Distribution Patterns of Migratory Striped Bass in Plum Island Estuary, Massachusetts

DISTRIBUTION PATTERNS OF MIGRATORY STRIPED BASS IN PLUM ISLAND ESTUARY, MASSACHUSETTS

A Thesis Presented

by

SARAH M. PAUTZKE

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER of SCIENCE

September 2008

School of Marine Sciences

DISTRIBUTION PATTERNS OF MIGRATORY STRIPED BASS
IN PLUM ISLAND ESTUARY, MASSACHUSETTS

Thesis Presented
by
Sarah M. Pautzke

Approved as to style and content by:

_____
Martha E. Mather, Chair

_____
Linda A. Deegan, Member

_____
John T. Finn, Member

_____
Robert M. Muth, Member

_____
Steve Cadrin, Member

_____
Paul Fisette, Department Head
Department of Natural Resources

DEDICATION

To my wonderful, supportive parents

ACKNOWLEDGEMENTS

A very special thank you to my parents who first encouraged me to quit a lucrative yet miserable job to attend graduate school and then supported me emotionally, mentally, and financially. Thank you also to my fiancé, Chris, who also supported me mentally and emotionally, even when it meant filling me with ice cream to soothe frazzled nerves!

Thank you to my advisor, Dr. Martha Mather, who guided me thru field preparations, committee meetings, data analysis and thesis preparations, but who also put in a great amount of field work and pushed through, even when I made her seasick! I would like to thank Dr. Linda Deegan for her intellectual and emotional support, as well as the PIE LTER, which allowed me to use the field house and dock. And also, I'd like to extend my gratitude to my other committee members: Dr. Robert Muth, Dr. Jack Finn, and Dr. Steve Cadrin, who not only intellectually challenged me, but provided support any time I needed it.

I would like to thank the numerous scientists and friends who volunteered time to help with field work and to fix the boat, including Andria Villines, Fiona Hogan, Joseph Smith, Holly Frank, Christian Picard, Todd Surrette, and many others. Without their help, this project would have been much more difficult! Also, thank you to Dr. Callahan and Maurella from the Ipswich Animal Hospital who provided invaluable guidance about antibiotics and suturing, and went above the call of duty helping me order and prepare surgical supplies.

I thank Neil Perley for his help with the research boat and guidance about river navigation and boat maintenance. A big thank you also goes to Barry Clemson who not

only took us fishing and provided much-appreciated insight into striped bass behavior, but also came to the rescue when I learned an important lesson: never try to paddle 18 km against the current!

A big thank you goes to the Ipswich Yacht Club that allowed me to use a mooring and the dock from which to attach receivers. I would also like to thank the people who returned receivers that "got away" from their anchorings. An enormous thank you to all people who adopted bass and thus helped fund this project: Perley's Marina, NH CCC, Martha's Vineyard Surfcaster's Association, New England Saltwater FlyRodder's Association, Jack Finn, mom and dad, ReelTime Fishing Forum, New England Kayak Fishermen Forum, Jim Waldron, Bill DiMento, and many more. Thank you also to Brian Rothschild, Kevin Stokesbury, the UMass School for Marine Science and Technology, the School of Marine Sciences, and the Marine Fisheries Institute for funding this project for two years. A warm thank you to Dean Gamache of the School of Marine Sciences for providing funding for my third year.

Lastly, thank you to Tom Savoy of Connecticut Department of Environmental Protection and Dewayne Fox of Delaware State University for relaying data on my striped bass collected in their respective arrays in Long Island Sound and Delaware Bay.

ABSTRACT

DISTRIBUTION PATTERNS OF MIGRATORY STRIPED BASS
IN PLUM ISLAND ESTUARY, MASSACHUSETTS

September 2008

SARAH M. PAUTZKE, B. S., WESTERN WASHINGTON UNIVERSITY

M.S., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Dr. Martha E. Mather

This is the first study to assess how the coastal migratory stock of striped bass (*Morone saxatilis*) uses non-natal New England estuaries during their foraging migration. Using hydroacoustic telemetry from June through October in Plum Island Estuary, Massachusetts, I examined how long coastal migratory striped bass stayed throughout the seasons, if they were equally distributed, if individual striped bass were distributed differently, and if distribution changed with season, tide, or light. Striped bass, ages 2-5 (300-480 mm), were tagged with VEMCO transmitters in the spring and summer of 2005 (N=14) and 2006 (N=46). They stayed for an average of 66 days in 2005 (SE=7.6) and 72 days in 2006 (SE=6.2). Of the fish tagged in 2005 and 2006, 60% remained for longer than 30 days. This might reflect two striped bass migration strategies: 1) transient migration, in which striped bass visit many estuaries, and 2) estuary-specific, in which they reside in a single location for the summer. The amount of time the striped bass spent in six reaches delineated within the estuary was quantified. Striped bass were not evenly distributed across these reaches. Instead, they spent the most time in the mid Plum Island Sound and lower Rowley River reaches in both years. Three different uses of PIE were observed. Some striped bass stayed briefly (5-20 d; N=24), some stayed primarily in the

Rowley River (N=14), and others stayed primarily in Plum Island Sound (N=22). Striped bass use of the mid Plum Island Sound and lower Rowley River reaches remained consistently high in spring and summer, but decreased in fall, while use of the lower Plum Island Sound did not vary much. Use of other reaches varied seasonally. Tide and light were less associated with distribution, but in the summer the Rowley River use-group increased utilization of tidal creeks during the day, though not at high tide. These three use-groups identified in Plum Island Estuary may be foraging contingents that may learn how to forage in specific parts of the estuary demonstrated by over half the striped bass remaining for much of the summer and congregating in distinct areas.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Striped bass (*Morone saxatilis*) are top predators in marine, estuarine, and freshwater environments along the Atlantic Coast of the United States (Collette and Klein-MacPhee 2002) and exhibit several distinct distribution patterns. Some are coastal migrants (Clark 1968), some stay within a particular estuary and only make upriver-downriver migrations (Carmichael et al. 1998; Wingate and Secor 2007), and others remain landlocked in freshwater their entire lives (Farquhar and Gutreuter 1989; Jackson and Hightower 2001). In the spring, the majority of the coastal migratory stock of striped bass spawns in the Chesapeake Bay, Delaware Bay, and Hudson River (Figure 1). After spawning, they migrate as far north as Nova Scotia before returning to the mid-Atlantic in the fall (Clark 1968; Kohlenstein 1981; Dorazio et al. 1994; Waldman and Fabrizio 1994). These coastal migrants spend much of the summer feeding in New England (Kohlenstein 1981; Waldman and Fabrizio 1994). Existing studies of striped bass distribution and movement include older studies on coastal migrants using external tag data (e.g., anchor, ALS; Clark 1968; Kohlenstein 1981; McLaren et al. 1981; Boreman and Lewis 1987; Waldman et al. 1990; Dorazio et al. 1994). They also include more recent acoustic telemetry studies of fish that migrate up and down river and possibly move offshore in Albemarle Sound-Roanoke River, NC (Haeseker et al. 1996; Carmichael et al. 1998), or that are landlocked in Lake Gaston, VA-NC (Jackson and Hightower 2001; Hightower et al. 2001). Very recently, acoustic tagging studies have added to the literature about coastal migrants in the natal (spawning) Hudson River (Wingate and Secor 2007) and Delaware Bay (Tupper and Able 2000), and in the non-

natal estuaries of, Mullica River – Great Bay, and Saco River (Ng et al. 2007; Able and Grothues 2007; Grothues et al. *in review*). However, little is known from either external or acoustic tag data about the summer estuary use by coastal migratory striped bass in non-natal New England estuaries, even though this is a primary foraging location. In this study, I used acoustic telemetry to observe individual migratory striped bass within Plum Island Estuary (PIE) in Massachusetts, an integral estuary in their summer New England distribution, to determine the duration of estuary use and differences in individual behavior patterns.

How fish are distributed can directly affect fish growth, mortality, and diet (Szedlmayer and Schroepfer 2005; Wingate and Secor 2007). Thus, knowledge of distributions and migration patterns provides a sound basis for effective management and conservation such as habitat restoration, creation, or protection (Tupper and Able 2000; Starr et al. 2002; Clark et al. 2004; Szedlmayer and Schroepfer 2005). In the studies in Delaware Bay, Mullica River-Great Bay Estuary, Saco River Estuary, Lake Gaston, Roanoke River-Albemarle Sound, and the Hudson River, striped bass are often distributed non-randomly. This non-random distribution may be related to estuarine morphometry, temperature, salinity, or dissolved oxygen (Coutant 1985), or potentially to prey distributions. In some cases, striped bass concentrate near shorelines (Ng et al. 2007) or near structures (submerged or visible; Haeseker et al. 1996 Tupper and Able 2000), stay in one portion of the estuary, lake, or river for prolonged periods of time (Able and Grothues 2007; Jackson and Hightower 2001; Wingate and Secor 2007), congregate at creek mouths (Tupper and Able 2000), or remain in either the river or inlet (Grothues et al. *in review*). Striped bass are eurythermal (18-25°C tolerance, 20-22°C for

optimal growth; Coutant 1985), but their distribution can be influenced by changes in temperature (Coutant 1985; Coutant 1990; Tupper and Able 2000). Striped bass are euryhaline, residing in both the ocean and freshwater lakes, and salinity may or may not affect them directly. Striped bass distribution may be affected by dissolved oxygen (DO) in freshwater and estuarine habitats (Coutant 1985; Coutant 1990). Striped bass may also distribute themselves within an estuary based on prey availability. Striped bass are opportunistic and generalist feeders (Tupper and Able 2000; Hartman and Margraf 2003) that consume a variety of forage fish and invertebrates based on prey availability and abundance, the body size of the striped bass, and the foraging habitat (Nelson et al. 2003; Walter et al. 2003; Nelson 2005). Striped bass are often distributed at creek mouths and other restrictive places (Waldman et al. 1990; Tupper and Able 2000) that may congregate prey. Striped bass distribution may change with tide or light. Tupper and Able (2000) showed that striped bass move upriver on ebb tide and downriver on flood tide, possibly allowing striped bass to stay with their prey.

PIE experiences distinct changes in seasonal productivity, which is common to many temperate estuaries (Day et al. 1989). Because of its location, food resources for migrating fish may be available for a longer period than in other coastal estuaries that migratory striped bass encounter. Within this spatially-heterogeneous and temporally-dynamic estuary, striped bass may exhibit different patterns of estuary use within and across seasons.

The primary objectives of this study were to use hydroacoustic telemetry to assess migratory striped bass distribution in non-natal PIE, determine their residency within and across seasons, and examine if individual fish behaved differently. First, I assessed if

there was prolonged use of the estuary by the same striped bass from late May through October, i.e., if striped bass stayed more than 30 non-consecutive days within PIE, thus exhibiting residency. Second, I determined if they were distributed non-randomly, i.e. spent equal time in all reaches throughout PIE or if they favored specific reaches. Third, I determined if individual striped bass used PIE differently, allowing classification of striped bass into distinct groups. Finally, I asked if season, and/or tide or light, might alter migratory striped bass distribution within PIE.

CHAPTER 2

METHODS

Study Site

Plum Island Estuary (PIE) is the largest salt marsh-dominated estuary in New England (60 km^2; 42° 43' N x 70° 48'W; PIE-LTER 2001; Komarow et al. 1999) and is part of the Great Salt Marsh ecosystem, a barrier beach dune / salt marsh system that includes 101 km^2 of contiguous salt marsh (Figure 2; WHSRN 2005). PIE is comprised of three coastal rivers, multiple tidal creeks, and a large embayment – Plum Island Sound (PIS) (Figure 2). The Ipswich River and Parker River are the two major drainages, with the Rowley River (RR) considered a secondary drainage of PIE (Vallino et al. 2005). PIE is a coastal plain, bar-built estuary with extensive productive marshes and a large semidiurnal tidal range of 2.9 m (Vallino et al. 2005). The entire estuary, including the rivers, tidal creeks, and PIS, is vertically well-mixed due to the large tidal amplitude, shallow depths, and low freshwater input (Deegan and Garritt 1997; Vallino et al. 2005). The water body area of the entire estuary at high tide is 20 km^2 and at low tide is 12.8 km^2, during which extensive areas of nonvegetative tidal flats are exposed (Vallino et al. 2005). PIE has an annual dissolved oxygen (DO) range from 4.8 to 12.8 mg/L (Vallino et al. 2005). During the summer, water temperatures throughout PIE range from <18 ^{o} C to >25° C and DO is usually greater than 4.8 mg/L (Young et al. 1999; Vallino et al. 2005; PIE 2007; Deegan et al. 2007). Salinity typically ranges from 22-30 PSU because there is little freshwater input and high tidal exchange (spring neap range: 2.6 – 4m; Young et al. 1999; Vallino et al. 2005; Deegan et al. 2007). PIE hosts a range of striped

bass prey including crabs, *Crangon*, menhaden, and herring (Deegan and Garritt 1997; Hughes et al. 2000; Tupper and Able 2000; Walter et al. 2003).

PIE, in this study, was divided into two areas: Plum Island Sound (PIS) and the Rowley River (RR) (lengths 8 km and 7.6 km, respectively) (Figure 3). Each area was divided into three reaches, which are defined as sections with qualitatively comparable habitats. Below I describe the salinity, substrate, and bathymetry within each reach and also the respective locations, temperatures, depths, and tidal extents because they might affect striped bass distribution.

PIS has a general salinity of about 29.1 PSU (Deegan et al. 2007). The bathymetry and substrate change from the southernmost entrance of PIS to the northern end. Three reaches comprise PIS: lower PIS, mid PIS, and upper PIS (Figure 3). The first southern-most reach, lower PIS (length 2.4 km, area 1.97 km^2), includes the entrance from the ocean, is deep (~4.7 m; Vallino et al. 2005) and wide (average 720.7 m) with steep shores, and is fed by the Ipswich River. The substrate is primarily rock and sand (Figure 3) (Deegan and Garritt 1997) and is the coolest of the reaches during the summer (average temperature ~15°C). Mid PIS, the second reach (length 3 km, area 3.96 km^2), is shallow (~1.8 m; Vallino et al. 2005) and wide (average 1506.8 m) with a sandy bottom. The RR drains into the mid PIS reach (Figure 3). Middle Ground, an island in the mid PIS reach, has a salt marsh landscape at high tide, but has extensive sand flats at low tide that lead to mussel beds in the surrounding shallow waters. It is only slightly warmer than lower PIS with an average summer temperature of 15.3 ^{o}C. The third northern-most reach, upper PIS (length 2.6 km, area 2.91 km^2), is wide (average 496.4 m) and deep (~5.7 m; Vallino et al. 2005) and is fed by the deeper Parker River (Figure 3). A

connection between the upper PIS reach and the Merrimac River exists at high tide via Plum Island River, which provides access to the ocean. In this reach, the substrate ranges from sandy at the confluence of the Parker and Plum Island Rivers with PIS (which is exposed at low tide) to muddy and more constricted within the two rivers. Upper PIS is warmer (average summer temperature ~18° C) than the other two PIS reaches.

The second area, RR, is narrow, lies within a well-defined channel, drains salt marsh, and is fed by numerous tidal creeks (Figure 3). Because of limited freshwater input during the summer, the salinity does not vary much throughout the RR or its tidal creeks, being controlled instead by the tides. RR was divided into three reaches: lower Rowley River, the upper Rowley River, and the tidal creeks (Figure 3). The lower Rowley River reach (length 2.3 km, average width 166.4 m, area 0.52 km^2; Figure 3), which includes the mouth of the Rowley River, has a combination of a sandy bottom, shellfish beds, muddy banks, and numerous tidal creek mouths. High tide inundates the surrounding salt marsh, while low tide reveals some muddy banks (mean depth ~3 m). It is cooler (average temperature ~17° C) than the other two RR reaches and, in general, salinity ranges from 26 to 32 PSU (Hopkinson et al. 1999). The fifth reach, the upper Rowley River (length 3.4 km, average width 42.2 m, area 0.19 km^2; Figure 3), is more narrow and shallow (mean depth ~2.5 m) than the lower Rowley River and has mostly muddy substrate. At high tide, the salt marsh is inundated with water, but at low tide, the steep muddy banks of the channel are exposed. It is warmer (average temperature ~18.5^{o} C) than the lower RR. The last reach within the Rowley River is comprised of two tidal creeks (length 1.9 km, average width 25.5 m, area 0.06 km^2; Figure 3), which are warmer

(average temperature ~18° C) than the lower Rowley reach and get very shallow or go dry at low tide (depth <1 m; high tide depth ~2 m), revealing extensive muddy tidal flats.

Tagging

I used VEMCO V13-1H-R256 coded hydroacoustic tags with a frequency of 69 kHz and a ping rate of 20 to 120 seconds (20 to 90 seconds in 2005; 40 to 120 seconds in 2006), resulting in an average tag life of 100 days in 2005 and 275 days in 2006. A trade-off exists between tag battery size and size of animal being tagged. A rule of thumb is that tags should weigh no more than 2% of the body weight of a fish in air (Winter 1983), although tag volume may be more important than weight (Brown et al. 1999). The acoustic tags (16 mm; 6.6 g in water) weighed less than 1.8% of the lightest tagged striped bass (368 g) and 0.8% of the mean striped bass weight (789 g).

Striped bass were caught via daytime hook-and-line fly-fishing on an ebb tide in the Mid PIS and lower RR reaches (Figure 2), sites that were about 1km apart. In 2005, fourteen striped bass (mean total length [TL] 418.9 mm, SE=15.2, range 335-510 mm; Table 1)] were caught and tagged on July 15, August 8, and August 26 (Table 2). In 2006, 46 fish (mean TL 433.7 mm, SE=7.6, range 380-634; Table 1) were caught and tagged in two batches: May 27-29 and July 6-7 (Table 2). In 2006, I targeted the 400-500 mm size-class, which is the size group most common to PIE. These fish were 2-6 year striped bass, with the majority being 3-4 years (Nelson 2005).

After capture, fish were held in a large continually-aerated holding tank (378.5 L; 1.3 m x 0.79 m x 0.64 m) before surgery. I surgically implanted the tags into the striped bass, which is a common tag attachment method for striped bass (Haeseker et al. 1996;

Tupper and Able 2000; Wingate and Secor 2007). This method decreases drag and entanglement with the environment, as compared with external attachment (Bridger and Booth 2003). Clove oil, an effective anesthetic for reducing short-term stress response related to handling and surgeries, was used to anesthetize the striped bass (1.5 ml/L; 7.8 minutes, SE=1.6; Ferry 2003) because it has faster anesthetization induction and recovery times compared to MS-222 (Cooke et al. 2004; Kildea et al. 2004). After anesthetization, I weighed the striped bass (wet weight, g) and took length measurements (TL, mm) on a moist measuring board. Equipment and tags were sterilized with Betadine (Szedlmayer and Schroepfer 2005). Using a sterile scalpel, a small incision 2-3 cm long (Figure 4A) was made 2 cm above the ventral midline approximately 1.5 cm behind the pelvic fin through the peritoneal cavity, while ensuring no internal organs were cut. The tag was inserted through the incision into the peritoneal cavity and the incision was closed with dissolvable suture (Haeseker et al. 1996; Szedlmayer and Schroepfer 2005; Figure 4A, B, C). To reduce stress during surgery, the gills and external body surface were irrigated at all times with estuary water. After tagging, the striped bass was then placed in a round recovery tank (113 L; 0.6 m x 0.6 m) filled with ambient estuary water until it was swimming upright (mean = 8.3 minutes, SE=1.2), at which point it was released. The tagging process, from anesthetization to recovery, took 11 minutes on average (SE=0.99). In 2005, all fish were taken to and tagged at a field lab 4.5 km upstream of the Rowley River mouth, held overnight to assay post-tagging mortality, then released on the morning ebb tide. In 2006, fish were tagged at their site of capture, received a dose of injectable Liquamyacin antibiotic (0.1 mg Liquamyacin to 1 kg fish) (Bridger and Booth 2003; Wingate and Secor 2007), and released immediately.

Control Experiment

To assess if striped bass survived tagging, I undertook two control experiments in 2005 and 2006. In the first control experiment in 2005, I held tagged striped bass in a pen after tagging. After 12 to 15 hours, I assessed survival and released the fish. In the second control experiment in August 2006, I held three pairs of tagged and untagged fish (N=6, mean TL 450.8 mm, SE 11.1) in each of three 1.2 m diameter x 1.2 m deep cylindrical holding pens. The pens were composed of cotton mesh netting and a smooth plastic bottom and were attached to floating docks in the Rowley River. The fish were held for 6 days; health and mortality was assessed daily. To assess possible mortality related to tagging, I collected three additional pieces of information: 1) I documented the minimum number of days tagged fish were present in PIE, 2) I determined if fish tagged in 2005 were seen again in PIE in 2006, and 3) I quantified detections of these striped bass in arrays along the coast in Long Island Sound and Delaware Bay operated by researchers at Delaware State University and Connecticut Department of Environmental Protection. I assumed that if fish were detected and moving, they were not killed by the tagging procedure.

Receivers

Placement. I placed receivers throughout the 6 reaches of PIE to provide extensive coverage with minimal overlap. I deployed 18 VR20 receivers in 2005 and 17 VR20 or VR1 receivers in 2006 (Figure 3; Table 3). In 2005, 14 receivers were placed throughout the three RR reaches and four receivers were deployed throughout the three PIS reaches. The receivers in PIS in 2005 were used as gates to ascertain if striped bass

left the study area. Receiver placement was slightly altered in 2006 to reduce coverage in the RR and increase coverage in PIS. In 2006, four sites in the RR were not used and four sites were added to PIS. Additionally, only three sites were used in the tidal creeks in 2006. The receiver orientation, placement in the water column, and direction of the hydrophone dictates how well the tags are heard at each site (Clements et al. 2005; Heupel et al. 2006). The VR20s (2005 N=18, 2006 N=10) were anchored to the bottom; the VR1s (2006 N=8) were suspended 1 m below the water surface. All receivers were moored such that the hydrophone pointed upwards towards the water surface.

Range tests. I assessed the site-specific range of each receiver by moving a tag away from each fixed receiver. Using time-specific GPS, I noted at which point the receiver was unable to detect the tag. This *in situ* range test was performed for each receiver at high and low tides. By inputting the time of tag detections and the time-specified GPS tracks into ArcGIS (Appendix 1), I created vector plots that illustrate the distance that tags could be detected by each receiver at low and high tides (Figure 5). For example, site 2 could hear tags from 80 - 247 m at low tide and 105 - 703 m at high tide (Table 4). Using these vector plots (Appendix 2), I drew polygons in ArcView to quantify the areas that each receiver heard at both high and low tides (Figure 6; Table 4; Appendix 3). Averaged for high and low tides, the receivers could hear for 0.002 - 0.196 km^2 (Table 4). For sites with only mid-tide range test data, the mid-tide data was used as the average. The area for receiver site 10, which had no range measurements because the receiver was damaged before the range test could be performed, was calculated by taking the average for each tide stage at sites 9, 11, 12, and 15 that share the lower Rowley River reach. Average hearing areas of each reach were calculated by summing the

average areas of receiver sites within their respective reaches (2005: 0.005-0.12 km^2; 2006: 0.003-0.15 km^2; Table 5) because striped bass distribution was compared across reaches (not individual receiver sites).

Dates of detection. In 2005, receivers were deployed between July 16 and November 18 and could have detected fish for a maximum of 125 days (Figure 7; Table 6). In 2006, receivers were deployed May 25 and removed November 18; they could have detected fish for a maximum of 177 days (Figure 7; Table 6). In both years, receivers were removed in November when they had not detected any tag for 2 or more weeks. The actual days receivers detected fish (functional receiver time) were reduced by dead batteries, low tide, and receiver malfunction. Thus, I calculated the proportion of deployment time the receivers were functional because I did not want to compare fish data for receivers that were operational for different periods of time. To create the functionality coefficient, I divided the number of days the receiver was deployed by the number of days the receiver was functional. For example, if a site was functional for 8 of 10 days, then the functionality coefficient was 1.25 (10/8). I summarized the dates the receivers were deployed and pulled, the number of days each receiver could detect a fish based on tagging and deployment dates, the number of days during the summer the receivers were functional, and I calculated the functionality coefficient (Table 6). Some receivers were not deployed in a particular year, so they have no information associated with them.

Duration the fish was at a receiver. Each fixed receiver in the array recorded the fish tag code, date, and time of each fish within its detection range. Because thousands of detections combined with varying tag ping rates were non-independent, these raw data

were difficult to interpret. To address this issue, I converted these data to the amount of time (in hours) each fish spent at each receiver. I termed this variable "duration" and calculated it by totaling the time between the first observation and last observation in a time sequence at a receiver in which observations were <15 minutes apart. For example, if a fish was at receiver 1 from 8am to 10am with pings every 5 minutes, then that would result in 2 hours duration at receiver site 1. But, if a fish was at receiver 1 from 8am to 10am, but detections only occurred at 8:00, 8:10, 9:45, and 10, that would result in 25 minutes duration recorded. A fish must have been heard more than one time (more than 1 ping within 15 minutes) to have its data included. The creation of the duration variable is not a common tool in the assessment of telemetry data because generally frequency analyses are performed on the number of pings collected per fish, but I think it serves a number of purposes. Most importantly, it allowed me to avoid the difficult data manipulation necessary to eliminate temporally correlated ping data at any single receiver. Although the time a fish spent at different receivers may be correlated, the time a fish spent at one receiver is not. This is because the ping data were converted into one single duration variable, eliminating the correlation between sequential pings. This duration data at each site for each fish was then multiplied by the respective sites' functionality coefficients to compensate for the time the receiver was not functioning. Durations at each site were combined within reaches for each striped bass. These duration data, duration for each fish per reach, were the data that were used in the repeated measures ANOVAs (described below). The duration data for each fish per receiver were multiplied by the average area of receiver coverage before being combined

into durations per reach for use in the Kolmogorov-Smirnof comparisons to establish observed values that have the same units as expected (hr*km^2) (described below).

Statistical Analyses

Data cleaning. Prior to performing statistical analyses, the quality of the telemetry data was checked by ensuring each fish passed each functional receiver consecutively and by discarding single hit data (Clements et al. 2005). In 2005, to compensate for the release of the striped bass 4 km from their catch site, data for the first four days post tagging were not used. However, no days were removed from the 2006 analysis because the fish were released at their capture site immediately after tagging. Duration of time spent within the six reaches was used (instead of individual site durations) to reduce "zero" data that can hamper statistical analyses. The experimental unit was the fish (White and Garrott 1990; Thomas and Taylor 2006; Guy and Brown 2007). All tests were considered significant at P values less than 0.1.

Residence in Plum Island Estuary. I am defining "residence" to be an extended period of time (>30 d) from late May through October during which striped bass are participating in a foraging migration. To determine residence, I summed the number of days each striped bass was present in PIE. Days present were utilized to determine residency instead of duration data because the entire estuary was not acoustically monitored and hours do not provide a good estimate of the fish's presence over the course of months. For example, two fish logging 200 hours in PIE may have been there for a different number of days. Fish number 1 may have accrued all 200 hours in 9 days,

while the second fish accrued the 200 hours over the course of 45 days, defining the first fish as a non-resident and the second as a resident.

Overall distribution. To ascertain if all striped bass (2005 N=14, 2006 N=46) spent equal times in all reaches or if there were certain reaches they used more than others, I examined how well the observed data (time spent in each reach) fit the expected distribution using the one-sample Kolmogorov-Smirnov (K-S) goodness-of-fit test (Zar 1984). Knowing what distribution striped bass would be expected to use is a difficult question, so I tested if striped bass were using the estuary locations equally (i.e., they were detected one-sixth of their time in each reach). Expected coverage (km^2 x hr) was determined for each site for average tide by multiplying the area for each site by functional receiver time (Table 7). The K-S goodness-of-fit test is used when comparing the goodness of fit of an observed to an expected cumulative frequency distribution to determine if a sample belongs to a predefined distribution. It is more powerful than the χ^2 test when the number of observations is small (Zar 1984; Sokal and Rohlf 1995), thus it was especially useful for 2005 (n=14). The other benefit of the K-S test for this study was that discrete duration data could be used. The assumptions were met for the K-S test: sampling was random, the hypothetical distribution was specified in advance, and ratio data were used (Garson 2007).

Use-groups or contingents, 2006. I plotted time spent in PIS versus time spent in the RR and the percent of time spent in PIS to the percent of time spent in the RR. Then I plotted the individual cumulative distribution frequencies, histograms, and movements. Lastly, I ran a hierarchical, agglomerative cluster analysis using Ward's linkage to partition the data into subsets, or clusters, by the common trait of the proportion of time

each fish spent in PIS and the RR. The cluster analysis was performed only on the striped bass that were in PIE for more than 30 days, i.e., were considered residents.

After the cluster analysis, a multivariate analysis of variance (MANOVA) was performed to test if use-groups (PIS fish and RR fish) used the six reaches differently (Aebischer et al. 1993; Tattersall et al. 2001; Starr et al. 2002; Clark et al. 2004; Menzel et al. 2005). The MANOVA was chosen because I had multiple response variables: duration within six reaches. The assumptions for the MANOVA are homogeneity of variances, no multivariate outliers, the observations are independent within and between samples, there are two or more observations per individual, and the observations are normally distributed (Quinn and Keough 2002; Dytham 2003). The individuals had two or more observations; all individuals were independent. Levene's test was used to test the assumption of homogeneity of variances. Although there is no objective way to fully evaluate the assumption of multivariate normality (McGarigal et al. 2000), I examined the residuals, normality plots, and outliers for all individual ANOVAs for the raw data and the following three transformations: $\log_{10}$, proportion, and arcsin of the proportion; I used the $\log_{10}$ transformation.

A two-population K-S test was used to assess if the use-groups were using the reaches equally and if the same use-group from each year was statistically similar. The non-parametric two-population K-S test is similar to the one-sample except that instead of comparing the observed distribution of a single sample to a theoretical expected distribution, observed distributions of two groups are compared against each other to determine if the observed distributions come from the same overall distribution.

I tested several possible explanations for differences among these use-groups. For example, were fish (2005 only) that resided in the RR smaller or tagged earlier than their PIS counterparts? Similarly, did RR residents exit the estuary earlier than PIS fish? Finally, did RR residents migrate to Delaware Bay as opposed to PIS that might have migrated elsewhere? Thus, I compared four variables across use-groups. This included fish size (2005 only), date of capture, date the striped bass departed the estuary, and whether they travelled to the same migratory destination. Size was tested via the two-population K-S test (Garvey et al. 1998) by grouping the striped bass into two size categories: larger (400+ mm) and smaller (<400 mm). The date of capture and departure, and whether they travelled to the same migratory destination was analyzed thru plotting a histogram to determine if there were any discernable patterns within them. Striped bass dates of departure were binned into 8 date ranges: June (May was included in June because there were only a few days during which the striped bass were tagged in May), July, August 1-15, August 16-31, September 1-15, September 16-30, October 1-15, and October 16-30 (fish were not seen after October 30 in either year), and the number of fish per use-group was compared. Likewise, the capture dates were binned into May, July, August 1-15, and August 16-31, and the number of fish present within each use-group was compared. Whether the striped bass all migrated to Long Island Sound, Delaware Bay, or both was assessed in a table by use-group to see if, for example, all PIS-designated fish went to Long Island Sound and all RR-designated fish went to Delaware Bay, or some other such discernable pattern.

Seasonal distribution. Striped bass distribution across the reaches by season was tested using the two-population K-S test (Garvey et al. 1998) and repeated measures

analysis of variance (RM ANOVA). Season was defined as follows: spring was May and June, summer was July and August, and fall was September to October. I chose the months within each season based on general shifts in water and air temperatures, the day length by September, and the total time striped bass are present in the estuary (mid-May to late October).

An RM ANOVA was used because each factor (season) was repeated for each individual (Jackson and Hightower 2001; Mendina-Vogel et al. 2003). The assumptions for an RM ANOVA are random sampling, normal distribution, homogeneity of variances, and homogeneity of covariances. Because of instances where an assumption was not met for 1 or more reach, a two-sample K-S test was used to support the findings of this season analysis by comparing the seasonal distributions against each other.

Light and tide distribution. Lastly, I wanted to identify the effect of light and tide seasonally on striped bass distribution, so I again used an RM ANOVA. The RM ANOVA allowed me to compare seasonally within each reach across all four light stages and tidal stages to discern their effects on distribution for 2006 (Jackson and Hightower 2001). The light stages were defined as: dawn was considered to be one hour before sunrise to one hour after sunrise, day was one hour after sunrise to one hour before sunset, dusk was one hour before sunset to one hour after sunset, and night was one hour after sunset to one hour before dawn. Similarly, tidal stages were assigned as follows: ebb tide was considered to be one hour after high tide to one hour before low tide, low slack was one hour before low tide to one hour after low tide, flood tide was one hour after low tide to one hour before high tide, and high slack was one hour before high tide to one hour after high tide. Although these stages are temporally variable, assigning

these categories allowed for ease of analysis. To compensate for the temporal variation, I multiplied the durations of low and high slack tides and dawn and dusk crepuscular periods by 12. I multiplied the ebb and flood tides and day and night periods by 2.4. These numbers represent the proportion of time during each 24 hour period that a striped bass could have been detected. For example, a striped bass could be detected 10 of 24 hours during the day, thus 24/10 provides a multiplier of 2.4. This was similar to the procedure for compensating for functional receiver time.

CHAPTER 3

RESULTS

Survival

I used five lines of evidence to evaluate if striped bass were adversely affected by tagging. First, in 2005, the 14 striped bass held overnight were alive and healthy at their release approximately 12 hours post-tagging. Second, the three pairs of tagged and untagged fish held for six days in the 2006 control experiment survived similarly. No fish died and no evidence of tagging stress was observed. All fish were alive and apparently healthy at the end of the experiment and the incisions of the tagged striped bass were healing well. Third, all tagged striped bass were detected at different locations in Plum Island Estuary (PIE), MA a minimum of 6 days after tagging. In the year of tagging, striped bass (2005: N=14; 2006: N=46) remained in PIE from 8-96 non-consecutive days in 2005 (mean=66, SE=7.6) and 6-122 non-consecutive days in 2006 (mean=72.2, SE=6.2) (Figure 8). Fourth, nine of the 14 striped bass tagged in 2005 were re-detected in PIE in 2006 (Figure 8, "PIE again" column), at least 215 days after tagging. Lastly, 32 of the striped bass tagged in PIE were detected in 2005 and/or 2006 in Long Island Sound and Delaware Bay receiver arrays during their fall, winter, and spring migration (Table 8) 90 to 470 days after tagging (Figure 8, "Atl. Coast" column). Many of the fish detected for only a very few days in PIE were detected in the other arrays. Thus, in both 2005 and 2006, all fish survived the tagging, survived the control experiments, and were detected in PIE or elsewhere for at least six days to 470 days post tagging.

Striped Bass Distribution within Plum Island Estuary

Residence in Plum Island Estuary. Coastal migratory striped bass tagged and released in PIE stayed an average of 66 days in 2005 (SE=7.6) and 72.2 days in 2006 (SE=6.2) (Figure 9). To separate fish that spent relatively little time in PIE from those that were present most of the summer, I grouped fish by whether they were detected for more or less than 30 days in PIE based on an observed natural break in the data (Figure 9). Of the 14 fish in 2005, 7 (50%) stayed within PIE for more than 30 days. In 2006, 29 of 46 (63%) striped bass stayed within PIE for more than 30 days. Fish that stayed <30 days were called "short-term fish" and were not included in statistical analyses other than assessing overall distribution. All striped bass left by October 31 in each year.

Overall distribution. Striped bass were not evenly distributed across the six PIE reaches (K-S Test, MANOVA on reaches; 2005 not significant; 2006 $P<0.0001$; Figure 10). Plotting cumulative distribution frequencies also showed that observed distribution differed from that expected based on equal use of all six reaches (Appendix 5). Instead, they spent the most time in the mid Plum Island Sound (PIS) and lower Rowley River (RR) reaches in both years (Figure 10). Similar trends were seen in both years (Figure 10), although they were statistically significant only in 2006, possibly because the larger sample size reduced within-reach variation.

Use-Groups or contingents, 2006. Individual striped bass exhibited different distribution patterns. Some stayed more in the PIS reaches (Figure 11, denoted by dark gray). Some stayed primarily in RR reaches (Figure 11, denoted by light gray). Others stayed in PIE for less than 30 days (Figure 11, denoted by black) (Appendix 6). I designated these groups the RR use-group (Figure 12A), the PIS use-group (Figure 12B),

and the short-term use-group (Figure 12C; excluded from statistical analyses). The PIS and RR groups' use of the six reaches was statistically different (MANOVA; 2006 only; PIS fish, N=18, P<0.0001; RR fish, N=11, P<0.0001). For fish that stayed in PIE more than 30 days, a cluster analysis supported the existence of two distinct groups of striped bass residing for the summer either in PIS or the RR (Figure 13A). Plotting durations of time and percentages of time each fish spent in the RR versus PIS (Figure 13B and C, respectively) reinforced the use-groups identified by the cluster analysis.

Individual examples of each use-group differ by tracks (Figure 14A1, B1, C1), durations in each reach (Figure 14A2, B2, C2), and cumulative observed distribution frequencies compared to that expected if all reaches were used equally (Figure 14A3, B3, C3). For example, a striped bass from the PIS use-group spent the greatest amount of time in the mid PIS reach (Figure 14A1, 2), which was higher than expected (Figure 14A3). A striped bass from the RR use-group spent the most time in the lower RR reach (Figure 14B1, 2), and spent less time than expected in all other reaches than expected (Figure 14B3). Short-term fish were found in both areas for a limited duration (Figure 14C).

These use groupings were not based on date of capture because generally members of all three use-groups were caught in each tagging session (Figure 15A), although more RR fish may arrive in PIE in June (between the May and July tagging dates). They were also not based on the date the striped bass left the estuary because, although short-term fish generally left earlier than their counterparts, there was no consistent pattern that characterized fish leaving PIE (Figure 15B). The groupings were not the result of fish size because tagged striped bass in both the PIS and RR were

comparably sized (two-population K-S test; 2005 P = 0.53, 2006 P = 0.31; Figure 15C). Finally, the use-group categories were also not based on their migratory destination because the proportion of striped bass that travelled to Long Island Sound, Delaware Bay, or both was the same for each use-group (Figure 15D).

Seasonal distribution. In 2006, striped bass changed their use of many reaches by season when considered together (Repeated Measures (RM) ANOVA - Season; Upper PIS P<0.0001, Lower RR P<0.0001, Upper RR P=0.0005, RR tidal creeks P<0.0001; Figure 16; Appendix 7) and when segregated into use-groups (RM ANOVA - Season; Mid PIS P=0.0007, Upper PIS P=0.0007, Lower RR P=0.0002, Upper RR P=0.02, RR tidal creeks P<0.0001; Figure 16; Appendix 7). Overall use declined from spring through fall in most PIS (Figure 16A-C) and RR (Figure 16D-F) reaches. The reaches that received the most use when all striped bass were grouped together were the mid (31%) and upper (23%) PIS and lower RR (25%) reaches in the spring; the mid PIS (27%) and lower RR (59%) reaches in the summer; and lower (37%) and mid (30%) PIS and lower RR (30%) reaches in the fall.

Consistently in all three seasons, the PIS use-group used the three PIS reaches more than did the other two use-groups. Their use peaked in the upper PIS reach in spring, mid PIS reach in summer, and lower PIS reach in fall. Their use of the mid and upper PIS reaches varied by season (Figure 17B, C). The PIS use-group use of lower PIS was greatest in the fall, increasing from <7% in spring and summer to 41% in fall (Figure 17A), although there was no statistical difference between seasons detected for lower PIS. The PIS use-group spent roughly 80% of its time in the spring and 89% of its time in the summer in the mid and upper PIS reaches (Figure 17B, C). Within the RR, the PIS

use-group primarily used the lower RR (Figure 17D), although it was used less than the PIS reaches and the use decreased drastically from spring through fall (Figure 17D).

The RR use-group spent more time in the RR reaches in all three seasons than the other two use-groups (Figure 17D-F). Their use of lower RR peaked in the summer when they used this reach ~96% of the time, then their use decreased substantially in fall to 77% (Figure 17D). The RR use-group use of the upper RR was highest in spring (39%), declining throughout the rest of the seasons (Figure 17E). They used the tidal creeks minimally compared to the other two RR reaches, ceasing use of this reach in the fall (Figure 17F). Although they spent a lot more time in the RR reaches than the PIS reaches in all three seasons, their highest use of PIS was in the upper PIS in spring (5% of their total time in spring) and lower PIS in fall (17.8% of their total time in fall).

Light and tide distribution. The PIS use-group varied their use by light stage in the mid PIS reach in the summer (RM ANOVA – Light by season, PIS fish only; Summer P=0.002), utilizing the reach more during the dawn and day (Figure 18B; light stages 1 and 2). In the fall, the PIS use-group spent more time in the lower PIS reach at night (RM ANOVA - Light by season, PIS fish only; Fall P=0.001; Figure 18A, light stage 4).

The PIS use-group varied their use by tide stage in mid PIS, upper PIS, and lower RR in spring and summer (RM ANOVA - Tide by season, PIS fish only; Spring: mid PIS P=0.02, upper PIS P=0.0004, lower RR P=0.002; Summer: mid PIS P=0.04, upper PIS P<0.0001, lower RR P=0.002; Figure 19B, C, D). Additionally, their use of the lower RR also varied across tide stage in the fall (RM ANOVA – Tide by season, PIS fish only; lower RR: Fall P=0.002). In the spring and summer, the PIS use-group consistently

utilized the mid PIS reach least at ebb tide (Figure 19B, tide stage 1) and the upper PIS and lower RR reaches the least at high slack (Figure 19C, D, tide stage 4). During the fall, although the use of the lower RR was not very great, the PIS use-group utilized this reach primarily at low slack and flood tides (Figure 19D, tide stages 2 and 3, respectively,).

The RR use-group varied their use by light stage only in the summer in the upper RR and RR tidal creeks (RM ANOVA - Light by season, RR fish only; Summer: upper RR P=0.06, RR tidal creeks P=0.0003; Figure 18E, F). In the summer, the RR use-group spent greater time in the upper RR at night and the least use at dusk (Figure 18E; light stages 4 and 3, respectively). In the RR tidal creeks, the RR use-group spent more time during the day and almost no time during dawn in the summer (Figure 18F, light stages 2 and 1, respectively).

The RR use-group varied their use of the lower RR, upper RR, and RR tidal creeks across tide stage only in the summer (RM ANOVA - Tide by season, RR fish only; Summer: lower RR P=0.009, upper RR P=0.002; RR tidal creeks P<0.0001; Figure 19D, E, F). During the summer, the RR use-group utilized the lower RR least at low slack and used the upper RR and RR tidal creeks least at high slack (Figure 19D, E, F, tide stages 2 and 4, respectively).

CHAPTER 4

DISCUSSION

Striped Bass Distribution within Plum Island Estuary

Residence in Plum Island Estuary. Overall, 60% of the migratory striped bass tagged in Plum Island Estuary (PIE) in 2005 and 2006 stayed within this estuary for more than 30 non-consecutive days (average = 69 d) from late May through October and were termed residents. Based on early tag-recapture studies that examine striped bass migratory patterns (Clark 1968; Kohlenstein 1981; Waldman et al. 1990; Dorazio et al. 1994), we know they migrate north in the spring from their natal grounds in the Chesapeake Bay, Delaware Bay, and Hudson River and then return south in the fall, spending much of the summer feeding season in New England waters, roughly between the months of April and November. However, tag-recapture studies do not provide information about the amount of time individual striped bass spend in any one estuary.

Recent studies have examined striped bass distribution via stationary and mobile telemetry for migratory and resident fish in the natal Hudson River (Wingate and Secor 2007), and for migratory striped bass in non-natal estuaries such as the Mullica River-Great Bay Estuary in New Jersey (Ng et al. 2007; Able and Grothues 2007) and the Saco River in Maine (Grothues et al. *in review*). In the Hudson River, resident striped bass generally spend from May through October in the freshwater tidal portion of the Hudson River (Wingate and Secor 2007) during the non spawning season. In the Mullica River-Great Bay Estuary, many striped bass (97.2%) are termed seasonal visitors because they are present in spring and fall, but a few (2.8%) of them stay for a prolonged period of time from April to December (>60d; Able and Grothues 2007; Ng et al. 2007), as they

also do in the Saco River Estuary in Maine from June to November (Grothues et al. *in review*). This is similar to the seasonal residency I observed for coastal migratory striped bass in non-natal PIE from late May through October. However, I found that over half (60%) stayed for a prolonged period of time (>30 d, 2005 and 2006 overall mean = 69 d). Thus, residency that differs in duration occurs for migratory striped bass in NJ, MA, and ME.

Overall distribution. Striped bass residents (present >30 d from May through October) were not evenly distributed throughout the estuary. Instead, the tagged striped bass predominantly used the lower Rowley River (RR) and mid Plum Island Sound (PIS), suggesting these might be focal points (hot spots) in this predator's distribution. The existence of these focal points could be the result of estuarine morphology, prey distribution, and/or temperature. The lower Rowley focal point includes mouths of numerous tidal creeks and complex bottom structure. The mid PIS focal point includes Middle Ground, an island at the center of the mid PIS reach, which provides structure from its banks and access to numerous mussel beds that surround the island, which in turn attract prey for the striped bass. Striped bass utilized the other four reaches much less, perhaps because the bottom structure may not be as complex in the lower and upper PIS reaches, and it may be too warm in the summer in the upper RR and RR tidal creek reaches. Others have also found that within and near estuaries, striped bass are more abundant in locations where prey concentrates, such as river mouths, entrances to tidal creeks, and on hard substrates (e.g., mussel beds) (Waldman et al. 1990; Haeseker et al. 1996; Tupper and Able 2000; Harding and Mann 2003; Ng et al. 2007).

The focal points in striped bass distribution indicate that they are not equally distributed throughout PIE. For coastal migrants, heterogeneous distributions also occur in New Jersey in the Mullica River-Great Bay Estuary and Delaware Bay from spring through fall. In these locations, striped bass are found in deeper water near shorelines (Ng et al. 2007) and at creek mouths (Tupper and Able 2000), and would stay in one area of the estuary for prolonged periods (up to 91% of their time; Able and Grothues 2007), possibly because of water temperature and substrate heterogeneity (Ng et al. 2007). A non-random distribution is also seen in the Saco River Estuary in Maine, where some striped bass spend a larger period of time in the Saco River, while others spend more time in the inlet (Grothues et al. *in review*). In the Hudson River, most non-migrating striped bass spend 1.5-5 months in specific sites with little to no movement to other areas (Wingate and Secor 2007). In Albemarle Sound, NC, which hosts mostly non-migrating striped bass, the striped bass are distributed disproportionately to area and volume of available suitable habitat during the summer, instead staying in proximity to visible structures, such as bridges and channel markers (Haeseker et al.1996). In the Combahee River in South Carolina, striped bass are generally located in proximity to structure, in deep pools, and at river confluences (Bjorgo et al. 2000). In freshwater Lake Gaston, VA-NC, striped bass stay within specific areas throughout all seasons and years, except during spawning (Jackson and Hightower 2001). Additionally, in freshwater Lake Whitney in Texas, striped bass are also found at confluences, creek mouths, and in channels (Farquhar and Gutreuter 1989). Thus, striped bass are often concentrated in specific areas and display a non-random distribution.

Use-groups or contingents, 2006. I identified three use-groups. The short-term use-group (N=17) consisted of striped bass that stayed less than 30 days within PIE. Of the residents (N=29), two more use-groups preferentially used PIS or the RR. The RR use-group (N=11) stayed in the lower RR (0.52 km^2) for almost 80% of the time, while the PIS use-group (N=18) stayed in mid PIS (3.96 km^2) and lower PIS (1.97 km^2) for more than 78% of their time. Fish size, date of departure from PIE, their migratory route, and/or their date of tagging may have explained the presence of an individual striped bass in one use-group or another. For example, larger fish may have used one area, while smaller fish used another. However, fish in the three use-groups did not differ in size.

Striped bass use-groups did not differ based on their date of departure from PIE. Based on their schooling behavior as small adults, each use-group may have migrated together and thus may have left the estuary at the same time. For example, those that resided in the RR might stay later in the estuary than those that resided in PIS. However, this was not the case. My tagged fish tended to trickle out of the estuary, with a specific use-group neither leaving together nor on the same day. These use-groups also did not share a migratory route. Fish that migrated from the Hudson River, for example, might have remained together, resided in one part of PIE together, and then returned to the Hudson River as a group. However, my results indicated that the use-groups that formed in PIE incorporated all three migratory patterns (Delaware Bay only, Long Island Sound only, and migrating to both places). Lastly, if use-groups arrived together, they might have settled into similar areas. Alternatively, the first to arrive may choose the most desirable habitat, leaving late-comers to use other areas. Although date of tagging (known) was not the same as date of arrival (unknown), date of tagging did not differ

much across use-groups. Consequently, obvious reasons (size, departure date, migratory destination, arrival date) did not explain my use-group formations.

My use-groups are similar in many ways to migratory contingents (Clark 1968; Secor 1999; Secor et al. 2001). A contingent was defined by Clark (1968) as a group of striped bass that "engage in a common pattern of seasonal migrations between feeding areas, wintering areas, and spawning areas" "not shared by fish of other contingents." Secor (1999) refined this as "a level of fish aggregation based upon divergent migration behaviors or habitat use within populations." These contingents could be formed by divergent early growth rates and dispersal behaviors associated with early growth (Secor and Piccoli 2007), the grouping by size into distinct behavioral groups (Waldman et al. 1990), heterogeneous distribution of habitat (Secor 1999), or "formed simply by the accident of being brought together in one nursery area as juveniles" (Clark 1968).

There are three contingents within the Hudson River based on spawning and migratory behavior: Hudson River resident, estuarine, and ocean (Hudson Atlantic) migrants (Clark 1968; Secor et al. 2001) and three migratory behaviors within the resident Hudson River contingent (Wingate and Secor 2007). Able and Grothues (2007) identified four different behaviors of striped bass in the Mullica River-Great Bay Estuary: resident, seasonal inlet, seasonal estuary, and seasonal river, but did not use contingents as a conceptual framework to evaluate this behavior. In the NJ study, the authors note that segregation into similar contingents may be difficult because the striped bass were assessed only in two-week observation periods (Grothues et al. *in review*). My study of migratory striped bass in PIE is the first to group individuals based on their use of a estuary utilized for feeding into use-groups, or foraging contingents. These use-groups

within PIE could be classified as foraging contingents if contingents are defined as groups that can change with size, group, and ecological conditions. It is likely that the use-groups will change with ecological conditions and fish size, so probably are not whole-life behaviors. Wingate and Secor (2007) also noted that migratory shifts found in the Hudson River resident contingent provide evidence that "contingents do not have static designations and may shift over time," as opposed to previous definitions of migratory contingents as groups that persist through lives of juveniles and adults (Secor 1999).

Seasonal distribution. As a group, PIS fish utilized several reaches throughout PIE during the spring, but settled into a single reach during the summer. Specifically, the time the PIS use-group spent in PIS increased from 75% in the spring to greater than 90% in summer and fall. RR fish spent more than 93% of their time in the spring and summer in the Rowley River, and their use of the river dropped in the fall (to 77%) when they expanded their use to the lower PIS reach. Such seasonally-dependent behavior also occurs in the Mullica River-Great Bay estuary in New Jersey as well, where, from May through October, striped bass use is divided between the Mullica River and Great Bay (Ng et al. 2007). By September, striped bass in PIE almost entirely ceased use of the Rowley tidal creeks, upper Rowley, and upper PIS, while their use of the lower PIS reach increased, signaling their movement out of the estuary on their migration south in the fall. This trend also occurs in New Jersey in November and December when striped bass move out of the Mullica River and from within the Great Bay estuary to the entrance of the estuary (Ng et al. 2007).

Light and tide distribution. Striped bass use of the estuary did not shift much with different light stages (i.e., dawn, day, dusk, and night). The most notable shift in estuary use with light stage occurred during the summer, when the RR fish displayed increased utilization of the tidal creeks during the day (although their primary use was of the upper and lower RR reaches). Their decreased use of the upper RR from spring to summer during the day was perhaps due to their increased utilization of the tidal creeks. This shift from the upper Rowley to the Rowley tidal creeks may have occurred because the tidal creeks become more productive during the summer than they are in spring, providing increased foraging opportunities. For example, mummichog (*Fundulus heteroclitus*) are nearly absent in June, but increase rapidly in abundance through September, as does the abundance of grass shrimp (*Palaemonetes pugio*) (Deegan et al. 2007). Striped bass are visual predators (Clark et al. 2003), thus it may be advantageous for them to forage during the day in the turbid waters of the tidal creeks to take advantage of increased visibility provided by daylight.

The distribution of striped bass only shifted slightly by tidal stage. Although striped bass primarily used the lower Rowley and mid PIS reaches, the most notable shift in reach use across tide stages was tidal creek use by the RR use-group. Surprisingly, the RR use-group utilized the tidal creeks at ebb, low slack, and flood tides, but were completely absent from them at high slack tide. While tidal creeks may not provide optimal habitat for striped bass at low tide (because of increased temperature due to solar warming of the shallow, slow-moving water), their presence in this reach (except at high tide) could be because the decreased quantity of water concentrates the prey (Tupper and Able 2000) and does not allow the prey refuge within the salt marsh grasses, which are

inundated with water at high tide. The striped bass avoided this reach at high tide, possibly because foraging benefits are lower due to increased prey refugia.

Migratory Behavior

Coastal striped bass undergo a seasonal migration in which they leave their spawning grounds in Delaware Bay, Chesapeake Bay, and the Hudson River in the spring and migrate north as far as Nova Scotia and return south in the fall (Clark 1968; Kohlenstein 1981; Dorazio et al. 1994). Striped bass tagged in PIE (78%) were detected on receiver arrays in Long Island Sound (near the Hudson River) and in Delaware Bay, confirming the fish of this study were part of the coastal migratory stock. The coastal migratory striped bass might migrate in two ways. First, striped bass could be treating each estuary as a temporary food resource. In this transient pattern, striped bass stop by various estuaries on their migration north and south without staying long in any one in particular (Able and Grothues 2007; Grothues et al. *in review*). In this case, the striped bass may not "learn" the estuary and so may not gain as much foraging benefits from each stop as they could otherwise. They may not grow as well if they have more difficulty finding food; however, they may find a more productive estuary. Alternatively, the striped bass of PIE could be exhibiting an "estuary-specific pattern." In this pattern, the striped bass are treating PIE like a summer cottage, staying for an extended period of time throughout the season (Grothues et al. *in review*). This may allow them to learn the estuary, thus knowing where the prey are and how best to forage, which may in turn increase their growth potential. The same patterns may not necessarily be seen everywhere along the Atlantic Coast and are not necessarily mutually exclusive. Rather,

the striped bass may be employing a combination of these two migratory patterns. My short-term fish may represent the fish displaying the transient pattern, while the seasonal residents displayed the estuary-specific pattern. However, my short-term fish displaying a transient pattern of migration in PIE may alternatively display an estuary-specific pattern in a different estuary, such as Saco River Estuary in Maine. These two options can have management implications if sub-lethal effects on seasonal growth and mortality are increased in high catch-and-release areas because people are catching the same fish repeatedly (Stockwell et al. 2002). Additionally, if the same fish are in an estuary all summer, the number of fish people could harvest may need to be reduced in that estuary if it is an estuary in which fishing levels are high, while harvest numbers could be increased in other estuaries that do not see a high amount of fishing.

Table 1. The number of striped bass caught per 25 mm length categories from 325-650 mm.

Size range (mm)	2005	2006
325 - 349	4	
350 - 374		
375 - 399	1	5
400 - 424		22
425 - 449	3	11
450 - 474	5	2
475 - 499		1
500 - 524	1	2
525 - 549		
550 - 574		1
575 - 599		1
600 - 624		
625 - 650		1
Mean	418.9	433.7
Standard Error	15.2	7.6
Median	438.5	413.5

Table 2. Number of striped bass caught per tagging session and location in 2005 and 2006. Fish were released across three dates in 2005 and two sessions in 2006. In 2005, fish were caught without prior catch location designation. In 2006, catch locations were solidified as Mid PIS and lower Rowley River and the catch was divided equally between the two in both release events.

Year	Date	Total Fish	Mid PIS	Rowley River (RR)
2005				
	July 15	6	2	4
	August 8	5	5	0
	August 26	3	3	0
2006				
	May 27-29	24	13	11
	July 6-7	22	11	11

Table 3. The two major areas, six reaches, the number of receiver sites per year, and site numbers associated with each reach in 2005 and 2006. PIS is Plum Island Sound and RR is the Rowley River.

Area	Reach names	Number of receiver sites in 2005	Number of receiver sites in 2006	Receiver Sites
PIS	Lower PIS	2	3	1 – 3
PIS	Mid PIS	1	2	4 – 5
PIS	Upper PIS	1	3	6 – 8
RR	Lower RR	5	3	9 – 12, 15
RR	Upper RR	5	3	18 – 22
RR	RR Tidal Creeks	4	3	13, 14, 16, 17

Table 4. Detection ranges and areas for receiver sites at low and high tide.

	High Tide Range (m)			Low Tide Range (m)			High Tide	Low Tide	Average
Site	min	max	avg	min	max	avg	Area (km^2)	Area (km^2)	Area (km^2)
1	42	598	320	61.3	272	166.7	0.363	0.029	0.196
2	105	703	404	80	247	163.5	0.040	0.127	0.084
3	39	552	295.5	87	480	283.5	0.078	0.247	0.163
4	18	446	232	117	322	219.5	0.084	0.166	0.125
5	70.5	401	235.8	77	204	140.5	0.018	0.284	0.151
6	21.7	791.5	406.6				0.018	0.066	0.042
7	106	312	209	109	127	118	0.004	0.042	0.023
8	17	426	221.5	31	307	169	0.020	0.117	0.069
9	99	432	265.5	39	363	201	0.016	0.123	0.070
10**			240.3				0.026	0.105	0.066
11	192		192	157	350	253.5	0.068	0.156	0.112
12	79	448	263.5	43	134	88.5	0.009	0.117	0.063
13	42	148	95				0.000	0.004	0.002
14				86	238	162	0.006	0.024	0.015
15				27	289	158	0.008	0.046	0.027
16	18	245	131.5	54	129	91.5	0.001	0.010	0.006
17	14	150	82	22	103	62.5	0.000	0.003	0.002
18	20	152	86	17.5	56	36.8	0.002	0.012	0.007
19	16	294	155	11	179	95	0.005	0.015	0.010
20*	42	142	92			92	0.005	0.005	0.005
21	29	59	44	24	56	40	0.001	0.001	0.005
22*	9.2	165	87.1			87.1	0.003	0.003	0.003

Table 5. Reach area, receiver coverage within each reach, and percent of receiver coverage per reach for 2005 and 2006. Reach areas were much greater than the receiver coverage within each reach. The area of each reach was calculated within GIS and compared to the actual receiver coverage within each reach. There was some variability in percent-coverage between years, but it was minimal.

		RECEIVER COVERAGE			
Reach	Reach Area (km^2)	2005 (km^2)	2005 % Coverage	2006 (km^2)	2006 % Coverage
Lower PIS	1.97	0.12	6.3	0.15	7.5
Mid PIS	3.96	0.15	3.8	0.14	3.5
Upper PIS	2.91	0.02	0.8	0.04	1.5
Lower RR	0.52	.06	12.4	0.08	15.7
Upper RR	0.19	.005	2.7	0.006	3.1
RR Tidal Creeks	0.06	.006	10.1	0.003	5.0

Table 6. Dates each receiver was deployed and pulled, the number of days it was functional, and the respective functionality coefficients. The number of days functional includes only the number of days the receiver was functional when fish were tagged. For example, receivers were deployed on 6/30/05 but fish were not tagged until July 17, 2005. Sites with 0 for the functionality coefficient in 2005 were not included in the duration analysis because there were so few days. In 2006, site 6 was lost and never replaced. The functionality coefficient was the number used to compensate for different receiver availabilities by multiplying it with the duration of time observed for each fish at each particular receiver site.

	2005					2006				
Site	Date Deployed	Date Pulled	# Days Deployed	# Days Functional	Functionality Coefficient	Date Deployed	Date Pulled	# Days Deployed	# Days Functional	Functionality Coefficient
1	NA	NA	NA	NA	NA	5/26/06	11/18/06	176	155	1.13
2	8/1/05	11/8/05	99	99	1	5/26/06	11/18/06	176	175	1
3	8/1/05	11/18/05	109	88	1.24	5/26/06	11/16/06	175	112	1.54
4	NA	NA	NA	NA	NA	5/26/06	11/16/06	174	142	1.22
5	8/2/05	11/18/05	108	99	1.09	5/26/06	11/16/06	174	154	1.12
6	NA	NA	NA	NA	NA	5/26/06	7/19/06	54	53	1
7	8/2/05	11/18/05	108	97	1.11	5/26/06	11/10/06	168	129	1.29
8	NA	NA	NA	NA	NA	5/26/06	11/16/06	174	173	1
9	6/30/05	8/5/05	36	11	0 *	5/25/06	11/16/06	175	142	1.22
10	7/29/05	11/5/05	99	97	1.02	NA	NA	NA	NA	NA
11	6/30/05	7/27/05	27	2	0 *	5/25/06	11/1/06	160	148	1.07
12	6/30/05	11/5/05	128	93	1.2	5/25/06	11/16/06	175	128	1.35
13	7/29/05	10/7/05	70	70	1	5/25/06	11/10/06	169	134	1.25
14	6/30/05	11/18/05	141	124	1.01	NA	NA	NA	NA	NA
15	6/30/05	11/5/05	128	93	1.19	NA	NA	NA	NA	NA
16	6/30/05	11/5/05	128	73	1.53	5/25/06	11/8/06	167	149	1.11
17	7/29/05	9/2/05	35	35	1	5/25/06	11/8/06	167	146	1.11
18	6/29/05	11/5/05	129	93	1.2	5/25/06	11/8/06	167	134	1.23
19	7/17/05	11/5/05	111	83	1.34	5/25/06	11/8/06	167	108	1.52
20	6/29/05	9/2/05	65	42	1.14	NA	NA	NA	NA	NA
21	6/29/05	11/5/05	129	104	1.08	5/25/06	11/8/06	167	123	1.34
22	6/30/05	9/2/05	64	37	1.3	NA	NA	NA	NA	NA

Table 7. Expected values for each reach utilized in the cumulative distribution statistics. The expected values (km^2*hr) were calculated for each reach based on the receiver site area coverage. These values are the result of averaging between high and low tide coverage (km^2) and compensating for variability of receiver listening times (hr).

Reach	2005 Expected Values (km^2*hr)	2006 Expected Values (km^2*hr)
Lower PIS	542.4	1518.3
Mid PIS	358.4	983.6
Upper PIS	54.1	410.7
Lower RR	354.4	785.1
Upper RR	45.0	51.2
RR Tidal Creeks	59.2	26.0

Table 8**.** Quantities and dates of striped bass heard in other arrays in Delaware Bay and Long Island Sound. Fish were heard again in 2005 and 2006 in Delaware Bay (DE Bay), Long Island Sound (LIS), and both areas. The days included in the date span are not necessarily consecutively spent in that area. For example, code 231 was seen in Delaware Bay on December 24, 2005 and from March 23, 2006, to April 23, 2006. However, this code is listed from December 24, 2005, to April 23, 2006.

Tag Year	Fish (N)	Location	Date first heard	Date last heard	Location	Date first heard	Date last heard
2005	2	DE Bay	12/22/05	04/23/06			
2006	15	LIS	10/27/06	11/29/06			
2006	6	DE Bay	10/13/06	04/14/07			
2006	15	LIS	10/28/06	12/06/06	DB	11/05/06	05/10/06

Figure 1. Map of the Atlantic Coast depicting striped bass spawning locations. Striped bass of the coastal migratory stock primarily spawn in Chesapeake Bay, Delaware Bay, and the Hudson River.

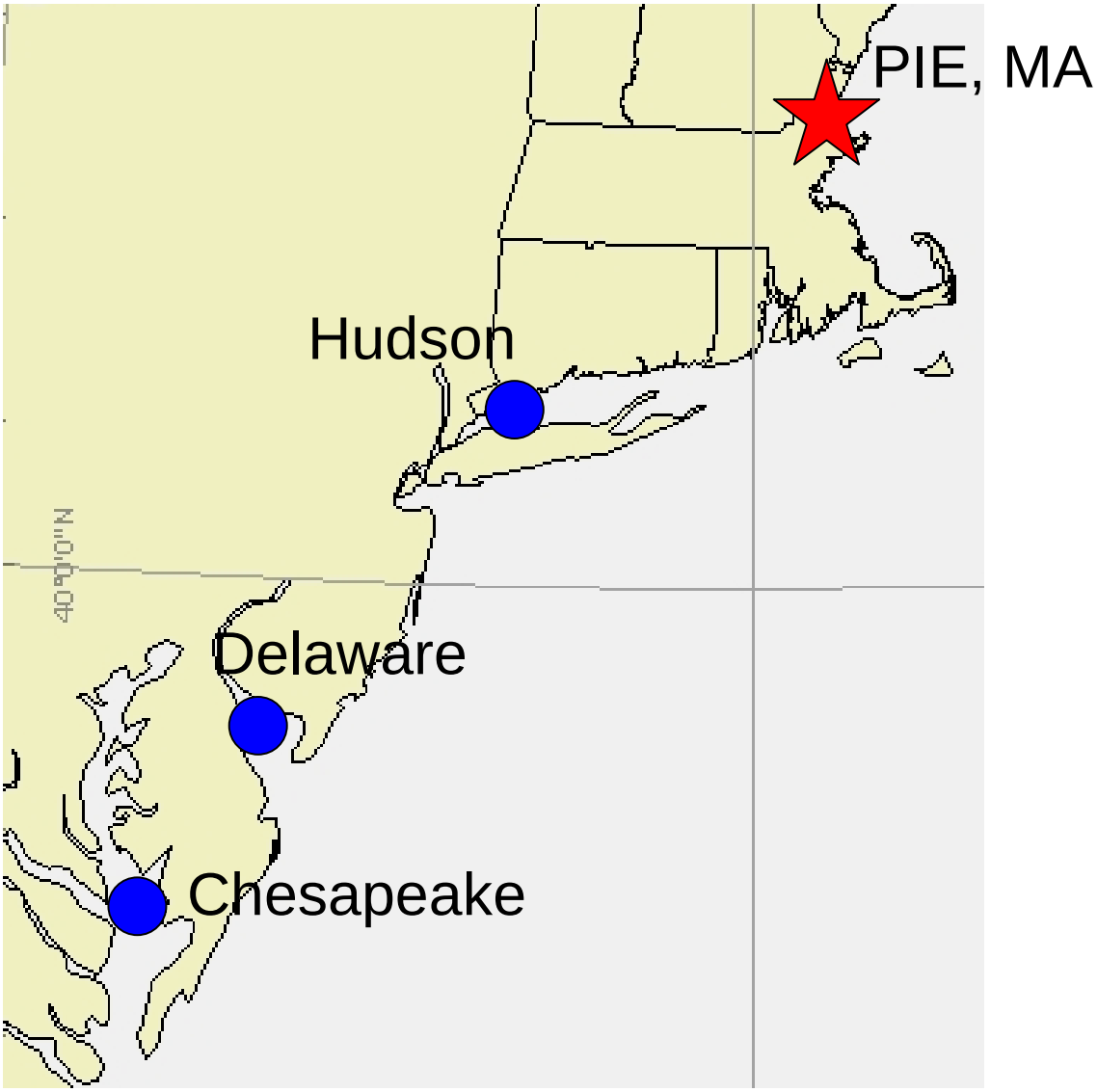

PIE, MA
Hudson
Delaware
Chesapeake
40°0'0"N

Figure 2. Map of the Great Salt Marsh showing the location of Plum Island Estuary within the Marsh. The Great Salt Marsh runs from Essex, Massachusetts north through southern New Hampshire.

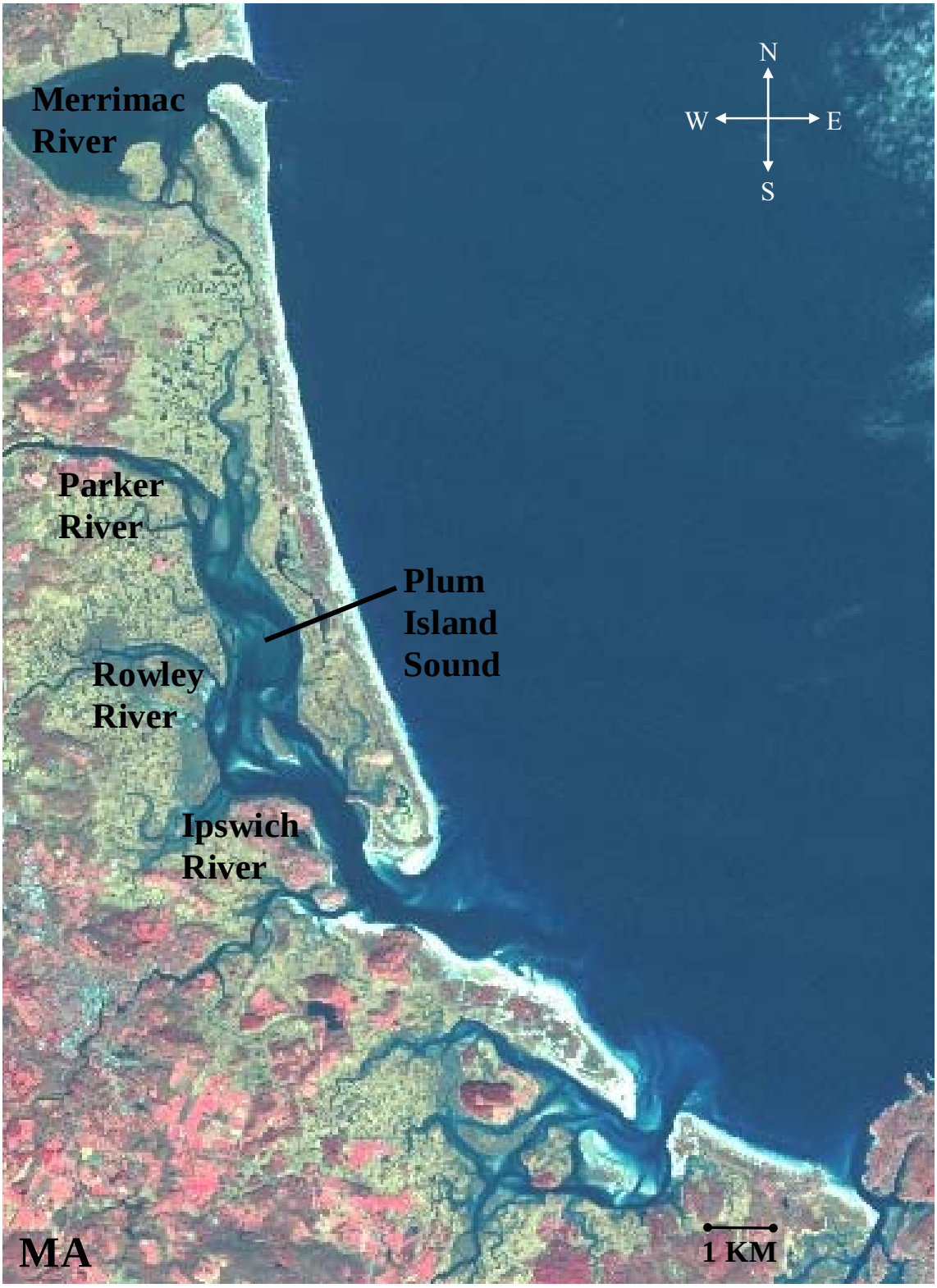

Merrimac River
N
W
E
S
Parker River
Plum Island Sound
Rowley River
Ipswich River
MA
1 KM

Figure 3. The tagging procedure, including incision, tag insertion, and suturing. A) An incision was made into the peritoneal cavity of the striped bass through which the 13 mm tag was inserted. B) The incision was sutured with dissolvable suture using a running loop stitch. C) The tagged striped bass with sutured incision.

A)

B)

C)

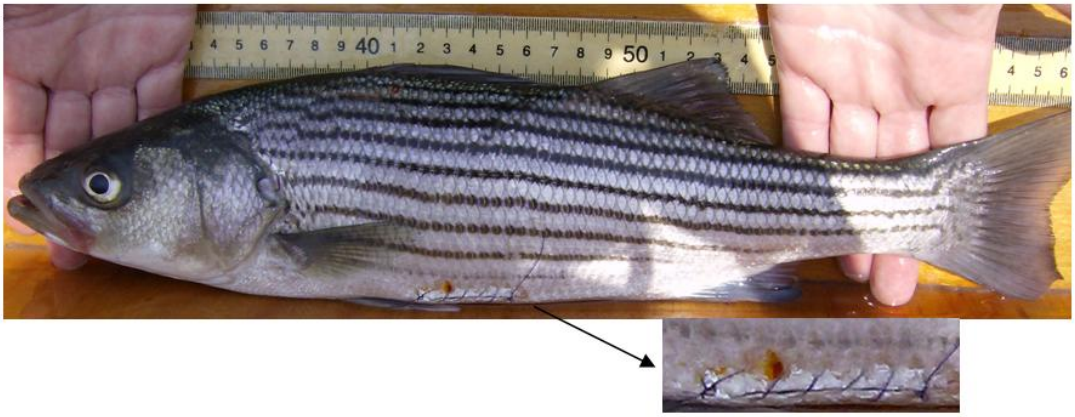


Figure 4. Map of Plum Island Estuary divided into Plum Island Sound and the Rowley River and the six reaches with the receiver locations marked. Plum Island Estuary (PIE) is comprised of 2 areas: Plum Island Sound (PIS) and Rowley River (RR). Three reaches exist within each area (Lower PIS, Mid PIS, Upper PIS, Lower RR, Upper RR, and RR tidal creeks). Circles represent receiver sites that were the same throughout both 2005 and 2006. Asterisks were sites that were only utilized in 2005; triangles were sites utilized only in 2006.

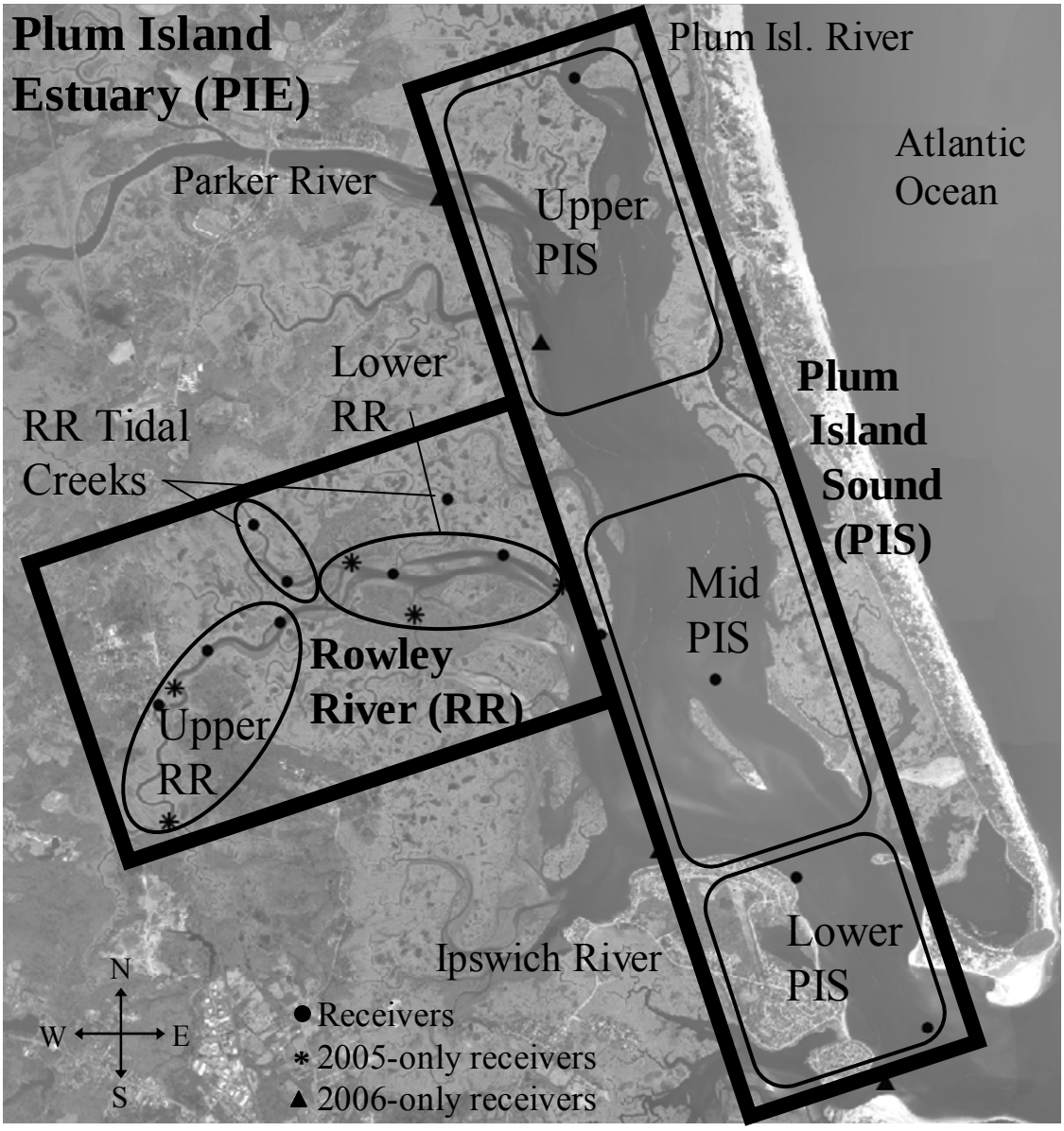
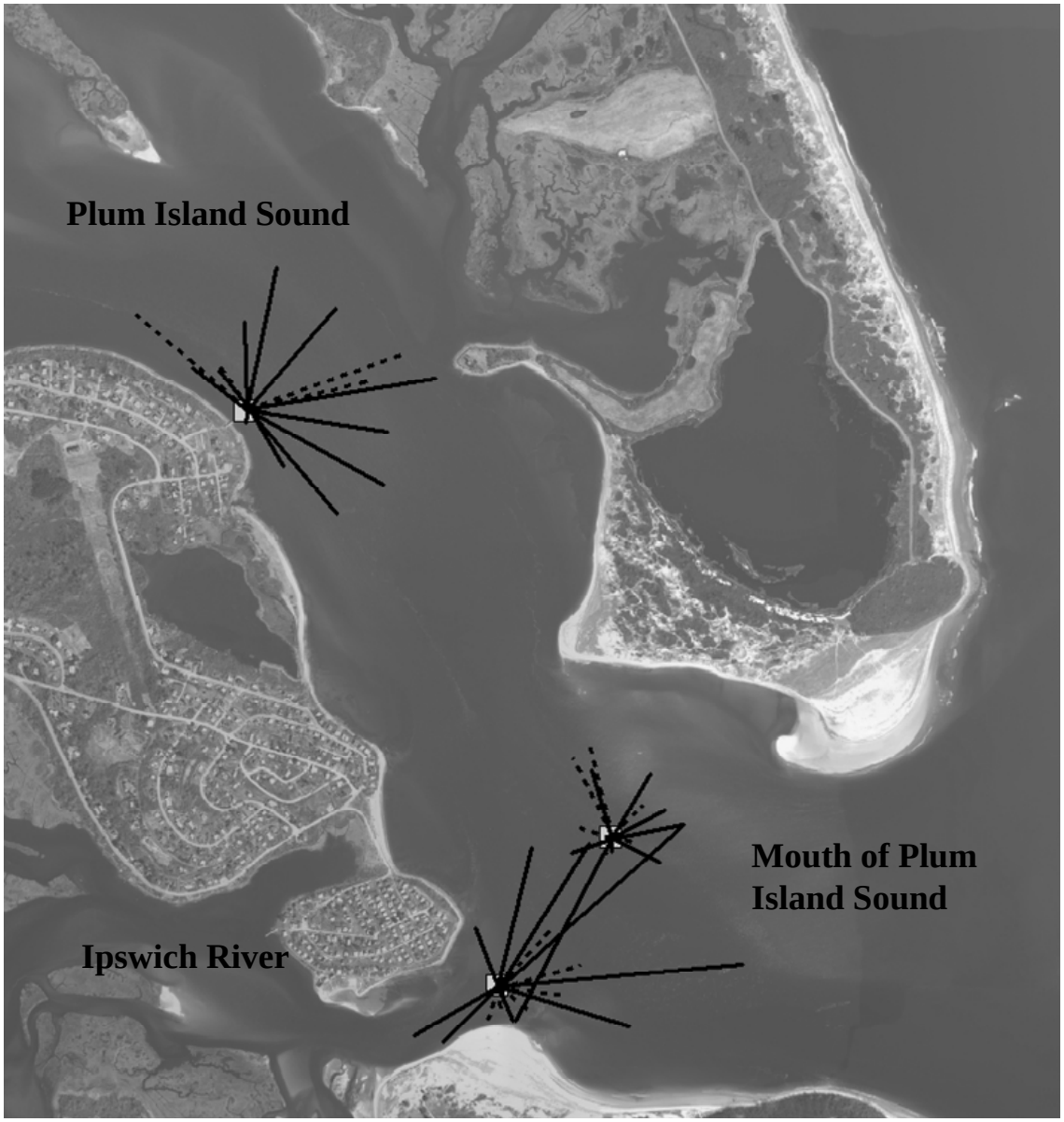
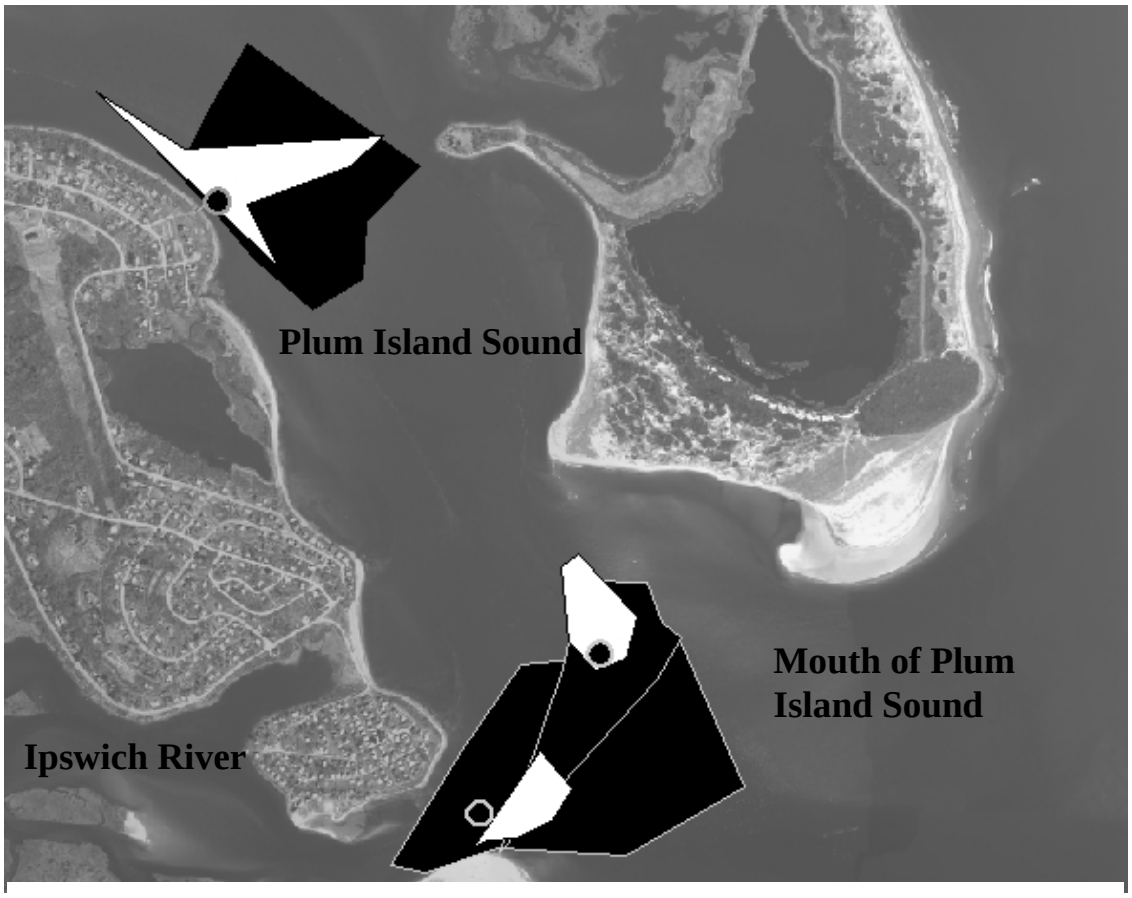

Plum Island Estuary (PIE)
Plum Isl. River
Atlantic Ocean
Parker River
Upper PIS
Lower RR
RR Tidal Creeks
Plum Island Sound (PIS)
Mid PIS
Rowley River (RR)
Upper RR
Lower PIS
Ipswich River
N
W
E
S
Receivers
2005-only receivers
2006-only receivers

Figure 5. Examples of hearing ranges for three receivers at high and low tide. The following map shows an example of the range test at high and low tides at the mouth of the Ipswich River and at the receiver site at the mouth of Plum Island Sound. The starburst pattern of lines represents the distance the receiver could hear. The solid line is high tide and the dotted line is low tide.



High tide range
Low tide range

Figure 6. Examples of hearing area for two receivers at high and low tide. The following map shows the areas that were calculated for high and low tides in the lower Plum Island Sound reach. The black area is high tide and the white area is low tide. The black dot with gray outline is the receiver site from which the distances and areas were calculated.



High tide area
Low tide area

Figure 7. Graphic representation by day and week for each site in 2005 and 2006 of the time the receiver was functional. Column A is year. In column B, 1 represents Area 1, which is Plum Island Sound, and 2 represents the Rowley River. Column C corresponds to the 6 reaches (lower PIS = 1, mid PIS = 2, upper PIS = 3, lower RR = 4, upper RR = 5, and RR tidal creeks = 6). Each box within column D represents an individual receiver site for each respective year. The remaining columns represent 7 day increments from May 25th through November 18th. Black represents when the receiver was functional all day; gray represents when the receiver was functional for less than ¾ of the day; white represents when the receiver was not functional; cross-hatching represents when the hydrophone was out of the water for a small portion of low tide.


A
B
C
D
5-25 – 5/27
5/28 – 6/3
6/4 – 6/10
6/10 – 6/17
6/18 – 6/24
6/25 – 7/1
7/2 – 7/8
7/9 – 7/15
7/16 - 7/22
7/23 – 7/29
7/30 – 8/5
8/6 – 8/12
8/13 – 8/19
8/20 – 8/26
8/27 – 9/2
9/3 – 9/9
9/10 – 9/16
9/17 – 9/23
9/24 – 9/30
10/1 – 10/7
10/8 – 10/14
10/15 – 10/21
10/22 – 10/28
10/29 – 11/4
11/5 – 11/11
11/11 – 11/18
2005
2006
1
2
3
4
5
6

Figure 8. Graphic representation by day and week for each striped bass tagged in 2005 and 2006 of the number of days each was present, whether it was seen again in 2006 (if it was tagged in 2005), and if it was seen again in a different array. Column A is the year of release. Which release the striped bass was in is denoted by a 1, 2, or 3 in column B (2005: 1 = July, 2 and 3 = August; 2006: 1 = May, 2 = July). Dots in the column titled "PIE again" denote striped bass tagged in 2005 that were detected in PIE again in 2006. Dots in the column titled "Atl. Coast" represent striped bass that were heard by other researchers in their arrays on the Atlantic Coast in either Delaware Bay or Long Island Sound.

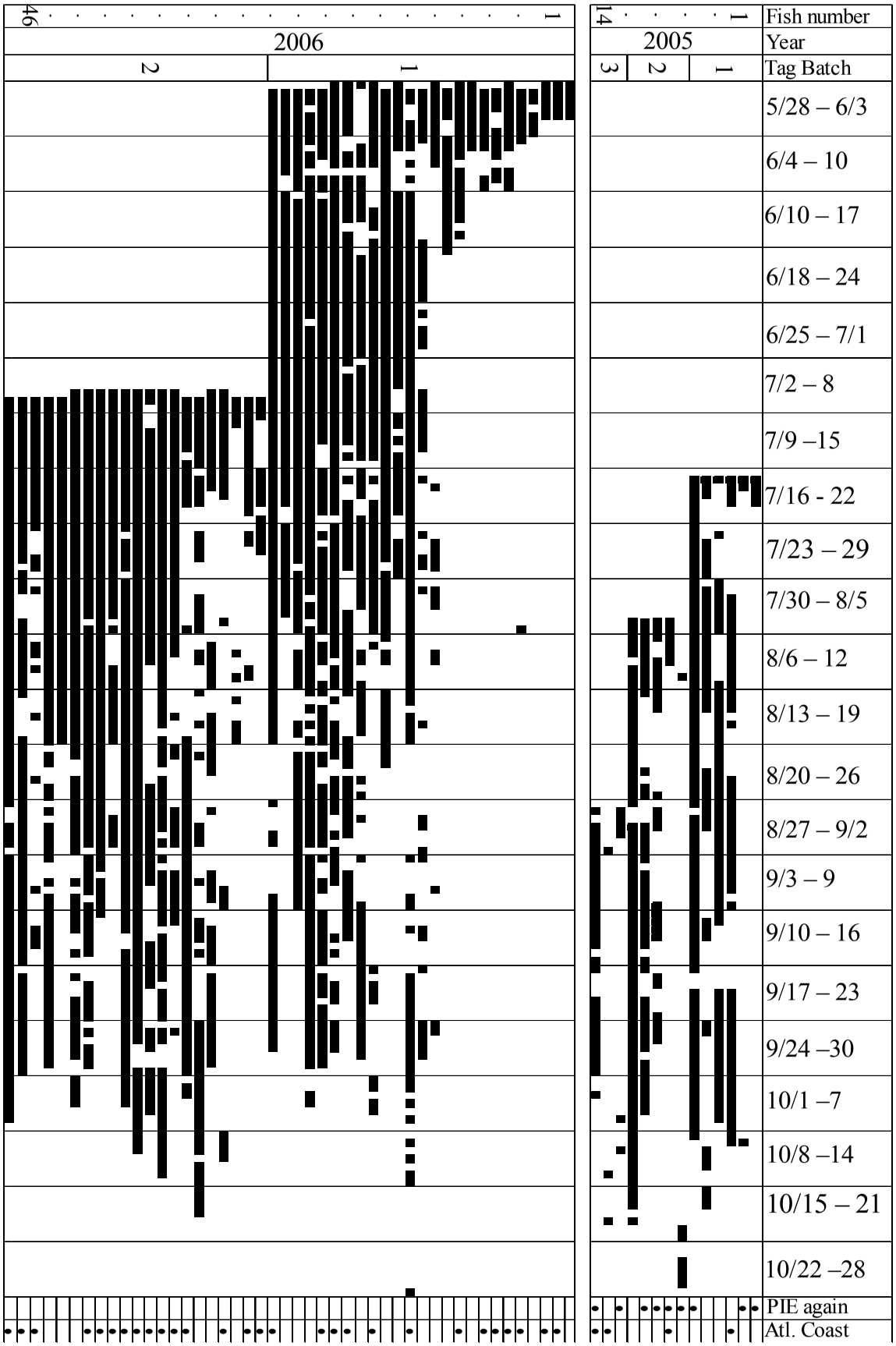

46
1
2006
2
1
14
1
2005
3
2
1
Fish number
Year
Tag Batch
5/28 – 6/3
6/4 – 10
6/10 – 17
6/18 – 24
6/25 – 7/1
7/2 – 8
7/9 –15
7/16 - 22
7/23 – 29
7/30 – 8/5
8/6 – 12
8/13 – 19
8/20 – 26
8/27 – 9/2
9/3 – 9
9/10 – 16
9/17 – 23
9/24 –30
10/1 –7
10/8 –14
10/15 – 21
10/22 –28
PIE again
Atl. Coast

Figure 9. Plots of the number of days each striped bass was seen in Plum Island Estuary for 2005 and 2006. Striped bass were observed in Plum Island Estuary ranging from 5 to 106 non-consecutive days. Those who accumulated 30 or more days were included in the analyses. A) are striped bass that were tagged in 2005; B) are fish tagged in 2006. The dashed line indicates the separation of striped bass in the estuary for less than 30 days (light gray bars) and more than 30 days (dark gray bars).

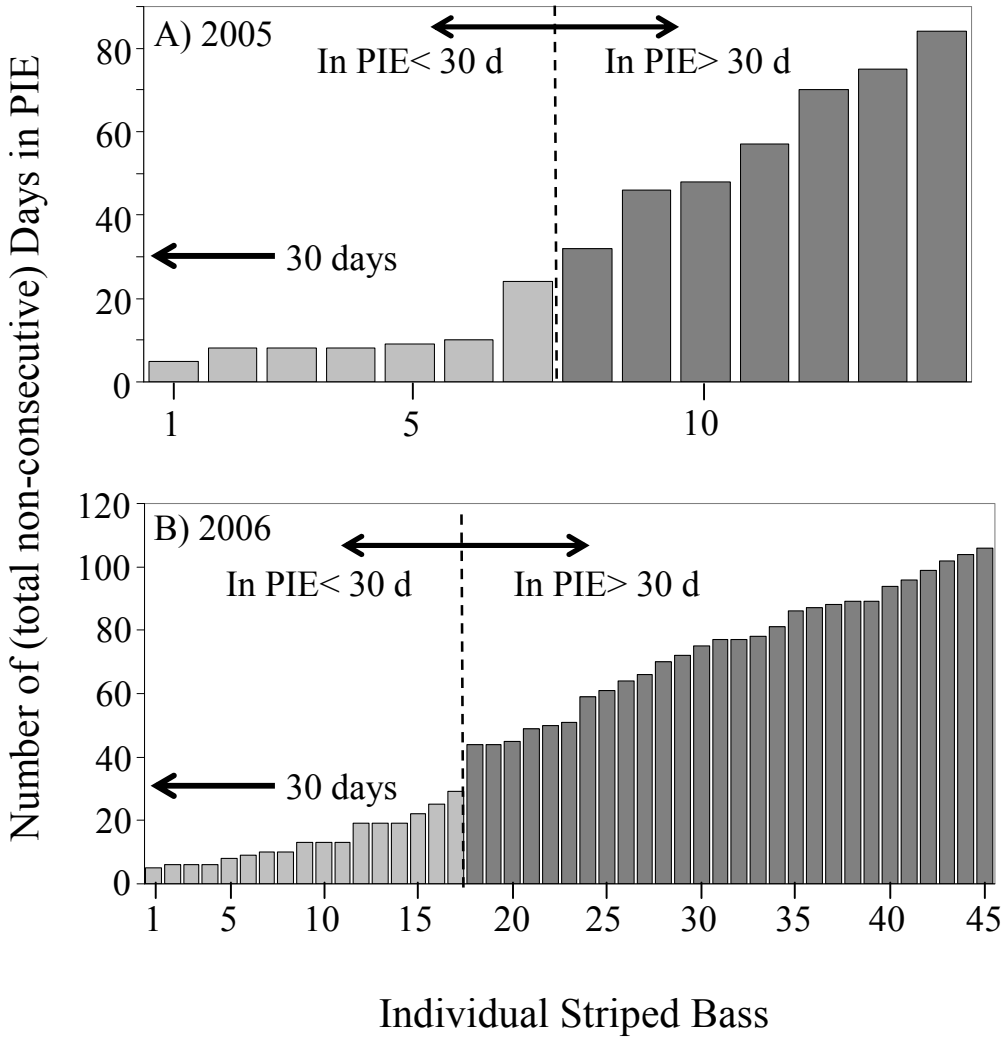

A) 2005
In PIE< 30 d
In PIE> 30 d
30 days
B) 2006
In PIE< 30 d
In PIE> 30 d
30 days
Number of (total non-consecutive) Days in PIE
Individual Striped Bass

Figure 10. Plots of mean durations by reach for all striped bass divided by year. Mean duration the striped bass spent in the 6 reaches ((A) 2005: N=14; (B) 2006: N=46). Durations represent the corrected fish hours spent within each reach.

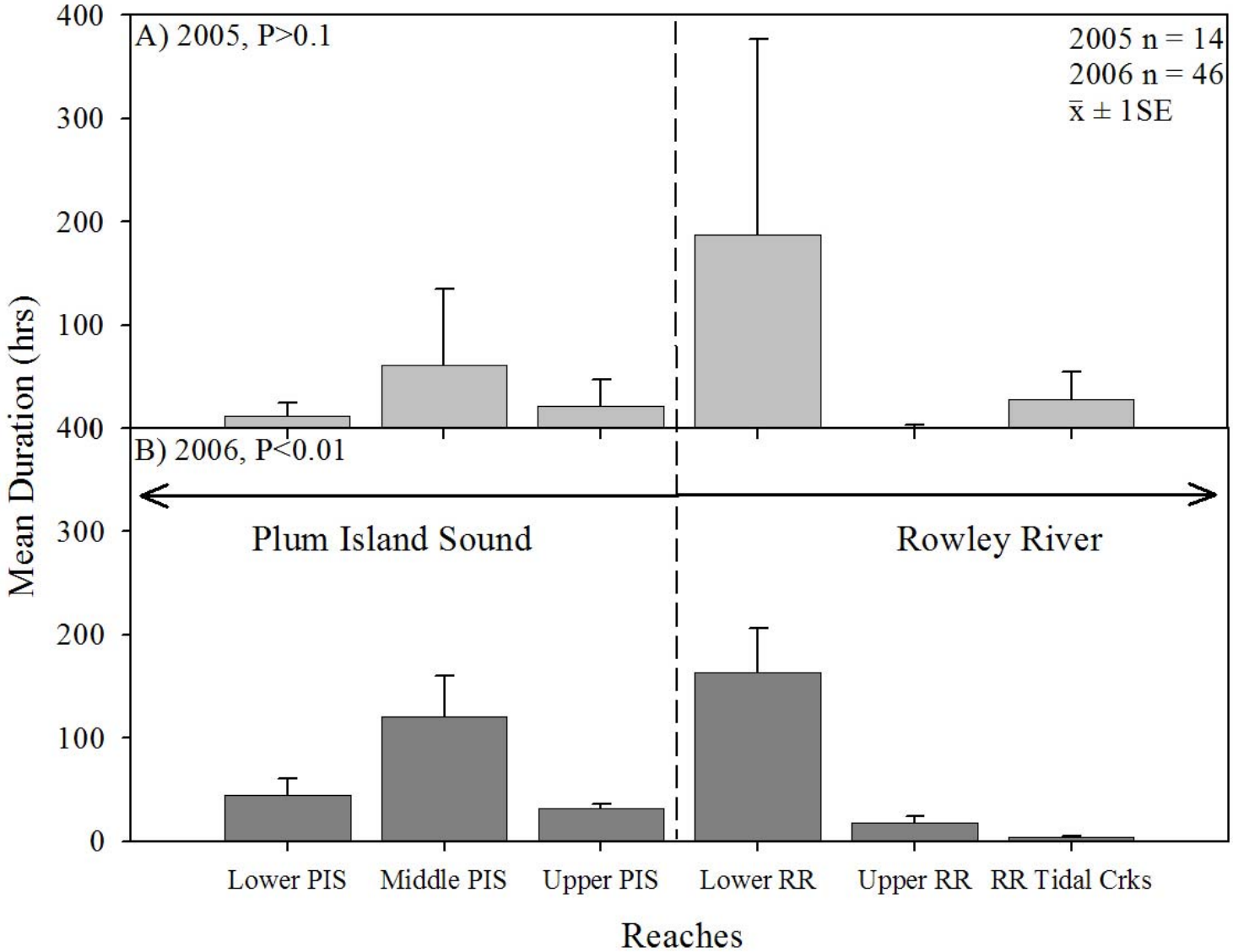

A) 2005, P>0.1
2005 n = 14
2006 n = 46
x̄ ± 1SE
B) 2006, P<0.01
Plum Island Sound
Rowley River
Mean Duration (hrs)
400
300
200
100
400
300
200
100
0
Lower PIS
Middle PIS
Upper PIS
Lower RR
Upper RR
RR Tidal Crks
Reaches

Figure 11. Plot of the individual durations per reach in 2006 on one graph. Dark gray represents the fish that stayed primarily in Plum Island Sound, light gray represents those fish that stayed primarily in the Rowley River, and black represents the fish that left the system before 30 days. Along the Z axis are the reaches in Plum Island Estuary: lower (L. PIS), mid (M. PIS), and upper (U. PIS) Plum Island Sound; lower (L. RR) and upper (U. RR) Rowley River; and Rowley River tidal creeks (RR TC).

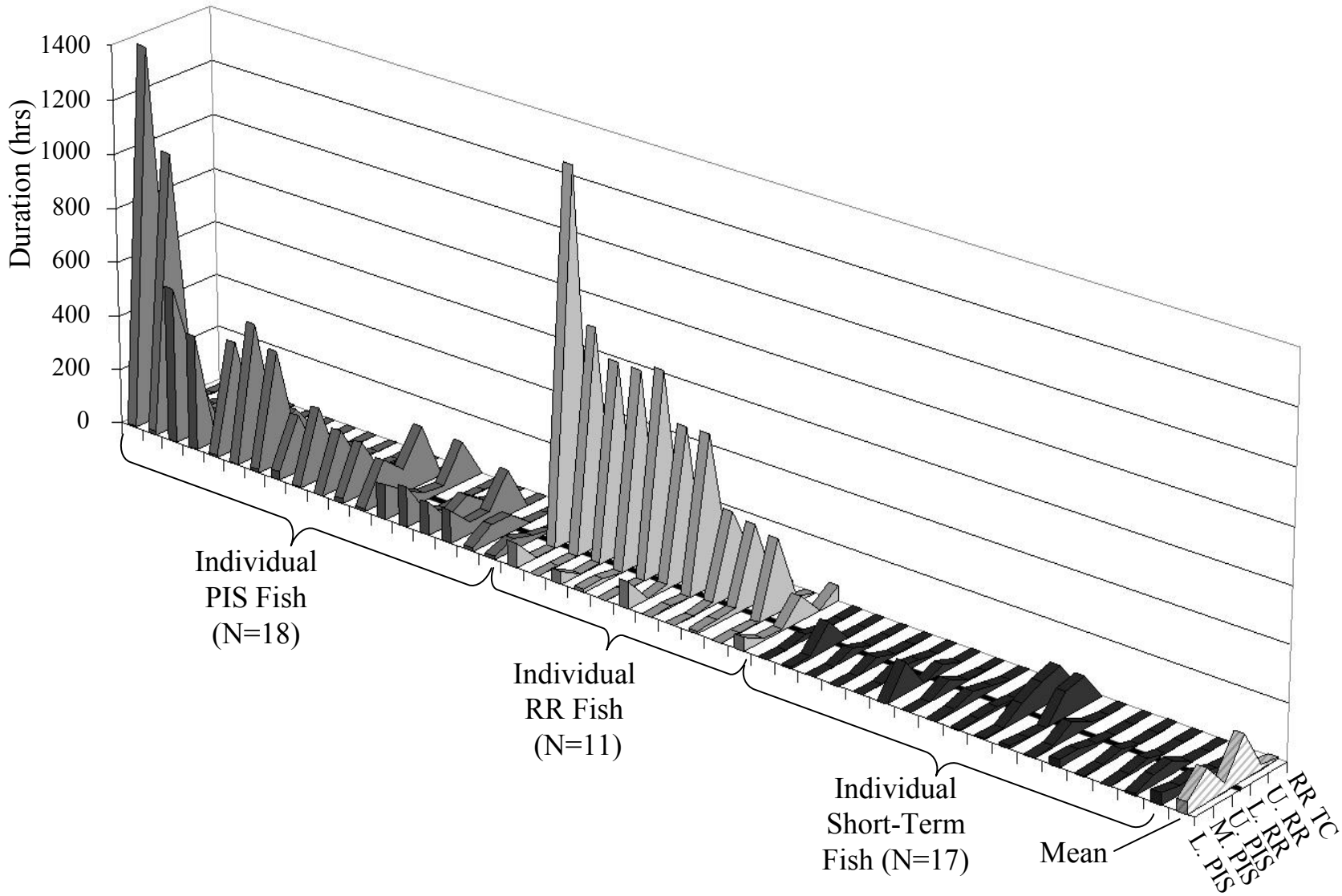

Duration (hrs)
1400
1200
1000
800
600
400
200
0
Individual
PIS Fish
(N=18)
Individual
RR Fish
(N=11)
Individual
Short-Term
Fish (N=17)
Mean
RR TC
U. RR
L. RR
U. PIS
M. PIS
L. PIS

Figure 12**.** Histogram plots of the mean durations (hrs) spent in each of the six Plum Island Estuary reaches by each of the three use-groups. When like-kinds of fish are grouped into use-groups, it becomes very apparent the part of Plum Island Estuary they are using. The following graph represents the 3 use-groups for 2006. A) is the Rowley River (RR) use-group. B) is the Plum Island Sound (PIS) use-group. C) is the short-term use-group.

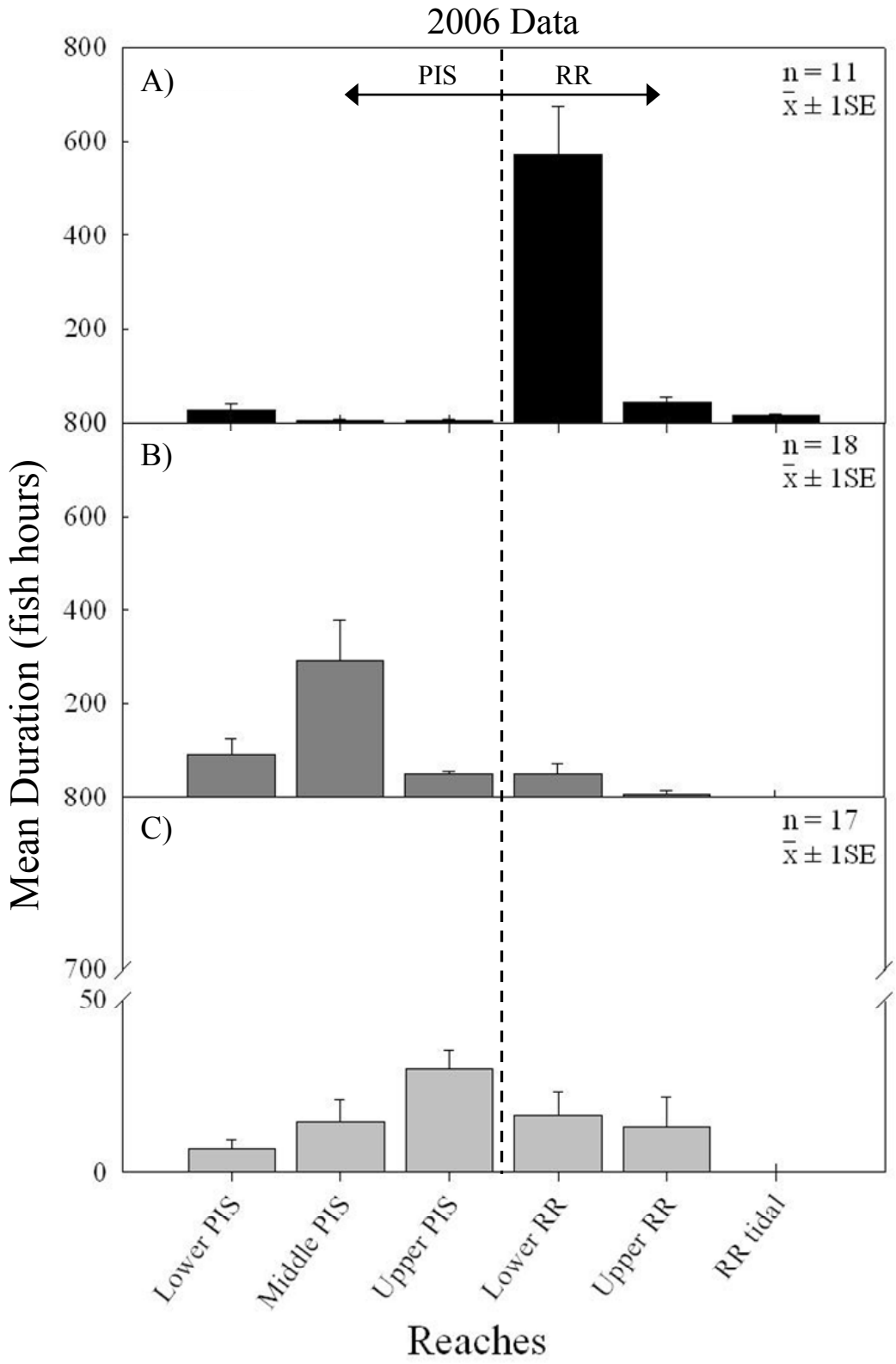
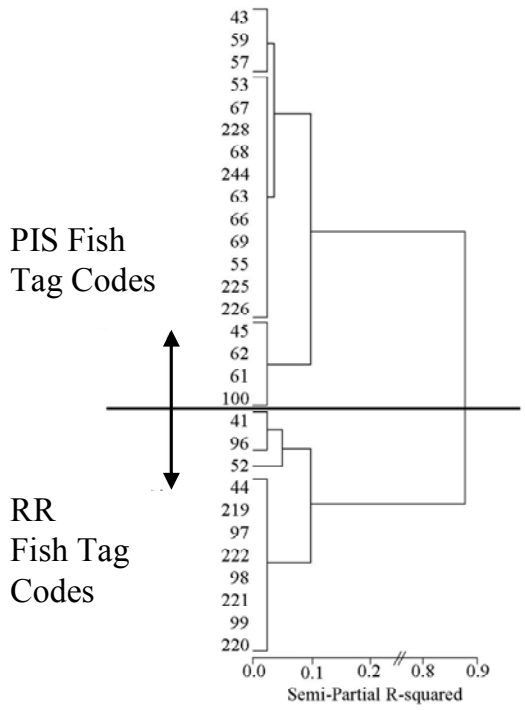
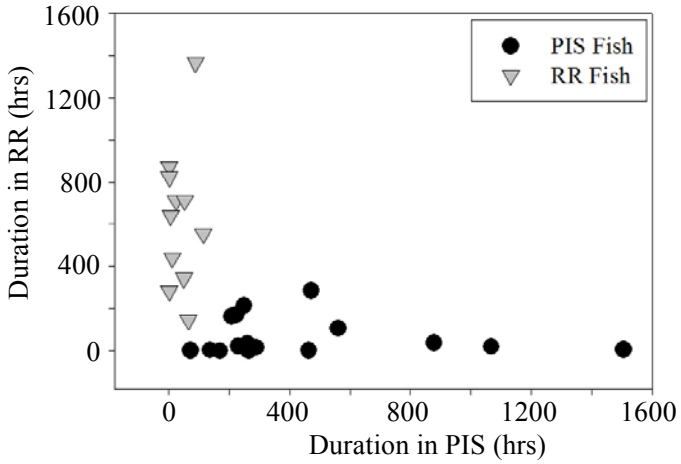

2006 Data
A)
PIS
RR
n = 11
x̄ ± 1SE
B)
n = 18
x̄ ± 1SE
C)
n = 17
x̄ ± 1SE
800
600
400
200
800
600
400
200
800
700
50
0
Mean Duration (fish hours)
Lower PIS
Middle PIS
Upper PIS
Lower RR
Upper RR
RR tidal
Reaches

Figure 13. Cluster analysis and two plots of time spent in Plum Island Sound versus the Rowley River, first represented in hours then as percents. The cluster analysis (A) supported the groupings of striped bass tagged in 2006 into 2 groups: Rowley River and Plum Island Sound fish. The cluster analysis excludes striped bass that were in the short-term use-group. Plots B and C contain all fish tagged in 2006 and represent the plots of time spent in PIS versus the RR (B) and the proportion of time spent in PIS versus the RR (C).

A)


PIS Fish
Tag Codes
RR
Fish Tag
Codes
43
59
57
53
67
228
68
244
63
66
69
55
225
226
45
62
61
100
41
96
52
44
219
97
222
98
221
99
220
0.0
0.1
0.2
0.8
0.9
Semi-Partial R-squared

B)


PIS Fish
RR Fish
Duration in RR (hrs)
1600
1200
800
400
0
0
400
800
1200
1600
Duration in PIS (hrs)

C)

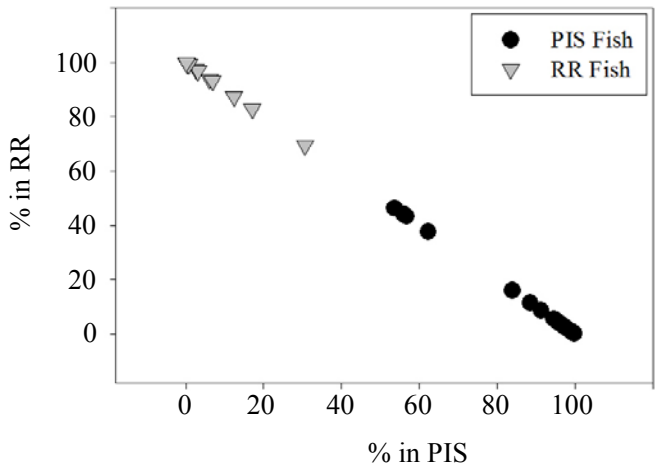

PIS Fish
RR Fish
% in RR
100
80
60
40
20
0
0
20
40
60
80
100
% in PIS

Figure 14. Tracks, histogram plot, and cumulative distribution plot for one fish for 2006 from the Plum Island Sound, Rowley River, and short-term use-groups. The three fish below are a representative sample from the 46 tagged striped bass: A) is the Plum Island Sound fish, B) is the Rowley River fish, and C) is the Short-Term fish. The map displays the tracks the fish made in Plum Island Estuary, the histogram plot displays the amount of time per reach spent by the individual fish, and the cumulative distribution frequency plot shows the agreement between the grouping of each particular fish into its respective use-group.

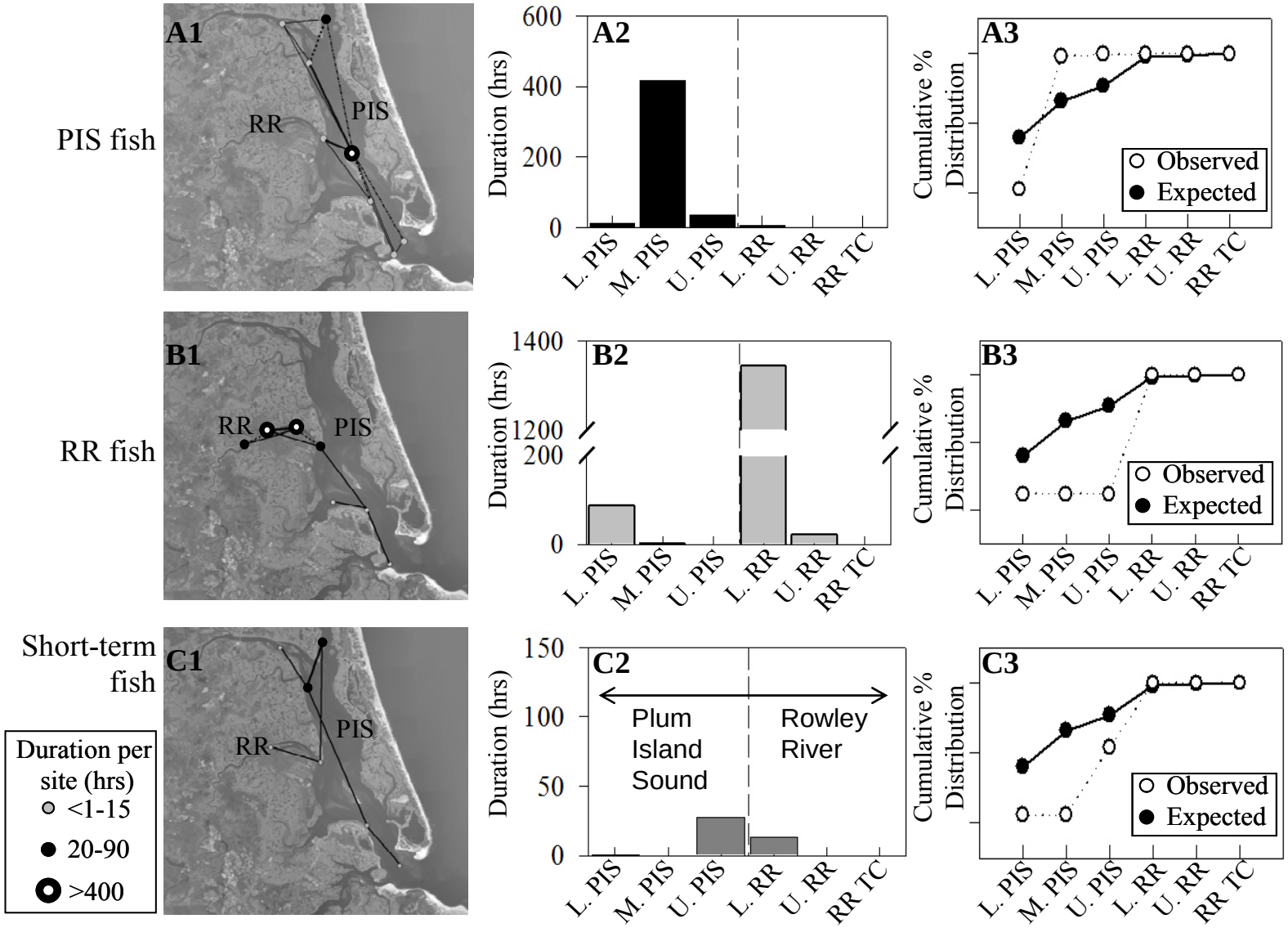
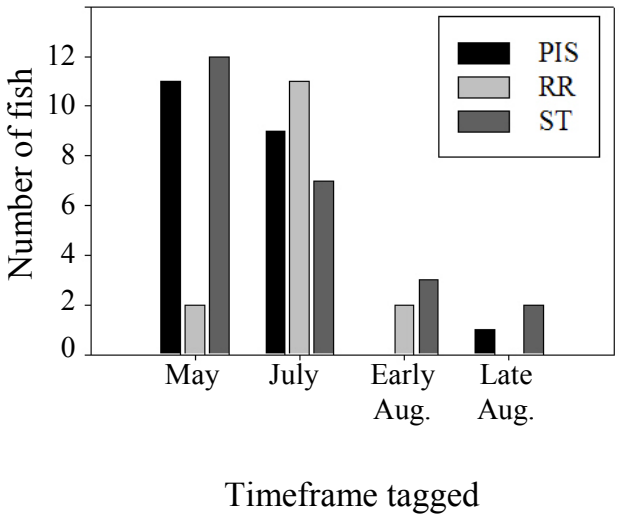
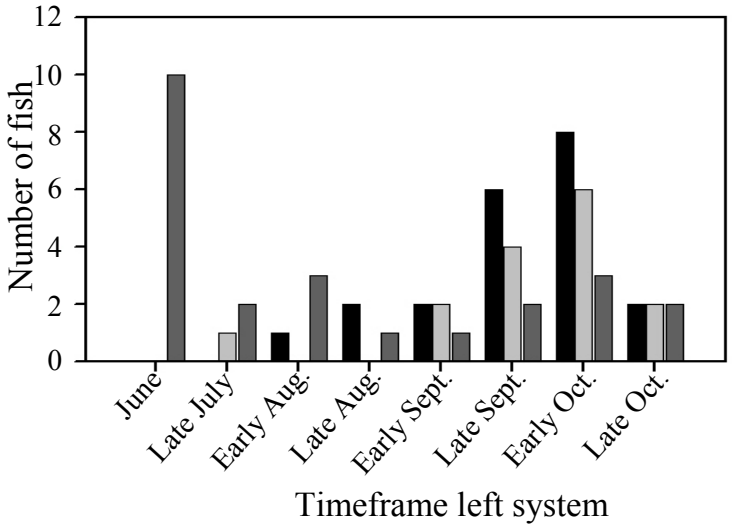

PIS fish
RR fish
Short-term fish
A1
RR
PIS
B1
RR
PIS
C1
RR
PIS
Duration per site (hrs)
<1-15
20-90
>400
A2
B2
C2
Duration (hrs)
600
400
200
0
1400
1200
200
150
100
50
Plum Island Sound
Rowley River
L. PIS
M. PIS
U. PIS
L. RR
U. RR
RR TC
A3
B3
C3
Cumulative % Distribution
Observed
Expected

Figure 15. Four use-group arguments for the 2005 and 2006 striped bass. Various arguments for use-group delineation are refuted in this figure. Striped bass tagged in 2005 and 2006 are included together. Panel A is date of tagging, Panel B is date the tagged fish left the estuary, Panel C is fish size, and Panel D displays the potential migration routes. Note that it appears, particularly in panel A, that short-term fish (N=24) make up a majority of all fish. However, when compared to the sum (N=36) of the Plum Island Sound (N=21) and Rowley River (N=15) use-groups, they actually comprise <50%.

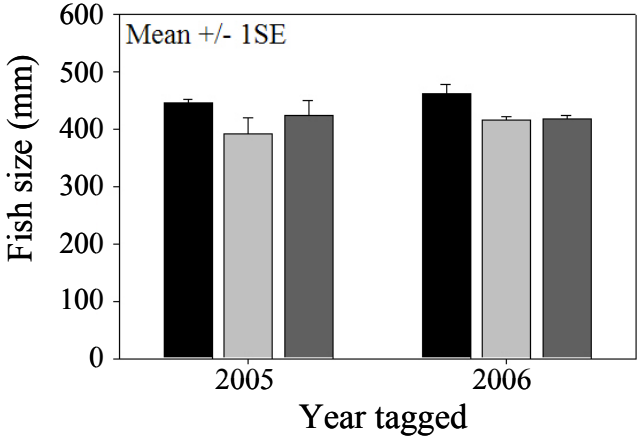
A. Were they tagged at different times? (NO)



B. Did they leave at different times? (NO)



C. Were they different sizes? (NO)



D. Did they go different places? (NO)

Use Group	Long Isl. Sound	DE Bay	LIS-DB	Migrant totals	PIE Use-Group Totals
PIS Fish	6	3	6	15	18
RR Fish	3	0	3	6	11
Short-term	6	2	6	14	17

Figure 16. Seasonal use by all fish together displayed by reach on a map of Plum Island Estuary. The graphs in this figure have all fish combined (2006; N=46). The X axis is season, where SP is spring, SU is summer, and FA is fall. The Y axis is the mean duration (in hours) after log10 transformation. The reaches that have asterisks (*) after their title are the reaches in which there was an overall statistical difference ($P \leq 0.1$) in reach use by all fish across seasons. Further statistics can be found in Appendix 7.

SEASON

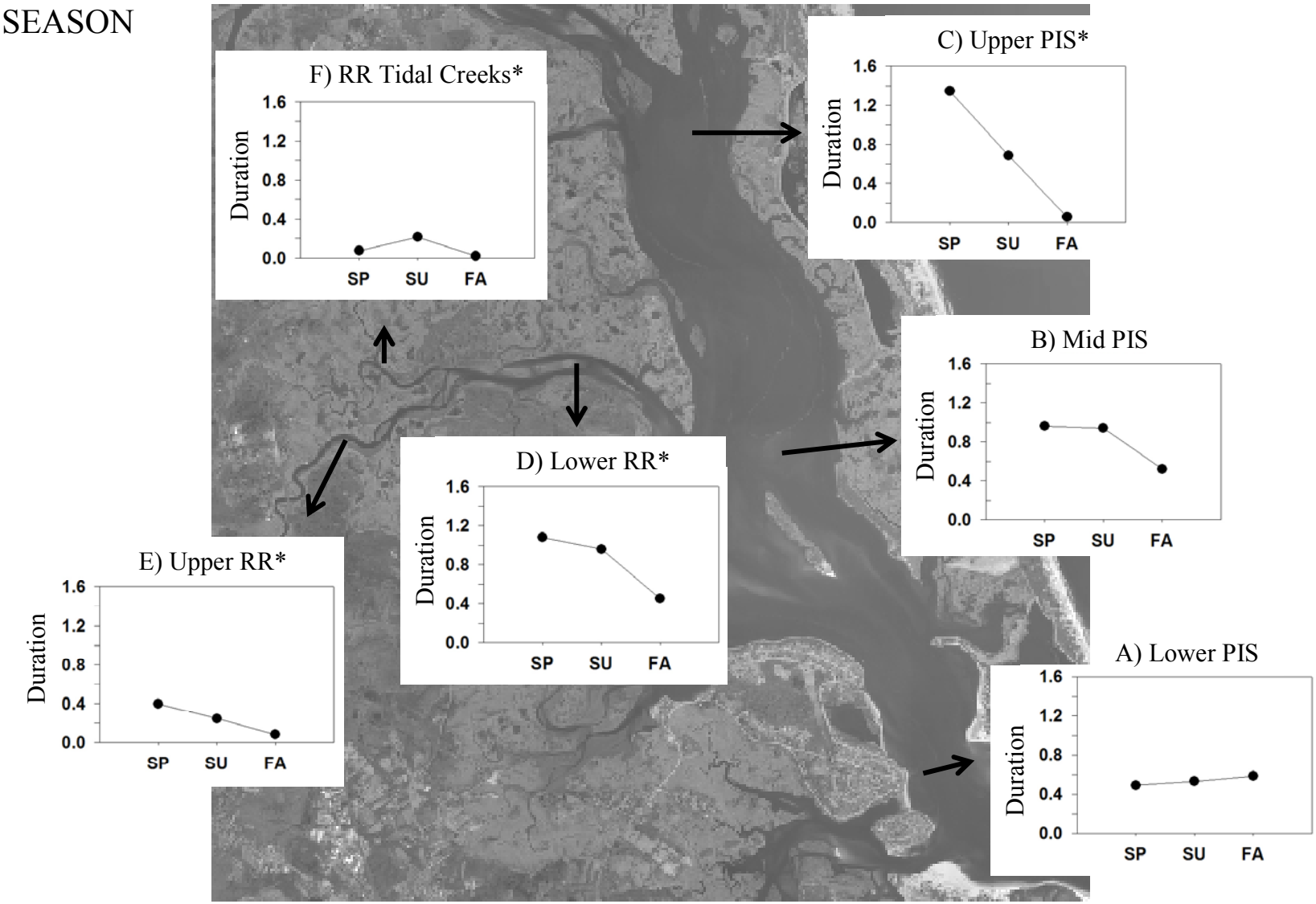

F) RR Tidal Creeks*
C) Upper PIS*
B) Mid PIS
D) Lower RR*
E) Upper RR*
A) Lower PIS
Duration
1.6
1.2
0.8
0.4
0.0
SP
SU
FA

Figure 17. Seasonal use by use-group displayed by reach on a map of Plum Island Estuary. The graphs in this figure display use for 2006 only. The x axis is season, where SP is spring, SU is summer, and FA is fall. The Y axis is the mean duration (in hours) after $\log_{10}$ transformation. The reaches that have asterisks (*) after their title are the reaches in which there was a statistically significant interaction ($P \leq 0.1$) between season and use-groups, i.e. the use-groups used the reaches differently by season. Further statistics can be found in Appendix 7.

SEASON

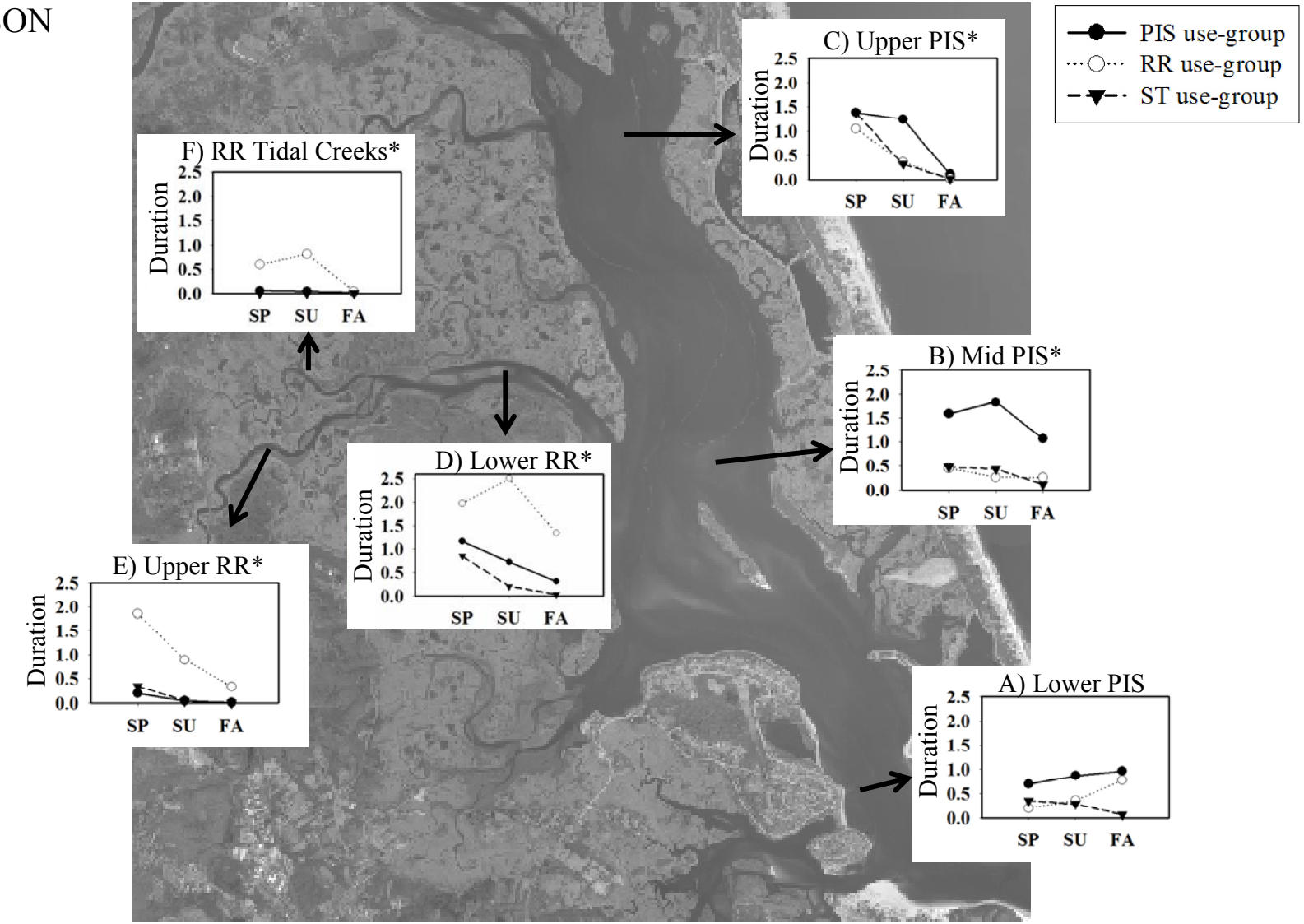

PIS use-group
RR use-group
ST use-group
C) Upper PIS*
B) Mid PIS*
D) Lower RR*
F) RR Tidal Creeks*
E) Upper RR*
A) Lower PIS
Duration
2.5
2.0
1.5
1.0
0.5
0.0
SP
SU
FA

Figure 18. Seasonal use by use-group across light stage displayed by reach on a map of Plum Island Estuary. Use of the PIE reaches varied by use-group across seasons for most light stages for 2006. The X axis is light stage and the Y axis is the mean duration spent in each reach in hours after $\log_{10}$ transformation. The reaches in which there are asterisks (*) after a season are reaches where there was a statistically significant interaction ($P \leq 0.1$) between light and use-groups, i.e. the use-groups used the reaches differently by light within that particular season.

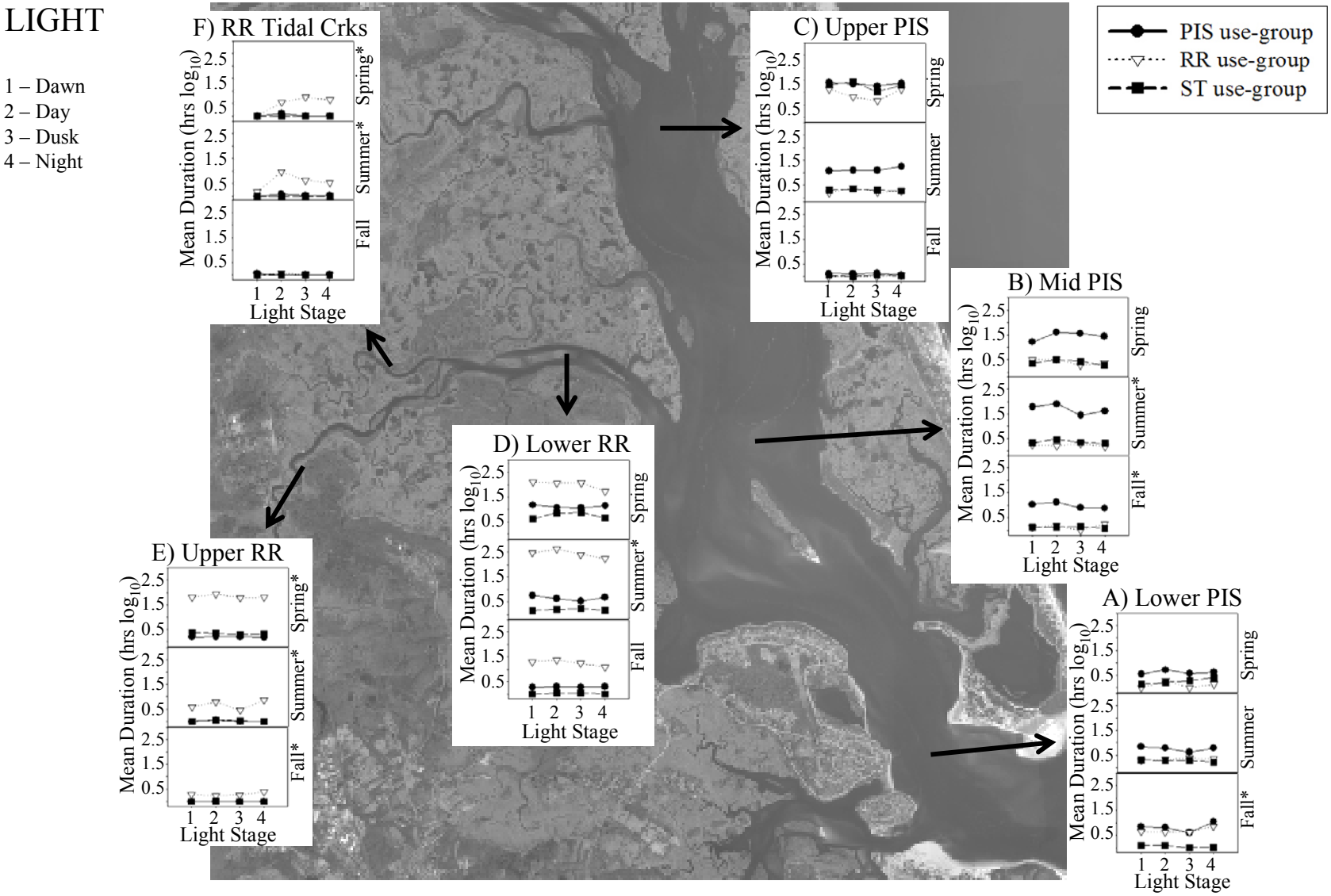
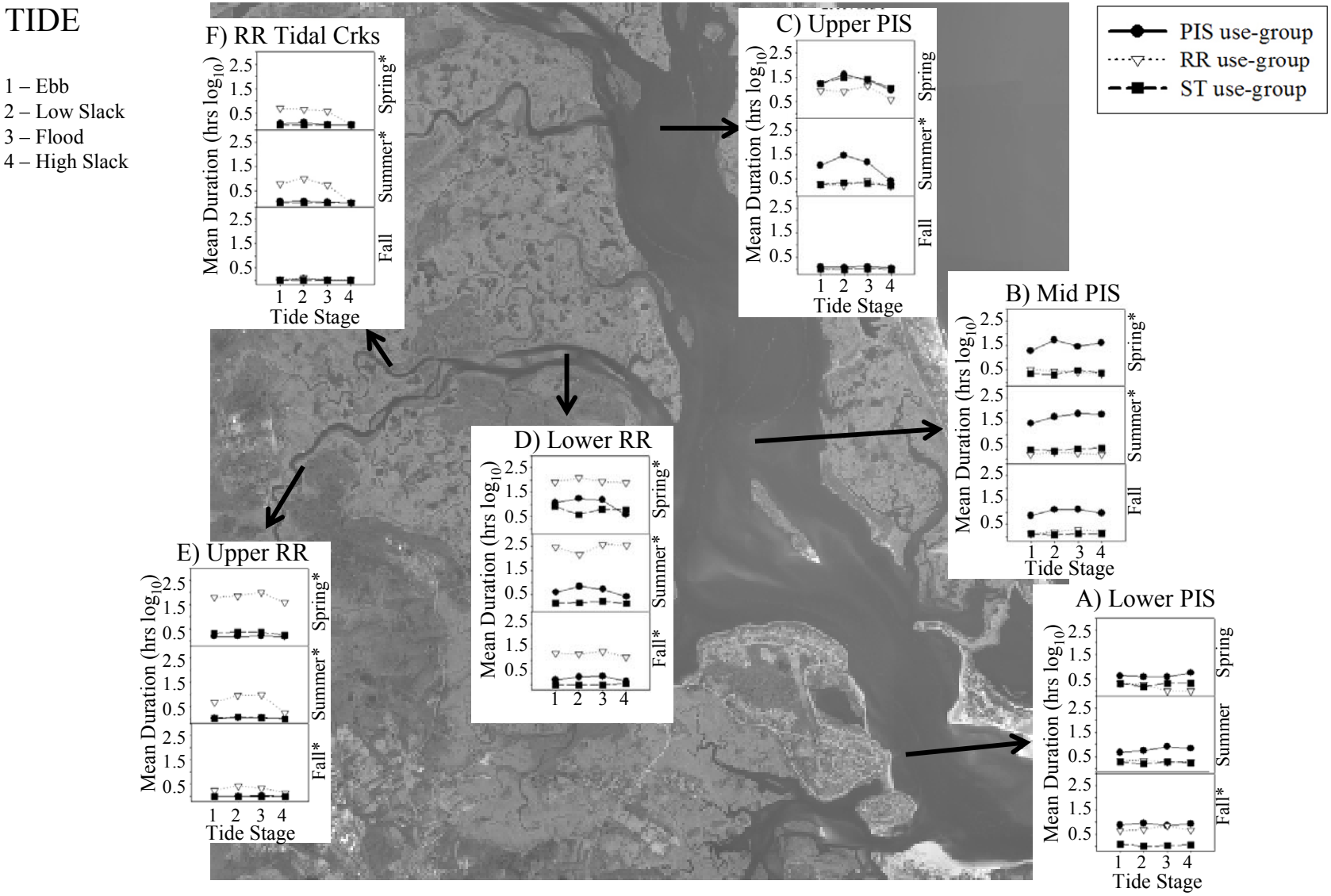
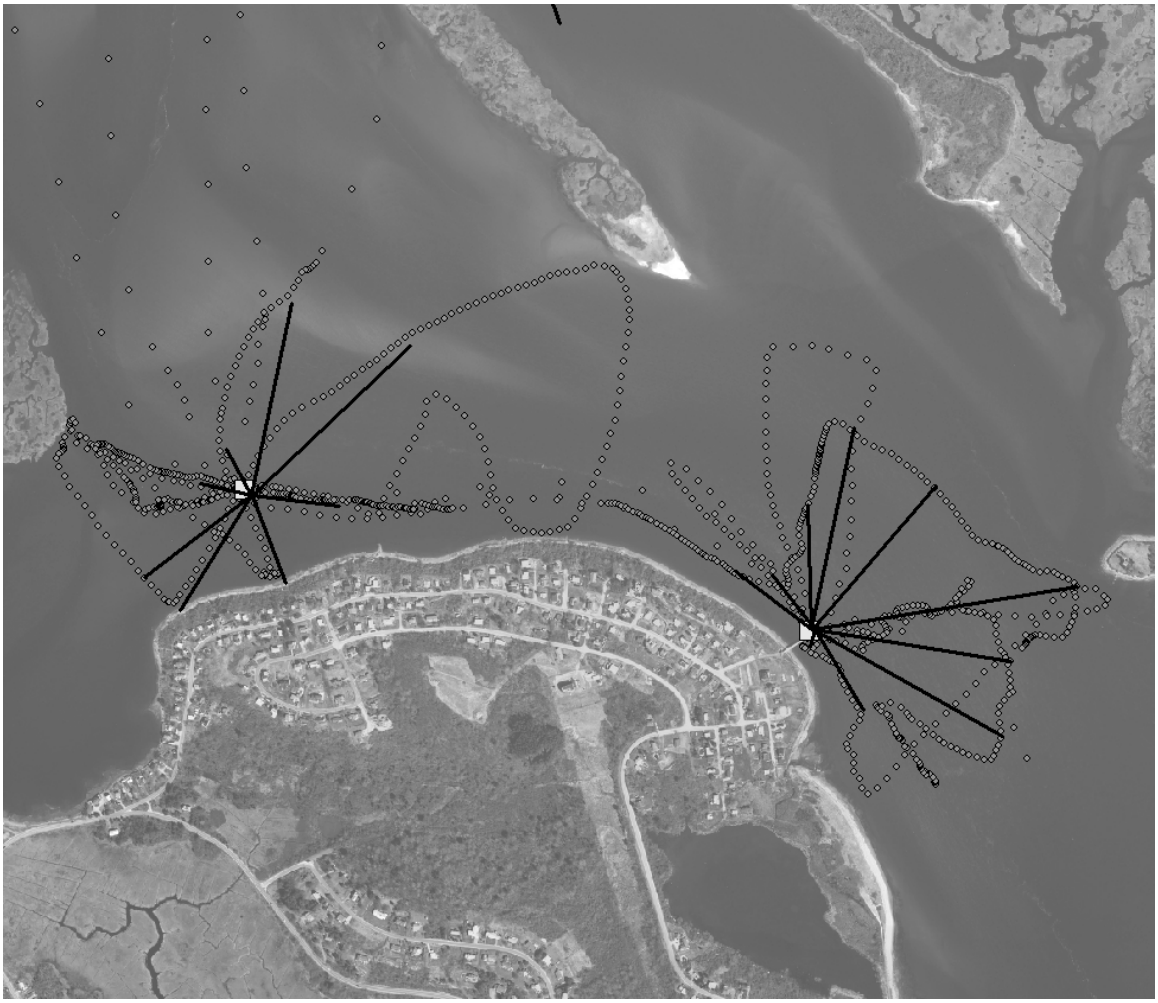

LIGHT
1 – Dawn
2 – Day
3 – Dusk
4 – Night
F) RR Tidal Crks
C) Upper PIS
B) Mid PIS
D) Lower RR
E) Upper RR
A) Lower PIS
PIS use-group
RR use-group
ST use-group
Mean Duration (hrs log10)
Light Stage
Spring
Summer
Fall
Spring*
Summer*
Fall*

Figure 19. Seasonal use by use-group across tide stage displayed by reach on a map of Plum Island Estuary. Use of the PIE reaches varied by use-group across seasons for most tide stages in 2006. The X axis is tide stage and the Y axis is mean duration in hours after $\log_{10}$ transformation. The reaches in which there are asterisks (*) after a season are reaches where there was a statistically significant interaction ($P \leq 0.1$) between tide and use-groups, i.e. the use-groups used the reaches differently by tide within that particular season.


TIDE
1 – Ebb
2 – Low Slack
3 – Flood
4 – High Slack
PIS use-group
RR use-group
ST use-group
F) RR Tidal Crks
C) Upper PIS
B) Mid PIS
D) Lower RR
E) Upper RR
A) Lower PIS
Mean Duration (hrs log10)
Tide Stage
Spring*
Summer*
Fall*
Spring
Summer
Fall

APPENDIX 1

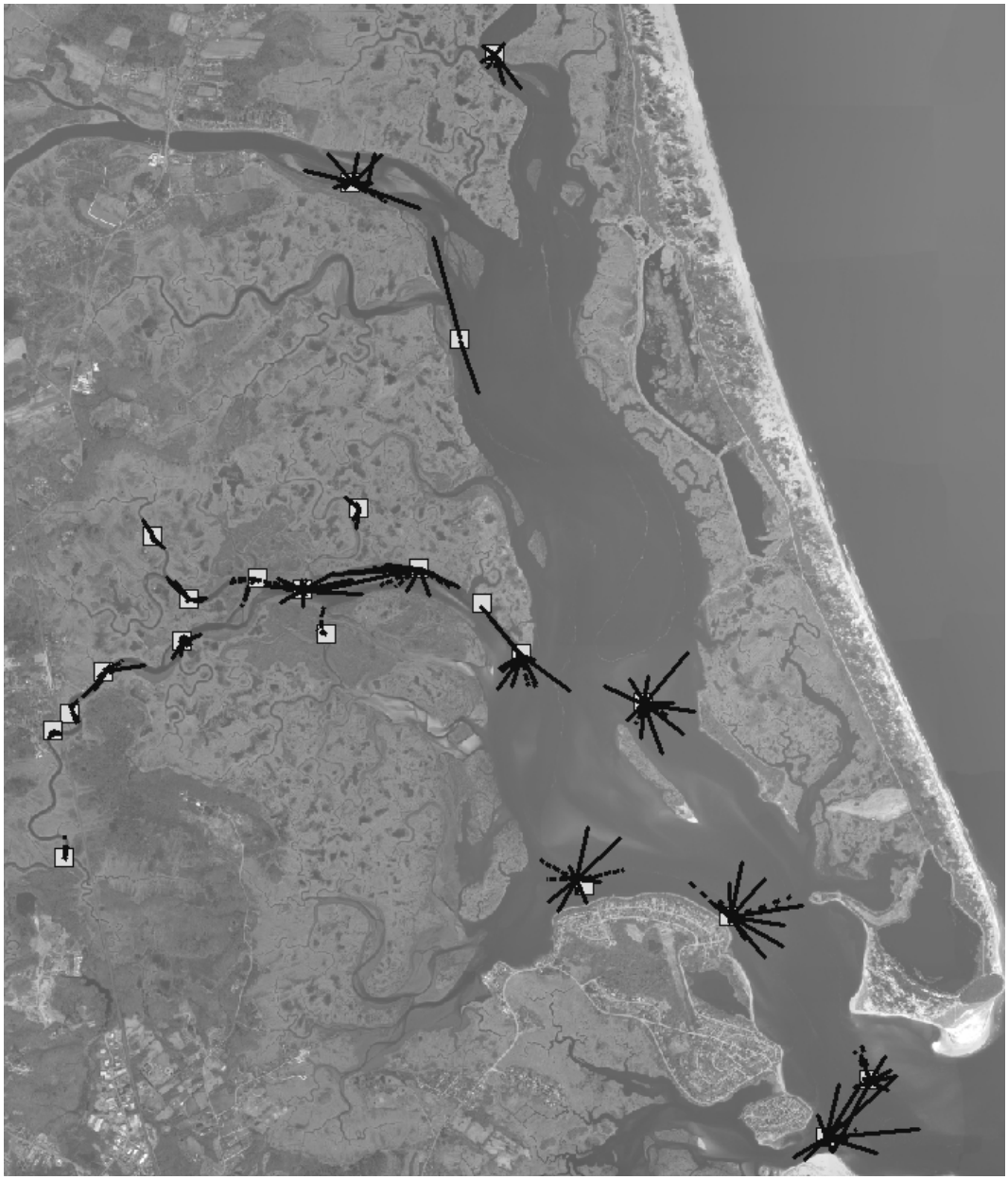
GPS TRACKS FOR TWO SITES OVERLAID WITH RECEIVER HEARING RANGE. The ranges were calculated by assessing the distance each receiver could hear. The following picture shows the tracks that were recorded by GIS on the boat at high tide and the resulting vectors of hearing distances that were determined for receiver sites 3 and 4 of the lower and mid PIS reaches, respectively. Similar tracks were made at each receiver for both high and low tides.



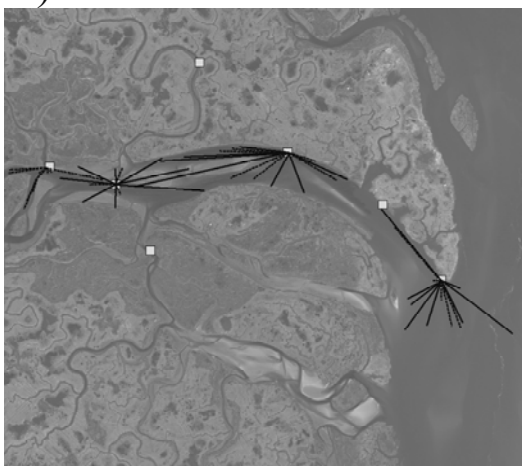
APPENDIX 2

RECEIVER RANGES AT HIGH AND LOW TIDE. The vectors from the range tests at high and low tide are depicted below. Solid lines represent high tide, while dashed lines are low tide. A) is the whole map, and B-G, next page) are zoomed in on the individual reaches. Light gray boxes are the receiver sites.

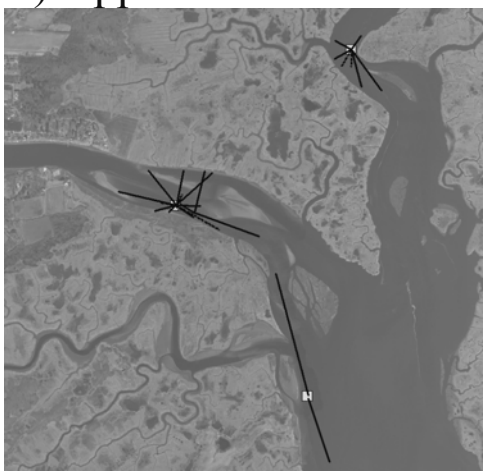
A)



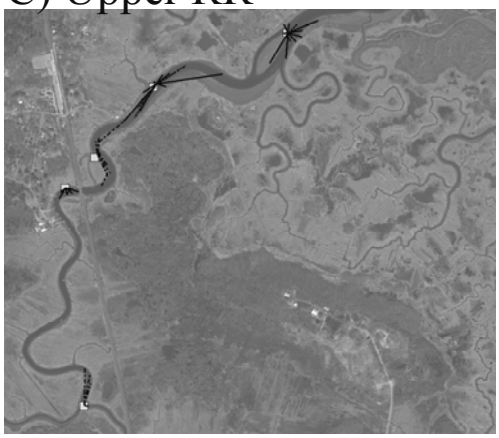
B) Lower RR



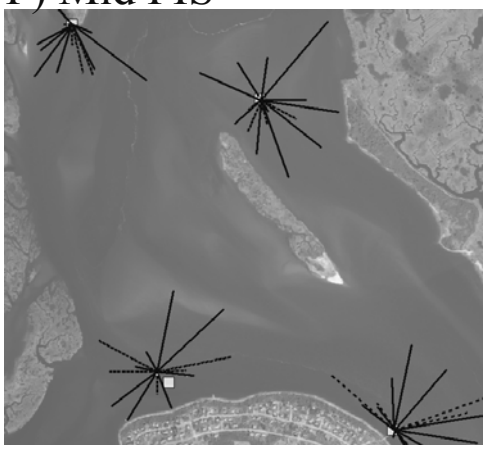
E) Upper PIS



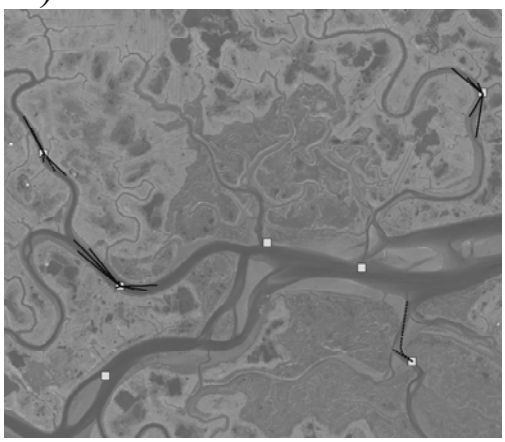
C) Upper RR



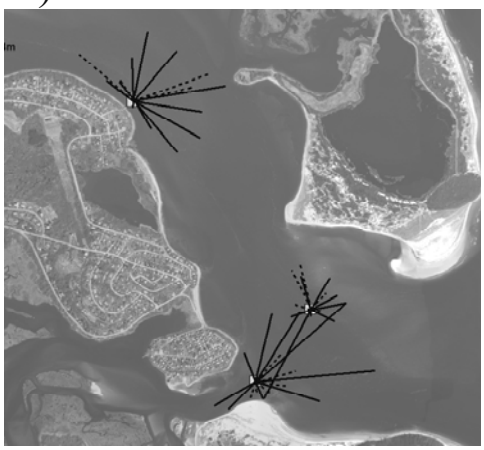
F) Mid PIS



D) RR Tidal Creeks

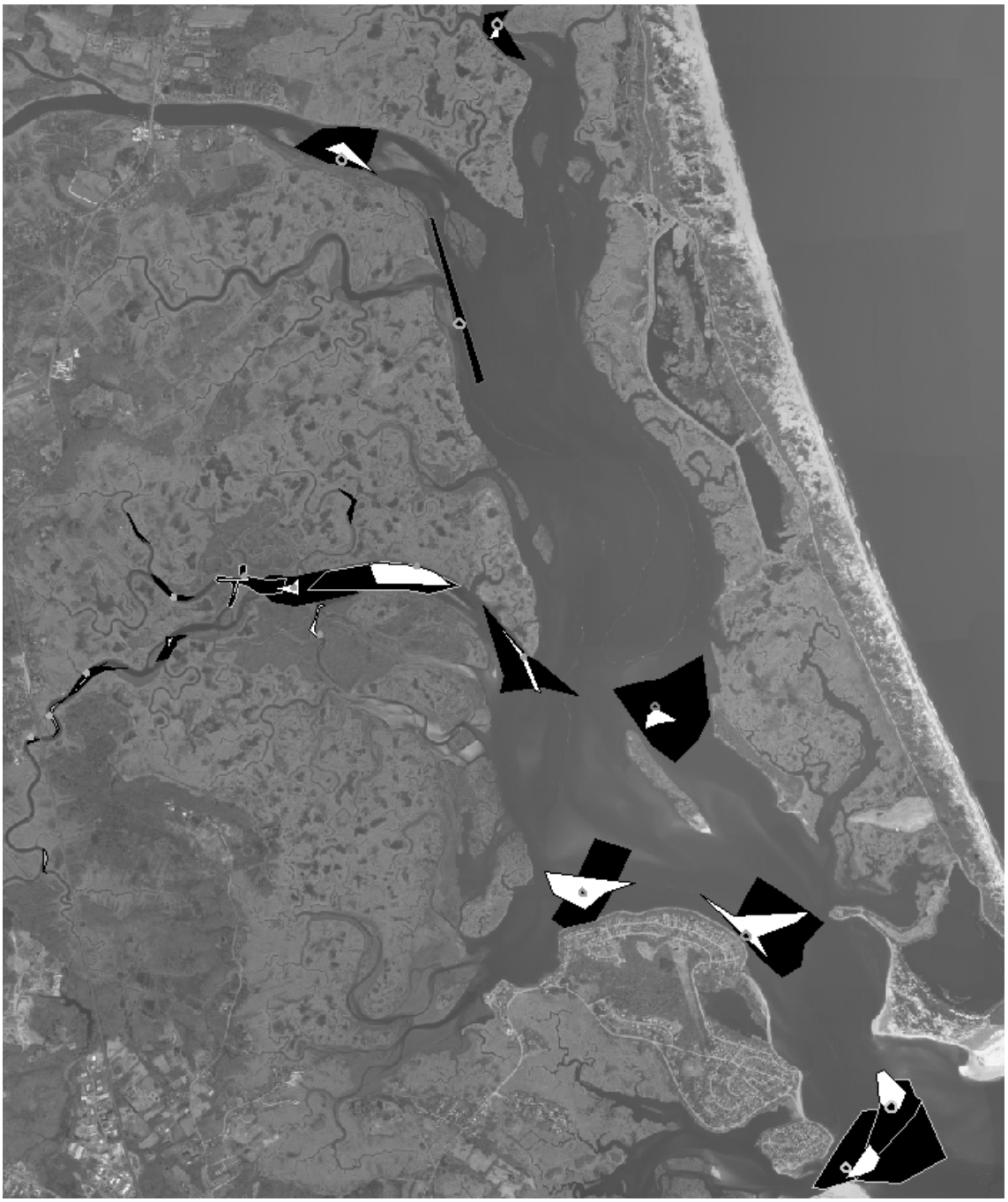


G) Lower PIS

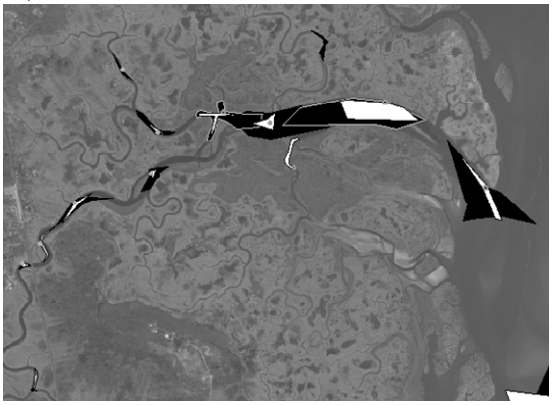


APPENDIX 3

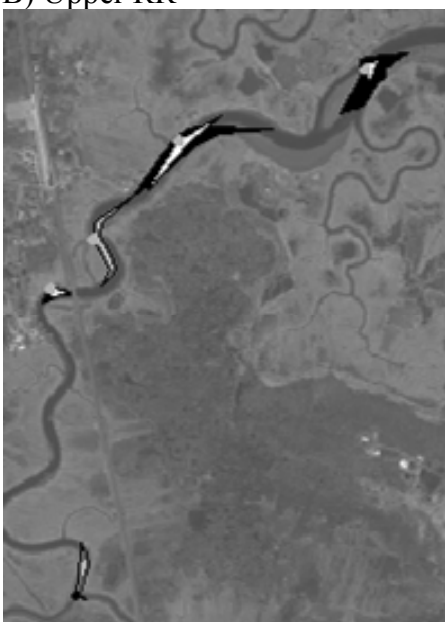
RECEIVER COVERAGE WITHIN EACH REACH OF PLUM ISLAND ESTUARY. The areas were figured for each receiver site within each reach. The black polygons are areas at high tide and white polygons are low tide areas.



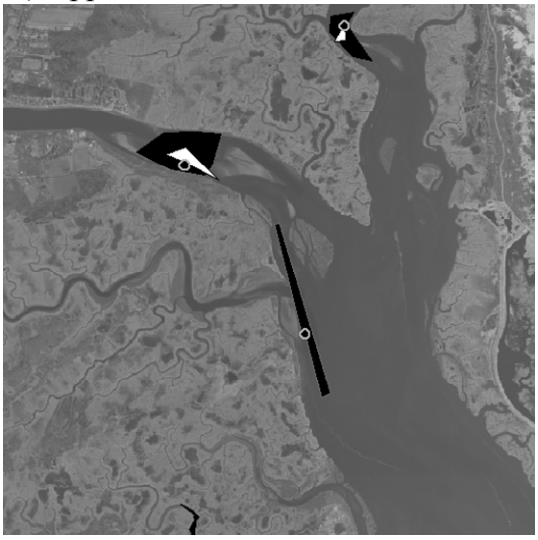
A) Lower RR and RR Tidal Creeks



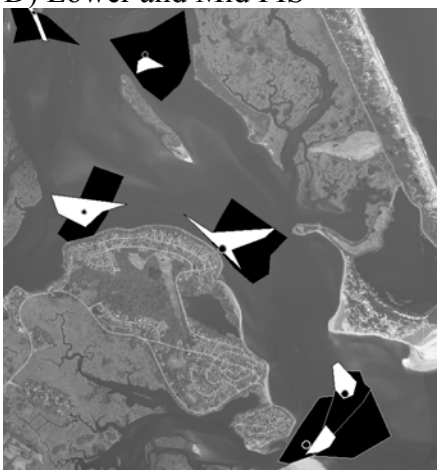
B) Upper RR



C) Upper PIS

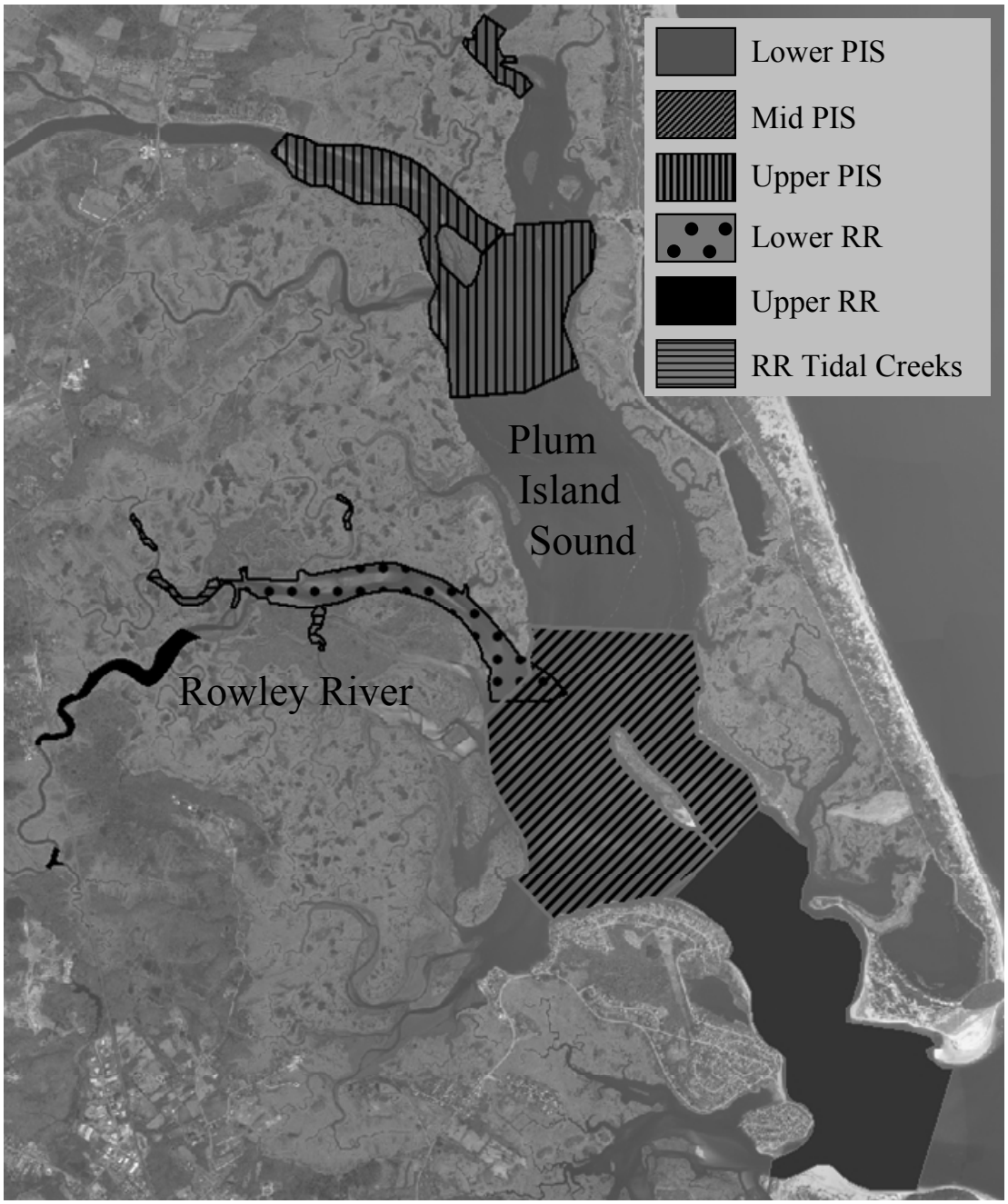


D) Lower and Mid PIS



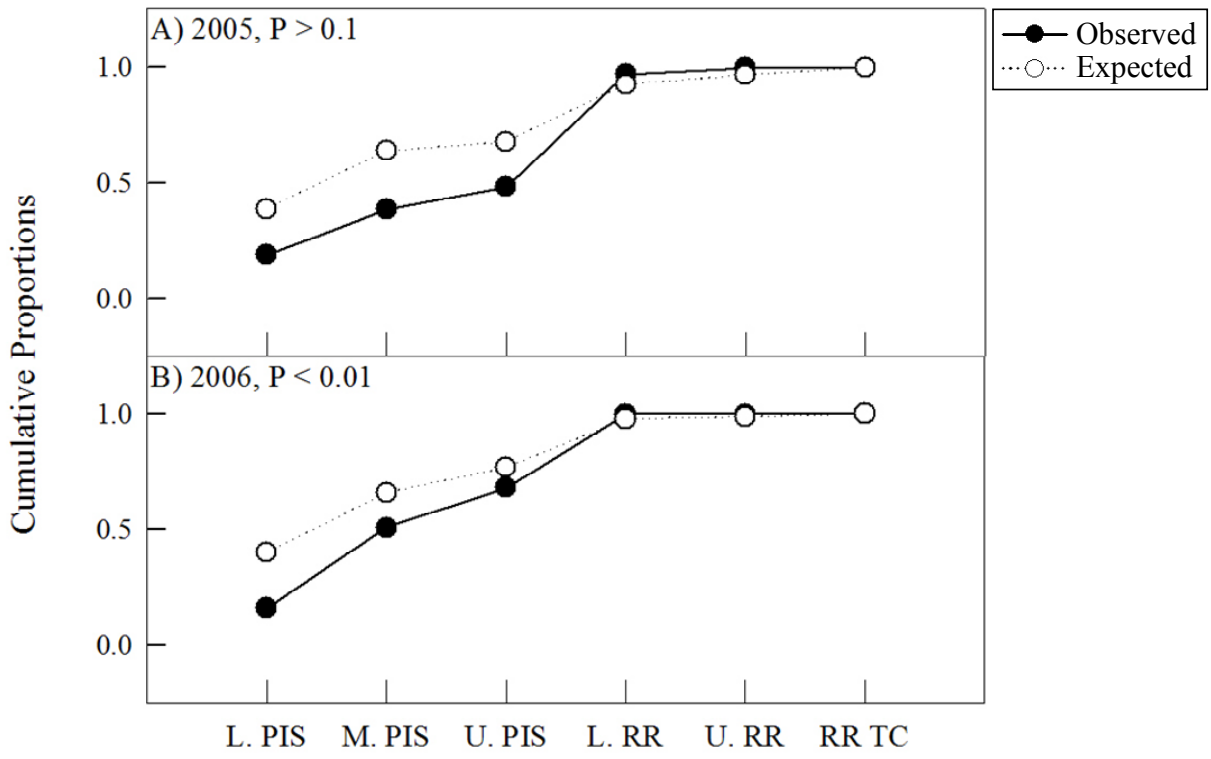
APPENDIX 4

AREAS OF EACH REACH OF PLUM ISLAND ESTUARY.


Lower PIS
Mid PIS
Upper PIS
Lower RR
Upper RR
RR Tidal Creeks
Plum
Island
Sound
Rowley River

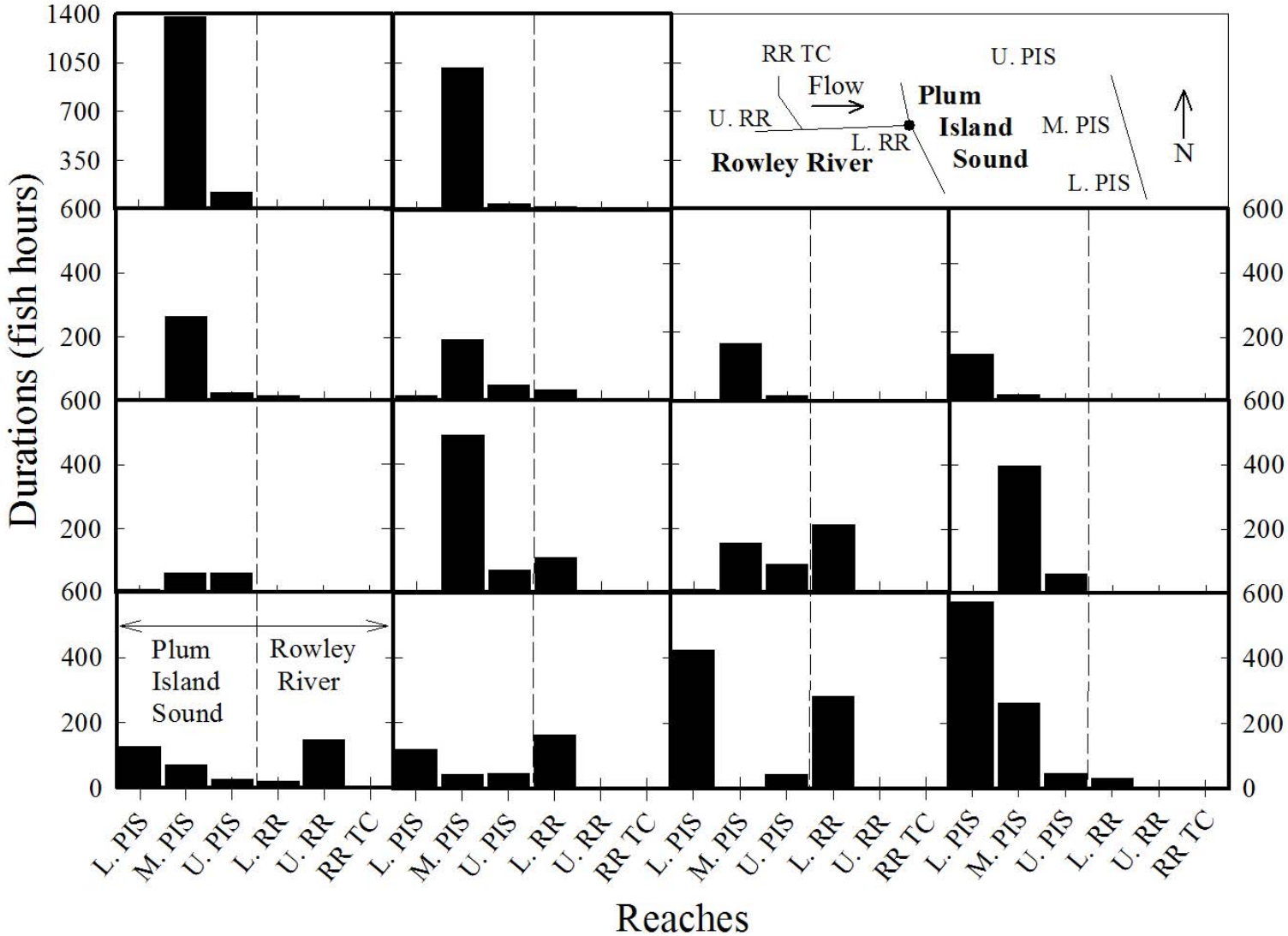
APPENDIX 5

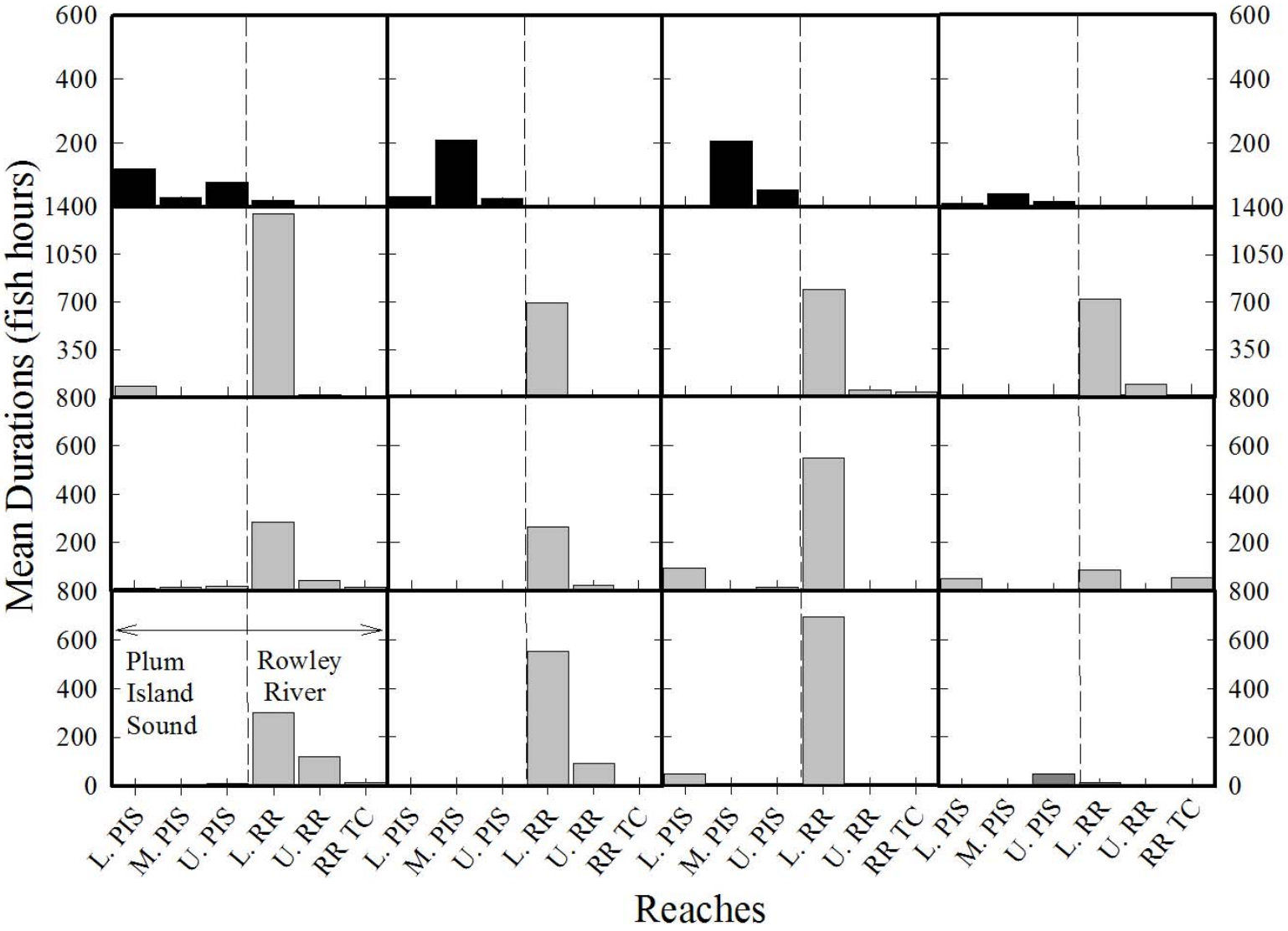
CUMULATIVE DISTRIBUTION GRAPHS FOR ALL FISH FOR 2005 AND 2006.
The X axis is the reaches of Plum Island Estuary: Lower Plum Island Sound (L. PIS), mid PIS (M. PIS), upper PIS (U. PIS), lower Rowley River (L. RR), upper RR (U. RR), and the RR tidal creeks (RR TC).

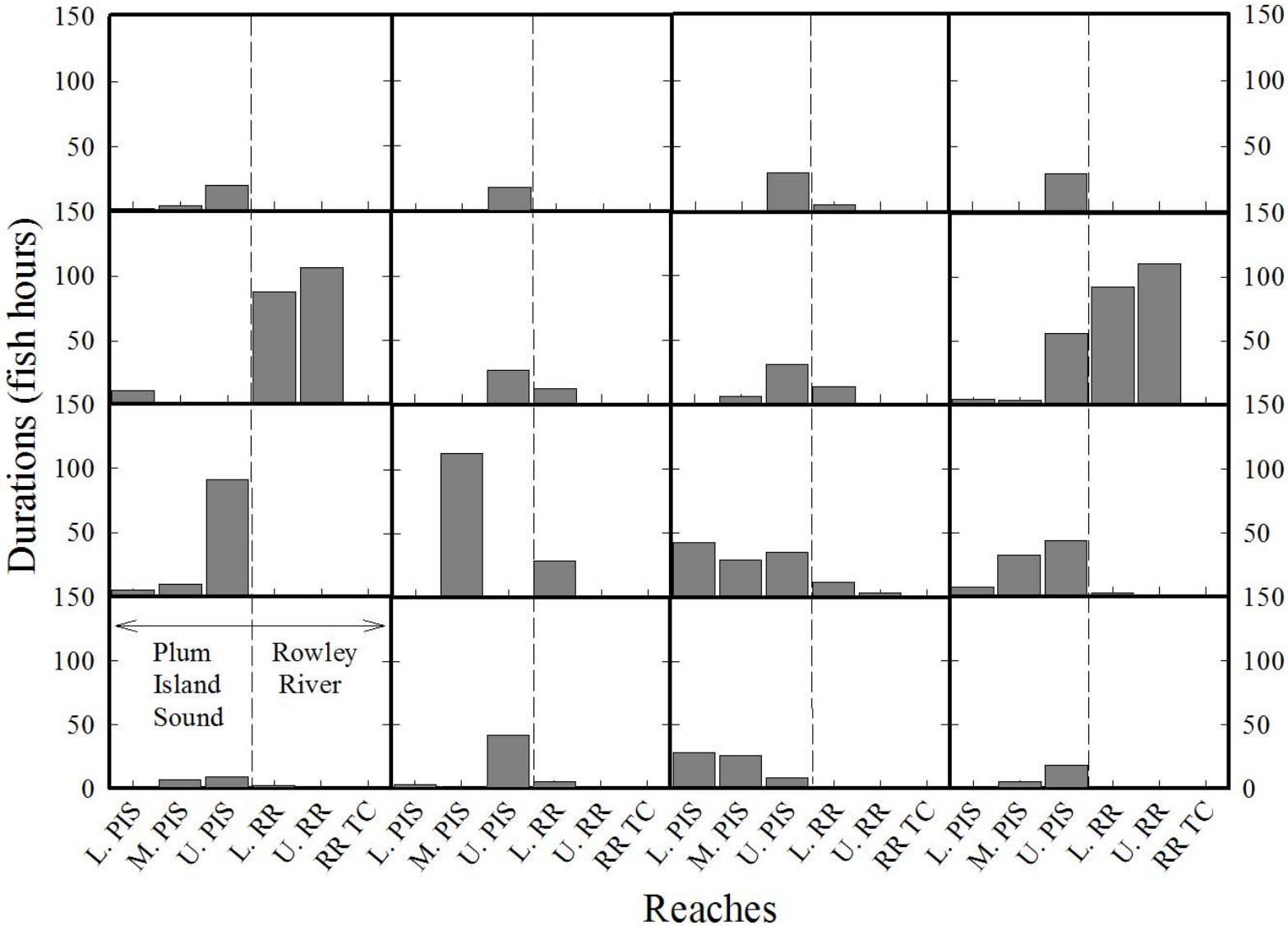

A) 2005, P > 0.1
B) 2006, P < 0.01
Observed
Expected
Cumulative Proportions
1.0
0.5
0.0
L. PIS
M. PIS
U. PIS
L. RR
U. RR
RR TC

APPENDIX 6

PLOTS OF INDIVIDUAL HISTOGRAMS PER REACH FOR STRIPED BASS TAGGED IN 2006. Black histograms represent PIS fish; light gray represents RR fish; and dark gray represents short-term fish.


Durations (fish hours)
1400
1050
700
350
600
400
200
0
RR TC
Flow
U. RR
L. RR
Rowley River
Plum
Island
Sound
U. PIS
M. PIS
L. PIS
N
Plum
Island
Sound
Rowley
River
L. PIS
M. PIS
U. PIS
L. RR
U. RR
RR TC
Reaches


Mean Durations (fish hours)
600
400
200
1400
1050
700
350
800
600
400
200
800
600
400
200
0
Plum
Island
Sound
Rowley
River
L. PIS
M. PIS
U. PIS
L. RR
U. RR
RR TC
Reaches


Durations (fish hours)
150
100
50
0
Plum Island Sound
Rowley River
L. PIS
M. PIS
U. PIS
L. RR
U. RR
RR TC
Reaches

APPENDIX 7

2006 SEASON REPEATED MEASURES ANOVA STATISTICS. The RM ANOVA was for season with the use-group (behavior) treatment included for all 6 reaches.

Year = 2006 Repeated Measures = SEASON
Area = Lower PIS Treatment = Behavior

MANOVA

Effect	Wilks Λ	F Value	Num DF	Den DF	Pr>F	
SEASON	1	0.01	2	21	0.99	NS
SEASON*Behavior	0.84	0.93	4	42	0.46	NS

Repeated Measures ANOVA

Effect	Source	DF	III SS	MS	F	Pr>F	
Between	Behavior	2	6.55	3.28	7.03	0.004	***
	Error	22	10.25	0.47	.		
Within	SEASON	2	0.001	0.0006	0.01	0.99	NS
	SEASON*Behavior	4	0.71	0.18	1.53	0.21	NS
	Error (SEASON)	44	5.14	0.12			

Year = 2006 Repeated Measures = SEASON
Area = Mid PIS Treatment = Behavior

MANOVA

Effect	Wilks Λ	F Value	Num DF	Den DF	Pr>F	
SEASON	0.85	1.85	2	21	0.18	NS
SEASON*Behavior	0.41	5.98	4	42	0.0007	****

Repeated Measures ANOVA

Effect	Source	DF	III SS	MS	F	Pr>F	
Between	Behavior	2	26.89	13.44	26.03	<.0001	****
	Error	22	11.36	0.52			
Within	SEASON	2	1	0.5	2.81	0.07	*
	SEASON*Behavior	4	2.8	0.7	3.94	0.008	***
	Error (SEASON)	44	7.82	0.18			

Year = 2006 Repeated Measures = SEASON
Area = Upper PIS Treatment = Behavior

MANOVA

Effect	Wilks Λ	F Value	Num DF	Den DF	Pr>F	
SEASON	0.22	37.45	2	21	<.0001	****
SEASON*Behavior	0.41	5.91	4	42	0.0007	****

Repeated Measures ANOVA

Effect	Source	DF	III SS	MS	F	Pr>F	
Between	Behavior	2	2.4	1.21	5.93	0.009	***
	Error	22	4.48	0.2			
Within	SEASON	2	9.79	4.89	40.18	<.0001	****
	SEASON*Behavior	4	3.67	0.91	7.44	1E-04	****
	Error (SEASON)	44	5.36	0.12			

Year = 2006 Repeated Measures = SEASON
Area = Lower RR Treatment = Behavior

MANOVA

Effect	Wilks Λ	F Value	Num DF	Den DF	Pr>F	
SEASON	0.28	27.49	2	21	<.0001	****
SEASON*Behavior	0.35	7.24	4	42	0.0002	***

Repeated Measures ANOVA

Effect	Source	DF	III SS	MS	F	Pr>F	
Between	Behavior	2	7.72	3.86	8.35	0.002	***
	Error	22	10.17	0.46			
Within	SEASON	2	8.11	4.05	27.16	<.0001	****
	SEASON*Behavior	4	2.13	0.53	3.57	0.01	**
	Error (SEASON)	44	6.57	0.15			

Year = 2006 Repeated Measures = SEASON
Area = Upper RR Treatment = Behavior

MANOVA

Effect	Wilks Λ	F Value	Num DF	Den DF	Pr>F	
SEASON	0.57	16.75	1	22	0.0005	****
SEASON*Behavior	0.7	4.7	2	22	0.02	**

Repeated Measures ANOVA

Effect	Source	DF	III SS	MS	F	Pr>F	
Between	Behavior	2	1.59	0.79	4.7	0.02	**

	Error	22	3.71	0.17			
Within	SEASON	2	5.66	2.83	16.75	<.0001	****
	SEASON*Behavior	4	3.17	0.79	0.47	0.003	***
	Error (SEASON)	44	7.43	0.17			

Year = 2006 Repeated Measures = SEASON
Area = RR TC Treatment = Behavior

MANOVA

Effect	Wilks Λ	F Value	Num DF	Den DF	Pr>F	
SEASON	0.26	30.16	2	21	<.0001	****
SEASON*Behavior	0.25	10.35	4	42	<.0001	****

Repeated Measures ANOVA

Effect	Source	DF	III SS	MS	F	Pr>F	
Between	Behavior	2	0.92	0.46	30.54	<.0001	****
	Error	22	0.33	0.02			
Within	SEASON	2	0.45	0.23	6.57	0.003	***
	SEASON*Behavior	4	0.47	0.17	3.38	0.02	**
	Error (SEASON)	44	1.52	0.03			

BIBLIOGRAPHY

Able, K. W., and T. M. Grothues. 2007. Diversity of estuarine movements of striped bass (*Morone saxatilis*): a synoptic examination of an estuarine system in southern New Jersey. *Fisheries Bulletin* 105: 426-435.

Aebischer, N. J., P. A. Robertson, and R. E. Kenward. 1993. Compositional analysis of habitat use from animal radio-tracking data. *Ecology* 74: 1313-1325.

Bjorgo, K. A., J. J. Isley, and C. S. Thomason. 2000. Seasonal movement and habitat use by striped bass in the Combahee River, South Carolina. *Transactions of the American Fisheries Society* 129: 1281-1287.

Bridger, C. J. and R. K. Booth. 2003. The effects of biotelemetry transmitter presence and attachment procedures on fish physiology and behavior. *Reviews in Fisheries Science* 11: 13-34.

Boreman, J., and R. R. Lewis. 1987. Atlantic coastal migration of striped bass. *American Fisheries Society Symposium* 1: 331-339.

Brown, R. S., S. J. Cooke, W. G. Anderson, and R. S. McKinley. 1999. Evidence to challenge the "2% Rule" for biotelemetry. *North American Journal of Fisheries Management* 19: 867-871.

Carmichael, J. T., S. L. Haeseker, and J. E. Hightower. 1998. Spawning migration of telemetered striped bass in the Roanoke River, North Carolina. *Transactions of the American Fisheries Society* 127: 286-297.

Clark, J. 1968. Seasonal movements of striped bass contingents of Long Island Sound and the New York Bight. *Transactions of the American Fisheries Society* 97: 320-343.

Clark, K. L., G. M. Ruiz, and A. H. Hines. 2003. Diel variation in predator abundance, predation risk and prey distribution in shallow-water estuarine habitats. *Journal of Experimental Marine Biology and Ecology* 187: 37-55.

Clark, R. D., J. D. Christensen, M. E. Monaco, P. A. Caldwell, G. A. Matthews, and T. J. Minello. 2004. A habitat-use model to determine essential fish habitat for juvenile brown shrimp (*Farfantepenaeus aztecus*) in Galveston Bay, Texas. *Fisheries Bulletin* 102: 264-277.

Clements, S., D. Jepsen, and M. Karnowski. 2005. Optimization of an acoustic telemetry array for detecting transmitter-implanted fish. *North American Journal of Fisheries Management* 25: 429-436.

Collette, B. B. and G. Klein-MacPhee. 2002. Bigelow, H. B. and W. C. Schroeder's Fishes of the Gulf of Maine, 3rd edition. Pages 377-389. Smithsonian Institution Press, Washington.

Cooke, S. J., C. D. Suski, K. G. Ostrand, B. L. Tufts, and D. H. Wahl. 2004. Behavioral and physiological assessment of low concentrations of clove oil anaesthetic for handling and transporting largemouth bass (*Micropterus salmoides*). *Aquaculture* 239: 509-529.

Coutant, C. C. 1985. Striped bass, temperature, and dissolved oxygen: a speculative hypothesis for environmental risk. *Transactions of the American Fisheries Society* 114: 31-61.

Coutant, C. C. 1990. Temperature-oxygen habitat for freshwater and coastal striped bass in a changing climate. *Transactions of the American Fisheries Society* 119: 240-253.

Day Jr., J. W., C. A. S. Hall, W. M. Kemp, and A. Yanez-Arancibia. 1989. *Estuarine Ecology*.

Deegan, L. A., J. L. Bowen, D. Drake, J. W. Fleeger, C. T. Friedrichs, K. A. Galvan, J. E. Hobbie, C. Hopkinson, D. S. Johnson, J. M. Johnson, L. E. LeMay, E. Miller, B. J. Peterson, C. Picard, S. Sheldon, M. Sutherland, J. Vallino, and R. S. Warren. 2007. Susceptibility of salt marshes to nutrient enrichment and predator removal. *Ecological Applications* 17: S42-S63.

Deegan, L. A., and R. H. Garritt. 1997. Evidence for spatial variability in estuarine food webs. *Marine Ecology Progress Series* 147: 31-47.

Dorazio, R. M., K. A. Hattala, C. B. McCollough, and J. E. Skjeveland. 1994. Tag recovery estimates of migration of striped bass from spawning areas of the Chesapeake Bay. *Transactions of the American Fisheries Society* 123: 950-963.

Dytham, C. 2003. *Choosing and using statistics: a biologist's guide*. Blackwell Publishing, Malden, MA.

Farquhar, B. W. and S. Gutreuter. 1989. Distribution and migration of adult striped bass in Lake Whitney, Texas. *Transactions of the American Fisheries Society* 118: 523-532.

Ferry, K. H. 2003. Factors driving distribution of migratory striped bass across Massachusetts estuaries: predator-prey interactions and implications for multispecies management. Pages 114. *Wildlife and Fisheries Conservation*. University of Massachusetts Amherst, Amherst.

Garson, G. D. One-Sample Kolmogorov-Smirnov Goodness-of-Fit Test. Accessed: 2007. http://www2.chass.ncsu.edu/garson/pa765/kolmo.htm, *last updated 4/24/2008.*

Garvey, J. E., E. A. Marschall, and R. A. Wright. 1998. From star charts to stoneflies: detecting relationships in continuous bivariate data. *Ecology* 79: 442-447.

Grothues, T. M., K. W. Able, J. Carter, and T. Arienti. 2008 *in review*. Migration patterns of striped bass (*Morone saxatilis*) through non-natal estuaries of the U.S. Atlantic Coast.

Guy, C. S. and M. L. Brown. 2007. Analysis of Movement and Habitat Use from Telemetry Data. Chapter 14. *Analysis and Interpretation of Freshwater Fisheries Data*. American Fisheries Society, Bethesda.

Haeseker, S. L., J. T. Carmichael, and J. E. Hightower. 1996. Summer distribution and condition of striped bass within Albemarle Sound, North Carolina. *Transactions of the American Fisheries Society* 125: 690-704.

Harding, J. M., and R. Mann. 2003. Influence of habitat on diet and distribution of striped bass (*Morone saxatilis*) in a temperate estuary. *Bulletin of Marine Science* 72: 841-851.

Hartman, K. J., and F. J. Margraf. 2003. US Atlantic coast striped bass: issues with a recovered population. *Fisheries Manage* 10: 309-312.

Heupel, M. R., J. M. Semmens, and A. J. Hobday. 2006. Automated acoustic tracking of aqautic animals: scales, design and deployment of listening station arrays. *Marine and Freshwater Research* 57: 1-13.

Hightower, J. E., J. R. Jackson, and K. H. Pollock. 2001. Use of telemetry methods to estimate natural and fishing mortality of striped bass in Lake Gaston, North Carolina. *Transactions of the American Fisheries Society* 130: 557-567.

Hopkinson, C. S., A. E. Giblin, J. Tucker, and R. H. Garritt. 1999. Benthic metabolism and nutrient cycling along an estuarine salinity gradient. *Estuaries* 22: 863-881.

Hughes, J. E., L. A. Deegan, B. J. Peterson, R. M. Holmes, and B. Fry. 2000. Nitrogen flow through the food web in the oligohaline zone of a New England estuary. *Ecology* 81: 433-452.

Jackson, J. R., and J. E. Hightower. 2001. Reservoir striped bass movements and site fidelity in relation to seasonal patterns in habitat quality. *North American Journal of Fisheries Management* 21: 34-45.

Kildea, M. A., G. L. Allan, and R. E. Kearney. 2004. Accumulation and clearance of the anaesthetics clove oil and Aqui-S^{TM} from the edible tissue of silver perch (*Bidyanus bidyanus*). *Aquaculture* 232: 265-277.

Kohlenstein, L. C. 1981. On the proportion of the Chesapeake Bay stock of striped bass that migrates into the coastal fishery. *Transactions of the American Fisheries Society* 110: 168-179.
Komarow, S., T. Young, L. Deegan, and R. Garritt. 1999. Influence of Marsh Flooding on the Abundance and Growth of *Fundulus heteroclitus* in Salt Marsh Creeks. *Biological Bulletin* 197: 299-300.

McGarigal, K., S. Cushman, and S. Stafford. 2000. *Multivariate Statistics for Wildlife and Ecology Research*. Springer Science+Business Media, Inc., New York.

McLaren, J. B, J. C. Cooper, T. B. Hoff, and V. Lander. 1981. Movements of Hudson River striped bass. *Transactions of the American Fisheries Society* 110: 158-167

Mendina-Vogel, G., V. S. Kaufman, R. Monsalve, and V. Gomez. 2003. The influence of riparian vegetation, woody debris, stream morphology and human activity on the use of rivers by southern river otters in *Lontra provocax* in Chile. *Oryx* 37: 422-430.

Menzel, J. M., W. M. Ford, M. A. Menzel, T. C. Carter, J. E. Gardner, J. D. Garner, and J. E. Hofmann. 2005. Summer habitat use and home-range analysis of the endangered Indiana bat. *Journal of Wildlife Management* 69: 430-436.

Nelson, G. A. 2005. Life history, population dynamics, and management of striped bass. Presentation to University of Massachusetts Department of Natural Resources Conservation.

Nelson, G. A., B. C. Chase, and J. Stockwell. 2003. Food habits of striped bass (*Morone Saxatilis*) in coastal waters of Massachusetts. *J. Northw. Atl. Fish. Sci.* 32.

Ng, C. L., K. W. Able, and T. M. Grothues. 2007. Habitat use, site fidelity, and movement of adult striped bass in a southern New Jersey estuary based on mobile acoustic telemetry. *Transactions of the American Fisheries Society* 136: 1344-1355.

PIE-LTER. 2001. Plum Island Long Term Ecological Research Site. Project Overview. Accessed: 2006. http://ecosystems.mbl.edu/PIE/over.htm.

Quinn, G. P., and M. J. Keough. 2002. *Experimental design and data analysis for biologists*. Cambridge University Press, New York.

Secor, D. H. 1999. Specifying divergent migrations in the concept of stock: the contingent hypothesis. *Fisheries Research* 43: 13-34.

Secor, D. H., and P. M. Piccoli. 2007. Oceanic migration rates of Upper Chesapeake Bay striped bass (*Morone Saxatilis*), determined by otolith microchemical analysis. *Fisheries Bulletin* 105: 62-73.

Secor, D. H., J. R. Rooker, E. Zlokovitz, and V. S. Zdanowicz. 2001. Identification of riverine, estuarine, and coastal contingents of Hudson River striped bass based upon otolith elemental fingerprints. *Marine Ecology Progress Series* 211: 245-253.

Sokal, R. R., and F. J. Rohlf. 1995. *Biometry the principles and practice of statistics in biological research.* W. H. Freeman and Company.

Starr, R. M., J. N. Heine, J. M. Felton, and G. M. Cailliet. 2002. Movements of bocaccio (*Sebastes paucispinis*) and greenspotted (*S. chlorostictus*) rockfishes in a Monterey submarine canyon: implications for the design of marine reserves. *Fisheries Bulletin* 100: 324-337.

Stockwell, J. D., P. J. Diodati, and M. P. Armstrong. 2002. A bioenergetic evaluation of the chronic-stress hypothesis: Can catch-and-release fishing constrain striped bass growth? *American Fisheries Society Symposium* 30: 144-147.

Szedlmayer, S. T., and R. L. Schroepfer. 2005. Long-term residence of red snapper on artificial reefs in the northeastern Gulf of Mexico. *Transactions of the American Fisheries Society* 134: 315-325.

Tattersall, F. H., D. W. Macdonald, B. J. Hart, W. J. Manley, and R. E. Feber. 2001. Habitat use by wood mice (*Apodemus sylvaticus*) in a changeable arable landscape. *Journal of the Zoological Society of London* 255: 487-494.

Thomas, D. L., and E. J. Taylor. 2006. Study designs and tests for comparing resource use and availability II. *Journal of Wildlife Management* 70: 324-336.

Tupper, M. and K. W. Able. 2000. Movements and food habits of striped bass (Morone Saxatilis) in Delaware Bay (USA) salt marshes: comparison of a restored and a reference marsh. *Marine Biology* 137: 1049-1058.

Vallino, J. J., C. S. Hopkinson, and R. H. Garritt. 2005. Estimating estuarine gross production, community respiration and net ecosystem production: a nonlinear inverse technique. *Ecological Modelling* 187: 281-296.

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

Waldman, J. R., and M. C. Fabrizio. 1994. Problems of stock definition in estimating relative contributions of Atlantic striped bass to the coastal fishery. *Transactions of the American Fisheries Society* 123: 766-778.

Walter, J. F., A. S. Overton, K. H. Ferry, and M. E. Mather. 2003. Atlantic coast feeding habits of striped bass: a synthesis supporting a coast-wide understanding of trophic biology. *Fisheries Management and Ecology* 10: 349-360.

White, G. C., and R. A. Garrott. 1990. *Analysis of wildlife radio-tracking data*. Academic Press, San Diego.

WHSRN. http://www.manomet.org/WHSRN/viewsite-new.php?id=77. 2005. Great Marsh, Massachusetts site description. Western Hemisphere Shorebird Reserve Network.

Wingate, R. L., and D. H. Secor. 2007. Intercept telemetry of the Hudson River striped bass resident contingent: migration and homing patterns. *Transactions of the American Fisheries Society* 136: 95-104.

Winter. J. D. 1983. Underwater biotelemetry. Pages 371–395 *in* Fisheries techniques. L. A. Nielsen and D. L. Johnson, editors. American Fisheries Society, Bethesda, Maryland.

Young, T., S. Komarow, L. Deegan, and R. Garritt. 1999. Population Size and Summer Home Range of the Green Crab, *Carcinus maenas*, in Salt Marsh Tidal Creeks. *Biological Bulletin* 197: 297-299.

Zar, J. H. 1984. *Biostatistical analysis*. Prentice-Hall, Englewood Cliffs.