributed in zone 4 throughout most of the study (Fig. 2). Although the number of receivers was low in Zone 4 (n = 2), they were deployed in channels where striped bass, if present, would likely be detected. Zone 4 is similar to each of the other zones within PKD Bay and contains comparable natural features and habitat variability; however, it is in close proximity to Plymouth Harbor.

Plymouth Harbor is a relatively large commercial and recreational boating port with an abundance of anthropogenic activity. Other top predators, such as juvenile sand tiger sharks, have been suggested to avoid Plymouth Harbor due to high boat activity in the area (Kneebone et al., 2012). Although it appears as though striped bass do not utilize zone 4 throughout the year (Fig. 2), a large school of striped bass was encountered in the shallow eelgrass flat to the west of the main channel that runs between R33 and R34 (personal observation, Jeff Kneebone). Therefore, fish may actually make use of this specific habitat within zone 4, however, the lack of a receiver in that very shallow area precluded a definitive assessment of its relative use.

Weekly activity space changed significantly across the study period concentrating within two main core habitats in zone 1 and 2 closest to the Black River and Jones River freshwater inputs within PKD Bay throughout the month of August. It then expanded again to encompass most of the estuary prior to emigration in September and October. Ng et al. (2007), similarly observed a decrease in detection of tagged fish in August, followed by an increase in movement rates during October in a New Jersey estuary. This increase was suggested to occur in response to cooler water temperatures and/or emigration from the estuary (Ng et al., 2007). Within PKD Bay, mean weekly water temperature could be a possible influencing factor (potentially altering prey distribution) leading to striped bass activity concentrating around major freshwater inflows for the estuary during the month of August when high water temperatures were observed (19.8± 1.5 °C across the bay). Further research is necessary in order to effectively assess the influence of environmental factors on striped bass habitat use in these dynamic areas.

Increases in activity space by striped bass during the end of the season may have also been related to increase foraging prior to emigration from the bay (Pautzke et al., 2010). Adult Striped bass typically forage heavily on forage fish, including Atlantic menhaden, before migration (Raney, 1952; Graves et al., 2009) while juvenile striped bass typically target prey such as insect larvae, small crustaceans, mayflies, and other larval fish (Karas, 1993). Menhaden schools were observed to be highly abundant during the season (also documented by Kneebone et al., 2012) and may have been targeted by the largest tagged individuals. Ecologically, factors such as water temperature and prey availability could drive striped bass distribution within New England estuaries and could be confirmed by further detailed studies.

4.3. Conclusion

Juvenile, small individual, and adult striped bass remain residents of PKD Bay through fall and seemingly use the estuary as a vital summer foraging area. Habitation of the estuary coincides with popular periods of commercial and recreational fishing which have grown extensively, making striped bass one of the most targeted species along the northeastern U.S. coast. This warrants the need for educated management decisions to maintain a healthy fishery and ecosystem. Further documentation of these free-ranging marine species in space and time is important to understanding the fundamentals of their natural history, ecological interactions, and habitat to aid in effective management and conservation efforts.

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