ESTUARINE HABitat Ecology Of
Adult weakfish (Cynoscion Regalis): A Multi-Scale Approach

By

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A thesis submitted to the

Graduate School-New Brunswick
Rutgers, The State University of New Jersey

in partial fulfillment of the requirements for the degree of

Master of Science

Graduate Program in Ecology and Evolution

written under the direction of

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and approved by

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New Brunswick, New Jersey

October 2010
ABSTRACT OF THE THESIS

Estuarine habitat ecology of adult weakfish (Cynoscion regalis): a multi-scale approach

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Thesis Director:
Dr. Kenneth W. Able

The habitat ecology of adult weakfish (Cynoscion regalis) remains poorly understood, although they comprise an important ecological and economic portion of estuarine environments. Weakfish are particularly susceptible to confusion over how to best delineate important habitat resources, such as those used for reproduction, because they may change over multiple spatial (coastal and estuary) and temporal (seasonal and diel) scales. In this study, weakfish habitat dynamics were evaluated at multiple scales using acoustic telemetry within the Mullica River-Great Bay estuary in southern New Jersey. At the broader estuary scale, residency, habitat use, and movements were quantified across the reproductive/post-reproductive season. Tagged adult weakfish were resident in bay, lower river, and subtidal creek habitats during reproduction (May through July) and following the reproductive season (August through November) but showed limited use of inlet and upriver habitats in both seasons. Movement rates increased at the end of the post-reproductive season and weakfish apparently moved into fringing, unmonitored habitats within the study area following the reproductive period. Estuarine egress occurred throughout the study period but was lowest during July and highest during the final month of emigration in November. At smaller spatial scales, weakfish
displayed patterns of site fidelity both seasonally and daily. At the seasonal scale, a majority of weakfish tagged in 2008 maintained fidelity to their original tagging location or established new “core areas” in other parts of the estuary. In both cases, fish were detected at these areas for the duration of their residency or made short- or long-term excursions before returning to their original core area. At the diel scale, weakfish displayed movements of varying distances from their original tagging location beginning around sundown and returning around the sunrise period, which also corresponds to the timing of nightly weakfish reproduction. These findings represent new evidence of the role that estuary habitats may play in adult weakfish life history and, because weakfish habitat dynamics may be influenced by reproduction, it will be important to incorporate these changes into future management of the fishery.
Acknowledgements and Dedication

Dedicated to the loving memory of Stacy Moore Hagan, who is probably most disappointed that I didn’t study killifish. You inspired a multitude of graduate students, technicians, and colleagues - including the one who writes these words - with your warm spirit, humor, and hard work. I will miss you deeply.

I first came to the Rutgers University Marine Field Station in 2004 with the hope that I could one day be directly involved in my own research. It was there that I both literally, and figuratively, got my feet wet (well, muddy) in the marine sciences. Much to my enjoyment, they haven’t been dry since; first as a technician and then as a graduate student. Most of all, I would like to thank my primary advisor Ken Able, who fostered in me an even greater appreciation for the estuarine world and made me a better scientist. Another big thank you goes to Thomas “Motz” Grothues for our many long, quantitative conversations, his insightful comments, and his professional mentorship through the years. Even at his own expense, he would always go the extra mile to increase my understanding. The remaining members of my committee, Dr. Rebecca Jordan and Dr. Bonnie McCay, provided invaluable comments to previous thesis drafts, as well as much-appreciated and well-timed humor. Carol Van Pelt worked her magic at RUMFS through her ability to do nearly everything, although I’m still not sure how she does it. My philosophical mentor during my time at RUMFS, Roland Hagan, brought me back to my roots while my brain was reaching for the branch tips, and I thank him deeply for that.

Numerous, amazing people associated with RUMFS assisted in everything from pulling telemetry buoys to data checking for this project. I’m indebted by the help
provided to me by technicians and friends Tom Malatesta, Steve Ordog, Jamie Caridad, Kim Capone, and Jen Smith, as well as intern Caitlin Kennedy, who was with me during the very beginnings of this project. Interns Brian Reckenbiel and Alex Pogue were great companions and researchers during the second year of tracking, always putting up with those late nights and early mornings with a smile. Bill Bessmer and James Bunkiewicz, although not around for a long time, also assisted in catching and tagging weakfish during that first year. I sincerely thank previous E&E students Jim Vasslides, Jackie Toth, and Matt Kimball for their help with data retrieval and analysis, as well as salient graduate school advice. RUMFS/JCNERR volunteers Richard Zaengle, Ken Mancini, and Mimi Lanfear were always willing to lend a hand when I needed them. The staff at JCNERR, specifically Gregg Sakowicz and Gina Petruzzelli, maintained the SWMP data set and subsequently provided the environmental data used in this research. Paige Roberts lent support in various forms for this project but I am especially grateful for her moral and personal guidance.

The act of catching a weakfish for tagging was always a hardship, but was made much easier with the help of several local fishermen, especially Scott Powell, who provided both resources and an uncanny ability to catch weakfish. His main reason for selflessly devoting himself to this project was so his grandson could have the chance to catch a weakfish when he grew older. I sincerely hope his efforts and this project will be one step towards that goal. Dave Messerschmid and Lee Webb were another source of local fishing knowledge. Jay Caldwell denoted his first three weakfish caught from the banks of Little Sheepshead Creek during the spring of 2007 to get the project underway. Other fellow bank fishermen Chris Hirose and Brian Cognigni delicately assisted with
and named the biggest fish tagged during the project (Olga, 864 mm TL; see pg.). Local commercial fisherman Kevin Wark, Pam Carlsen from the American Littoral Society, Gary Shepherd of NMFS, and John Clark from DNREC each made small, but noticeable, contributions to my knowledge of weakfish through several conversations and anecdotes that we shared. Local bait shops Scott’s, Chestnut Neck, and Captain Mike’s provided the fuel (literally) that kept our boats running and the bait that kept us tagging, not to mention numerous local fishing tips free-of-charge.

Although I spent much of my time as a graduate student at RUMFS tracking weakfish, I met a lot of wonderful people and received invaluable guidance and help from members of the Ecology and Evolution community. Thank you Marsha and Peter Morin for your willingness to take on students as if they were family. Jim Applegate and David Ehrenfeld taught me lessons I will carry with me forever. Fellow students and housemates Kenneth Elgersma, Ai Wen, Blake Mathys, Holly Vuong, and Anna Zdepski were great friends during my time in New Brunswick and helped with the transition into graduate school life.

It’s difficult to run a telemetry project without ample financial support, so I greatly thank my funding sources for allowing me to conduct this work. Primary research funding was provided through a NERR Graduate Research Fellowship from the Estuarine Reserves Division, Office of Ocean and Coastal Resource Management, National Ocean Service, National Oceanic and Atmospheric Administration. My support for attending graduate school was provided through IMCS and RUMFS/IMCS provided research support through a graduate research award. The Manasquan River Marlin and Tuna Club’s graduate scholarship also generously helped defray costs.
I’d be completely remiss not to mention the personal support I received before, during, and after this endeavor. The rock of my life, my mother, always dreamed of becoming a marine scientist herself, but instead endlessly supported her son to do the same. My dad always supported me in a multitude of ways, making me laugh all the way. Pop-Pop may have been the first to distill an appreciation for a life based around the tides with both his plethora of old fishing stories and my own experiences digging clams and netting fish with him. I thank Mom-Mom for always frying those fish we caught ‘just right.’ To Jenna Rackovan: words that convey the patience, support, and love during this (sometimes trying) time in my life could not fit within these pages.
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A GREAT CATCH OF FISH.

WHAT THREE STEAM SMACKS CAUGHT OFF ROCKAWAY.

A great catch of weak-fish was made yesterday about two miles off Rockaway Beach by the steam smacks E. T. De Blois, Capt. J. A. Keene; Leonard Brightman, Capt. Elijah Powers, and J. W. Hawkins, Capt. J. W. Hawkins. These smacks are engaged in the menhaden or "moss-bunker" fishery for the oil-rendering and fish-soup works on Barren island, and were cruising off Rockaway yesterday in search of schools. About noon a vast school of what the fishermen supposed at first to be menhaden was discovered stretching along the coast for miles. To borrow their language, "the water was red with the fish, but they didn't break the surface as menhaden always do." The boats were lowered, the seine spread, and then it was discovered that the school was of weak-fish and not menhaden. "I have been in the business for 20 years," said the mate of the Brightman, and I never saw anything like it before." The fish varied in length from one and a half to three feet, and in weight from three to seven pounds. The De Blois took over 200 barrels, the Hawkins 150 barrels, and the Brightman 350 barrels. The entire catch was estimated at something over 200,000 pounds, which, at the ordinary market price for weak-fish—7 cents a pound—would amount to $14,000. But, of course, the market price could not be maintained in the presence of such a catch as this, and it was said yesterday afternoon that a strong effort was being made by the wholesale fish-dealers of Fulton Market to prevent the greater part of the fish from being put on sale. The Captain of the Hawkins, which landed at Pier No. 33 East River, foot of Fulton street, obtained a promise from a Fulton Market dealer to take part of his catch, and then made overtures to Mr. Eugene G. Blackford, of E. G. Blackford & Co., Beekman-street, to sell the remainder. As soon, however, as the Fulton Market dealer learned of the offer to Mr. Blackford, he refused to take any of the fish. The Captain of the Brightman, however, had better luck. H. M. Rodgers & Co., of No. 11 Fulton Market, engaged to take his entire catch of 350 barrels, and immediately put two men in charge of the boat. The De Blois meanwhile had made fast against the bulkhead at the foot of Beekman-street, and Capt. Keene failing to come to terms with the Fulton Market dealers, enquired F. Owen, of No. 394 South-street, who manages the packing trade for the Fulton Market dealers, to dispose of his fish. A crowd speedily gathered about the boat, and the fish sold almost as fast as they could be hauled at 25 cents a pair. The pressure of the crowd became so great, at one time, that Police assistance was invoked, and Officer William Brown, of the steam-boat squad, was detailed to stay on the boat. While Owen was selling the fish at 25 cents a pair an attempt to break the price was made by two well-known "long shore" characters, Jack Sullivan, the shark catcher, and T. Long, alias "Blindy," who bought 1,000 pounds of the fish at 1 cent per pound, and stood on the street retailing them at 30 cents per pair.

Fish-dealers say that there will be no difficulty in selling all the fish this morning at from 12 to 15 cents per pound. Friday morning, they say, is the best in the week for the sale of fish. Tons of ice were cranked last evening and put on the fish to keep them fresh until to-day.

Source: The New York Times (July 1, 1881)
A distinctive characteristic of most animals is their ability to respond to environmental (e.g. temperature) and biotic (e.g. predation) change, which is crucial to survival of both individuals and populations. Habitat ecology generally encompasses the theoretical and empirical study of the interactions of organisms with their natural environment and the implications of these interactions on an organism at the individual, population, community, and/or ecosystem level. One type of response to dynamic variables is movement, which is “fundamental to the study of animal ecology and to the design of effective conservation…measures” (Pittman and McAlpine 2003). As with any ecological process, the importance of scale should not be understated and movement is an especially scale-dependent process since organisms have the ability to move within their environment at multiple spatial and temporal levels (Wiens 1989; Levin 1992). In the study of animal movements, however, scale has not been addressed sufficiently (Pittman and McAlpine 2003).

One application to the study of habitat ecology is in the management of ocean resources, a pertinent and urgent topic due to the collapse of many important fish stocks in recent years (Myers and Worm 2003). With the concurrent shift towards a holistic, ecosystem-based approach to fisheries management (Larkin 1996), there has also been more thorough acknowledgement of the role that the abiotic environment (i.e. habitat) plays in the life histories of fishes. These priorities have been recently manifested in legislation protecting essential fish habitat (EFH) (NOAA 1996) and the implementation of spatial management measures like marine reserves (discrete areas reserved for habitat
and fish stock preservation) (Agardy 1994; Botsford et al. 2009). Of course, a greater understanding of fish-habitat interactions will ultimately lead to more effective conservation measures.

A primary difficulty to overcome when attempting to study these interactions in fishes is simply the ability to sample. Physical constraints such as poor visibility and unsafe water conditions have pushed researchers into utilizing newer and more efficient approaches. One such approach, acoustic telemetry∗, takes advantage of the enhanced propagation of sound in water and has led to a greater understanding of fish behaviors within the last two decades. Whereas more traditional methods like mark-recapture are limited in their ability to elucidate fine-scale movements, telemetry can track individuals at multiple temporal and spatial scales. A further advantage to this approach is the focus on individuals. Coarse-scale sampling (e.g. trawls, gill-nets, seines) of fishes, while needed for understanding population-level metrics such as abundance, does little to sort out the effects of individual variation on fish dynamics.

One particular species where this approach to studying the complexities of scale-dependent fish-habitat interactions is appropriate is the weakfish (*Cynoscion regalis* Bloch and Schneider). A member of the family Sciaenidae, weakfish are an important asset to the ecology and economics of western Atlantic Ocean coastal ecosystems but have declined to historically low levels of abundance in recent years due to high rates of overfishing and natural mortality (Kahn et al. 2006; ASMFC 2009). In terms of economics, weakfish have traditionally supported a robust fishery along the eastern

∗ The automatic measurement and transmission of (sound signals)...from remote sources to receiving stations for recording and analysis (The American Heritage Dictionary, Fourth Edition, 2001)
United States since the 1800s (Nye et al. 2008), including both a commercial (i.e. gill-net, pound net) and recreational (hook-and-line) component. Ecologically, weakfish maintain dual roles as both high-level predators (i.e. adults; Merriner 1975, Bowman et al. 2000) and abundant prey species (i.e. juveniles; Maurer and Bowman 1975, Mancini and Able 2005). Although their center of abundance is from New York to North Carolina, weakfish infrequently range from Massachusetts to Florida (Shepherd and Grimes 1984), and within their geographical range are found primarily in coastal and estuarine systems. However, the relative importance of both habitats is unknown especially with regards to life history. Estuaries serve a role for juvenile weakfish in terms of nursery habitat (Able et al. 2006; Able et al. in press) and spawning sites for adults (Merriner 1976; Lowerre-Barbieri et al. 1996b; Nye et al. 2009; Able and Fahay 2010), but they may use inner-shelf habitat in the same ways (Able et al. 2006; Able et al. 2010; Able et al. in review). Therefore, the role of estuarine habitats in weakfish life history remains ambiguous. Additionally, weakfish reproduction occurs at both seasonal (Connaughton and Taylor 1994; Lowerre-Barbieri et al. 1996b; Able and Fahay 2010) and diel (Connaughton and Taylor 1995; Lowerre-Barbieri et al. 1996b) time scales, further confusing our understanding of weakfish ecology.

In the following study, various aspects of the estuarine habitat ecology (residency, habitat use, movement, and site fidelity) in weakfish are examined at multiple spatial and temporal scales using acoustic telemetry. In the next two chapters, weakfish habitat dynamics will be evaluated at both broad (Chapter 2) and fine (Chapter 3) spatial scales within the Mullica River-Great Bay, a relatively undisturbed estuary within the center of the weakfish’s geographic range. More specifically, broad-scale patterns of
habitat dynamics in Chapter 2 will be viewed in the context of the timing (phenology) of weakfish reproduction, a seasonally occurring event. In Chapter 3, fine-scale patterns of habitat site fidelity will be examined at two temporal scales, seasonal and diel, which are also relevant to the scales at which weakfish reproduction occurs. The last chapter will briefly discuss the broader conclusions and implications of this study, as well as ways to potentially improve upon future telemetry studies of weakfish. For ease of comprehension, both Chapters 2 and 3 were written in a self-contained format. Therefore, some information may be repeated, although references to previous or subsequent chapters are made when appropriate.
Acoustically tagged weakfish, *Cynoscion regalis* (June 25, 2008)
-CHAPTER 2-

Broad-scale patterns of estuarine residency, habitat use, and movement
in adult weakfish in relation to reproductive phenology

ABSTRACT

Habitat resources, such as those used for spawning, are difficult to evaluate with traditional sampling techniques but telemetry can reveal insights into habitat dynamics in relation to spawning phenology. Weakfish (*Cynoscion regalis*) are an important economic and ecological asset to Mid-Atlantic Bight estuaries, but a recent decline to historically low abundance rangewide has stimulated a need for greater understanding of their habitat ecology. Weakfish estuarine residency, habitat use, and movement were evaluated across the reproductive/post-reproductive spectrum using acoustic telemetry during 2007 and 2008 in the Mullica River-Great Bay estuary in southern New Jersey. Tagged adult weakfish (273-864 mm TL) were resident in bay, lower river, and subtidal creek habitats during reproduction (May through July) and following the reproductive season (August through November) but showed limited use of inlet and upriver habitats in both seasons. Although confounded by location of original capture, tagged weakfish densities were consistently greater in habitats characterized by deepwater channels and marsh edges during the reproductive period, followed by a gradual shift to shallow, open-bay habitats later in the season. Movement rates increased at the end of the post-reproductive season and weakfish apparently moved into fringing, unmonitored habitats within the study area following the reproductive period. Estuarine egress occurred throughout the study period but was lowest during July and highest during the final...
month of emigration in November. Given these habitat dynamics, it will be crucial to incorporate temporal shifts due to reproductive phenology into future estuarine and weakfish management plans if these observations prove to be consistent across other estuaries.

**INTRODUCTION**

The recent paradigm shift towards managing fisheries at the ecosystem level (NMFS, 1999; Browman and Stergiou, 2004; Pikitch et al., 2004) has brought concerns over habitat degradation to the forefront of fisheries ecology, originating in legislation protecting essential fish habitat (EFH) (NOAA, 1996). The relative importance of fish habitat using coarse-scale criteria, such as presence-absence and abundance, can be quantified using traditional sampling techniques but is limited in its usefulness (Able, 1999; Beck et al., 2001). The value of habitat for fishes becomes more difficult to assess when the metrics include growth, reproduction, and survival (Dahlgren et al., 2006; Sheaves et al., 2006). Several recent studies using passive acoustics have been successful in helping to dynamically define essential fish habitat in terms of reproductive effort (Connaughton and Taylor, 1995; Luczkovich et al., 2008; Walters et al., 2009; Mann and Grothues, 2009). There are limitations to these studies, however, including the lack of attention to variation in individual behavior and the effects of fine-scale habitat dynamics in fishes, both spatial and temporal.

If seasonal patterns of reproduction are well defined, as they are in many temperate marine fish species, studies of habitat use and movement during these periods can shed light on habitat dynamics, and thus the relative importance of that habitat, across the pre-reproductive/reproductive/post-reproductive spectrum. In many fishes,
reproduction occurs during well-defined periods that correspond to seasonal environmental triggers such as water temperature, day length, and/or lunar cycle (DeVlaming, 1972; Lobel, 1978; Taylor, 1984; Connaughton and Taylor, 1996). Evidence suggests that spawning periods that overlap with these critical abiotic factors may result in optimal conditions for subsequent young (Nikolsky, 1963; Cushing, 1975; Lasker, 1981; Bye, 1984; Cushing 1990; Wright and Trippel, 2009). When combined with information on the reproductive seasonality of a species, other advances in sampling techniques, such as acoustic telemetry, can elucidate these finer-scale individual dynamics (i.e. movement and habitat use) in relation to spawning phenology.

The reproductive biology of the economically and ecologically important weakfish (Sciaenidae: *Cynoscion regalis*) has been well studied along the central portion of its distribution from North Carolina to New York (Merriner, 1975; Shepherd and Grimes, 1984; Lowerre-Barbieri et al., 1996ab; Nye et al., 2008) but little attention has been given to fine-scale dynamics in individual habitat use and movement, especially in relation to reproduction. The information available on adult weakfish habitat utilization and movement is either very coarse (Nesbit, 1954) or limited to potentially atypical, urbanized systems, such as in a recent study in a northern New Jersey estuary (Manderson et al., 2007). Seasonal spawning activity in weakfish generally takes place in estuarine and near-shore coastal habitats from April through October in the southern portion of their range, with a more defined period of May through August in their northern range (Lowerre-Barbieri et al., 1996a; Able and Fahay, 1998). Although considered a facultative estuarine user (Able, 2005), spawning and associated behaviors (i.e. drumming/courtship) have been documented in both larger (Pamlico Sound, North
Carolina: Luczkovich et al., 1999; Chesapeake Bay: Lowerre-Barbieri et al., 1996b; Delaware Bay: Connaughton and Taylor, 1995) and smaller (Great Bay-Mullica River, New Jersey: Caitlin Kennedy, Rutgers University, New Jersey, pers. comm.) estuarine systems. Some evidence from otolith microchemistry suggests that weakfish exhibit natal homing behavior to estuarine spawning sites, although only larger systems have been studied (Thorrold et al., 2001).

Until recently, weakfish comprised a major recreational and commercial fishery along the western Atlantic coast, especially in the middle Atlantic bight (MAB). Given the weakfish stock’s recent decline to historically low levels (1.9 million pounds; ASMFC, 2009), consideration for data on basic weakfish ecology, such as habitat and ecosystems interactions, has taken on new relevance to fisheries management. In this study multiple acoustic telemetry techniques were used to examine adult weakfish habitat dynamics during the reproductive and post-reproductive periods in a MAB estuary. The spawning period was generally defined for the study area using larval ingress data from a long-term ichthyoplankton survey. Following this, the primary objectives of the study were to examine three components of weakfish estuarine habitat dynamics in relation to reproductive phenology: 1) residency, 2) habitat use, and 3) movement.

**MATERIALS AND METHODS**

**Study Area**

The study area comprises two distinct but overlapping estuaries within central-southern New Jersey on the eastern coast of the United States (Figure 2.1). The Great Bay-Mullica River estuary is characterized as a relatively shallow (<2 m), salt marsh-dominated, drowned river valley system (Figure 2.1). Owing to its largely undeveloped
watershed within the Pinelands National Reserve, the Great Bay-Mullica River system is considered one of the least impacted systems in the northeastern United States (Good & Good, 1984; Psuty et al., 1993; Kennish, 2004). Due to the unique nature of this estuarine system, forty-five thousand hectares adjacent to and including the estuary have been designated as part of the Jacques Cousteau National Estuarine Research Reserve (JCNERR; Kennish, 2004). Physico-chemical attributes within the study site are typical of similar estuarine habitats: water temperature regimes follow temperate seasonal patterns within the Mid-Atlantic Bight (<0°C in winter to >30°C in summer); salinity tracks an upriver gradient from polyhaline regions near Little Egg Inlet (salinity 32) to the freshwater-saltwater interface near Lower Bank (salinity 8) approximately 30 km upstream (Figure 2.1). Atypical of other systems, the Great Bay-Mullica River rarely approaches hypoxic dissolved oxygen levels (<4 mg/L) and is characterized in the upriver portions of the Mullica River by acidic pH levels (4-6), from tannins leached by the surrounding pine/oak-dominated watershed.

A smaller portion of the study area is located within Little Egg Harbor, a lagoon-type barrier island estuary north of the Great Bay-Mullica River system (Figure 2.1). Little Egg Harbor is also characterized by shallow depths (<2 m at mean low water), a narrow tidal range (<0.5-1 m), and similar water quality parameters as the Great Bay-Mullica River (Kennish, 2001). Unlike the Great Bay-Mullica River system, fresh water input is limited to smaller freshwater tributaries draining the Pine Barrens region to the west and watershed development and alteration is more extensive along this portion of the study area (Kennish, 2001). The Little Egg Harbor estuary is also included within the Jacques Cousteau National Estuarine Research Reserve system (Kennish, 2004).
**Ichthyoplankton Sampling**

To determine the timing of spawning and ingress of larval weakfish within and adjacent to the study area, weekly ichthyoplankton sampling took place from 1989-2007 during night flood tides using a 1-meter wide circular plankton net (1-mm mesh size) suspended from a bridge crossing a polyhaline thorofare in close proximity to Little Egg Inlet (Figure 2.1). Larval samples were first sorted by species, with individual fish then measured to the nearest 0.1 mm and total weekly abundance standardized to water volume (number of fish/m$^3$) (see Able and Fahay, 1998; Sullivan et al., 2006). Since larval abundance serves as only a relative proxy to spawning time, a window of approximate egg dispersal times were back-calculated using larval growth rates for weakfish in Delaware Bay under conservative biological and environmental conditions following Goshorn and Epifanio (1991a).

**Acoustic Telemetry**

**Tagging**

All adult fish (>250 mm; Nye et al., 2008) were captured within the Great Bay-Mullica River and Little Egg Harbor estuaries using hook-and-line methods (shore or boat-based), with the exception of one fish caught in a stationary multi-mesh gill net at the Rutgers University Marine Field Station (Figure 2.1). A total of 59 fish were captured and tagged (26 in 2007; 33 in 2008). Only fish greater than 250 mm were tagged, with the assumption that these would be reproductively mature (Nye et al., 2008). Following capture, each fish was placed immediately in a holding tank containing ambient seawater. Pre-surgical anesthesia took place in a diluted solution of MS-222 in ambient seawater (0.05 g/L; Sigma, Inc.) Individually coded acoustic transmitters of
various sizes (Table 2.1) were coated with antibiotic ointment (Neosporin), surgically implanted into the abdominal cavity following Bridger and Booth (2003) and Able and Grothues (2007), and sutured using either Ethilon® non-absorbable nylon (n=6 fish) or Ethilon® absorbable monofilament PDS-II sutures (n=53 fish). A high-visibility external t-bar tag (Floy, Inc., Seattle, WA) was inserted between the first and second pterygiophores of the spiny dorsal fin to visually identify acoustically tagged fish (Clark, 2006). Following surgery, fish were administered the broad-spectrum antibiotic oxytetracycline (0.1 mL/kg fish; Liquamycin, Pfizer, New York) to guard against latent infection and then placed in a holding tank of ambient seawater until recovery (maintenance of upright posture). Every acoustically tagged fish was released within 100-m of its original capture location, with all fish released on the same day of capture in 2007. In 2008, 10 fish were released on the same day of capture with the remaining 23 fish released within 1-6 days of initial capture. Transmitter model, and therefore battery duration, varied between and among years based on the limitations of tag and fish size (Table 2.1). Fish less than 400 mm were tagged with single-year tags (<1 year) and fish greater than 400 mm were tagged with both single-and multi-year tags (>1 year) (Table 2.1). Multi-year tags were deployed to detect returns to the study area during the following year, but all tags deployed during a given year lasted at least until the winter in the year of tagging.

Passive Telemetry

Broad-scale habitat use, movement, and estuarine residency patterns of weakfish were characterized using a moored, gated array of wireless hydrophones (WHS-1100, Lotek Wireless, Inc., St. John’s, NewfoundlLand, Canada) deployed at 6-8 locations in the
study area during 2007 and 2008 as part of a larger study to examine the movements and habitat utilization of estuarine megafauna (Figure 2.1; Grothues et al., 2005). Placed strategically at locations based on estuarine geomorphology, the hydrophones nearly continuously monitored the presence/absence of individual fish and determined estuarine immigration and emigration, as well as movements along the estuarine salinity gradient. Hydrophones 2-4 (considered 0 km from Little Egg Inlet) monitored migration into and out of Little Egg Inlet. Hydrophones 1 (considered 0 km from inlet) and 13 (7 km from inlet) monitored movement into and out of Little Egg Harbor and Great Bay, respectively. Hydrophone 5 (4.5 km from inlet) detected movement into Great Bay as well as into and out of Little Sheepshead Creek. Placement of hydrophone gates at the Garden State Parkway Bridge (Hydrophone 7; 18 km from inlet) and Lower Bank Bridge (Hydrophone 10; 28.3 km from inlet) were placed to detect fish that moved into the Mullica River and along the salinity gradient. Fish carrying acoustic transmitters could be detected within approximately 500 m of a moored hydrophone (Grothues et al., 2005).

The wireless hydrophones were suspended approximately 3.2 m below the water surface and transmitted the received sound through a VHF radio relay (148-152 MHz) to shoreside receivers (SRX-400, Lotek Wireless, Inc.) For each interpretable signal, the receiver recorded tag number, hydrophone number, date, time, and radio signal power (dB). Data was post-processed using MATLAB (The Mathworks, Inc., Natick, Massachusetts; see Grothues et al., 2005). Due to weather and logistical issues, as well as aperiodic equipment failure, the deployment of hydrophones varied among and within study years (Figure 2.2a). For instance, hydrophones 1 and 5 in 2007 were deployed periodically, while hydrophone 2 in 2008 was deployed as a more permanent part of the array (Figure
A more thorough description of the stationary array function and limitations can be found in Grothues et al. (2005).

**Mobile Telemetry**

To examine seasonal weakfish habitat use and movement within the study area in a more spatially explicit manner, frequent system-wide mobile tracking occurred during both study years. A directional hydrophone (LHP_1, Lotek Wireless, Inc.) attached to a signal processor (SRX-400, Lotek Wireless, Inc.) was deployed from a small boat and used to sample 113-120 predetermined points charted on a hand-held global positioning system (GPS) device during daylight hours (0700-1900) (Figure 2.3). All locations were sampled (within 100 m of the original location) by rotating the hydrophone in 90° increments to full rotation. Mobile hydrophone listening range varied greatly with ambient physical conditions but generally had a minimum detection range of 500 m (Figure 2.3; Ng et al., 2007). When a tagged fish was detected the boat was positioned so that the acoustic signal power was above 115 dB and below a gain of 15, then fish location was recorded using a hand-held GPS unit together with tag identification, general location, signal power (dB), and gain. Based on previous experiments, resolution of fish location could be determined to meter-scale (Sackett et al., 2007).

Mobile tracking effort varied between both study years (Figure 2.2b and Figure 2.2c). In 2007, sampling was aperiodic and less frequent due to logistical constraints, but a weekly sampling effort was maintained throughout most of 2008. Sampling varied spatially by year as well. In 2008, sampling locations increased by seven (from 113 to 120) to account for an additional tagging location (Big Creek, Figure 2.1). For further
description of the standardized mobile tracking protocol, see Ng et al. (2007) and Sackett et al. (2007).

Environmental Measures

To better understand weakfish habitat dynamics in relation to the physical nature of the reproductive and post-reproductive periods, environmental measures at both the estuary-scale and individual fish locations were taken throughout both study years. The JCNERR System-Wide Monitoring Program (SWMP; Kennish and O’Donnell, 2002) allowed for an estuary-wide characterization of water quality using stationary data loggers located along the salinity gradient of the Great Bay-Mullica River estuary (Figure 2.1). Sampling occurred every half-hour during the logger’s deployment and measured water temperature (°C), salinity, dissolved oxygen (mg/L), and pH. Deployments were occasionally interrupted due to equipment failure, maintenance, or inclement weather conditions, especially during the winter months. Water quality parameters (surface temperature (°C); surface dissolved oxygen (mg/L); surface salinity; pH; depth (m)) were also measured with a hand-held YSI (Model 85, Yellow Springs Instruments, Inc., Yellow Springs, OH) during mobile tracking events when/where an individual fish was detected. To relate environmental measures to weakfish reproductive phenology, water temperatures near Little Egg Inlet (SWMP data logger buoy 126; see Figure 2.1) were averaged across the range of the calculated spawning period using twelve years of available data (1996-2007).

Data Analysis

The sampling unit (n) used in analyzing telemetry data was defined as an individual tagged fish so that the problematic effects of pseudo-replication and
autocorrelation could be minimized (Rogers and White, 2007). Variables for quantitative analyses were therefore averaged or assigned to each tagged individual. If tags were considered lost (no movement after tagging), due to mortality or shed tags, fish were excluded from analyses (Table 2.2; 2007, n=2; 2008, n=4). Graphing procedures were performed using Sigmaplot (v 9.0, Systat Software, Inc., Chicago, Illinois) and spatial analyses were conducted with GIS software (ArcMap v9.3, ESRI, Redlands, California). Due to concerns with non-normality of data, the non-parametric Mann-Whitney U test (with normal approximation) was used to test for differences in mean variables. To examine aspects of weakfish habitat dynamics, both passive and active telemetry techniques were used either in conjunction or separately when the questions concerned different scales. The following approaches were used to examine residency, habitat use, and movement:

*Estuarine residency/emigration* - Estuarine residency was defined, on a monthly or weekly scale, as the continued presence of tagged weakfish within the study area. If fish were last detected at a stationary hydrophone gate where emigration from the study area was likely to occur (hydrophones 1, 2, 3, 4, 13) and not redetected during two consecutive mobile tracking events, a fish was determined to have emigrated. Fish were still considered residents if they were redetected in the study area after no detections for greater than two weeks and final detections were not near an emigration site. Tagged individuals who returned to the study area after last detection near an emigration site (after two weeks or greater of no redetections) were considered non-resident during their absence.
Final estuarine emigration was defined as the month in which the final detection (from the stationary array) occurred with no subsequent redetections during mobile tracking. In a few instances, fish were last detected during mobile tracking and the week of last location was considered the final emigration time if no redetections followed. If the final detection did not occur at an emigration site, the fish was still considered emigrated if no further redetections occurred. In these cases, we assumed that the final detection was missed at the stationary hydrophone gate or emigration occurred through a different route. Emigration rates were standardized based on availability and tagged fish were considered “available” if still resident within the estuary (see above for definition of residency).

Estuarine habitat use - Patterns of weakfish habitat utilization were analyzed using both passive and mobile telemetry techniques. For delineating habitat use with passive telemetry, hydrophones 1-4 were defined as “inlet” habitat; 5, 7, & 13 as “estuarine”; and 10 as “river.” Both the number of fish as a proportion of those available (tagged and not yet emigrated from the study area) and time spent at inlet and estuary hydrophones were calculated. Since the number of contacts determined fish presence at hydrophones within a 15-minute interval, time spent at hydrophones was also calculated in 15-minute increments. To determine finer-scale habitat use patterns along the salinity gradient, mobile tracking contacts were quantified using 13 equal-width (2 km) quadrants from Little Egg Inlet (quadrant 1) to Lower Bank (quadrant 13; Mullica River) (Figure 2.4; see Sackett et al., 2007 for a similar analysis technique). Fish densities were calculated for each region during the reproductive and post-reproductive seasons and standardized by water surface area (km$^2$) and the number of fish available.
When using mobile tracking data, direct comparisons between both study years was frequently confounded by changes in sampling effort (Figure 2.2b and Figure 2.2c). Due to the irregularity of sampling and the concomitant lack of data in 2007, most quantitative analyses were limited to the 2008 data set, although 2007 data has been presented for some comparisons. When both years were compared, the subset of seasonal and spatially overlapping sampling points was used in analyses. Spearman’s rank correlation coefficients (\(\rho\)) were calculated and tested for significance (\(\alpha=0.05\)) to examine the relationship between regional tagging density and regional fish density.

*Estuarine movement* - Seasonal movement patterns during 2008 were standardized using the metric minimum displacement per week (MDPW), which normalized tagged fish movement to the time between weekly mobile tracking relocations (Rogers and White, 2007). Minimum distance was calculated as the shortest distance from two locations that an individual would have to travel. A subset of data with consecutive weekly detections from 2008 was used to calculate weekly rates of movement because 2007 data could not be compared due to non-consecutive sampling.

**RESULTS**

**Reproductive Phenology**

Between 1989 and 2007, larval weakfish (n=2,248) were caught during a relatively restricted period each year in the weekly ichthyoplankton survey in Little Sheepshead Creek (Figure 2.5a). Larvae were present from weeks 21 through 36 (late May to early September), with the highest weekly average densities occurring during weeks 28 through 30 (77% of total; mid-to-late July) (Figure 2.5b). During these weeks,
lengths of larval weakfish ranged from 2-18 mm SL and spawning date was back-calculated to a period from weeks 20-29, which spans mid-May to mid-July.

Average water temperatures near Little Egg Inlet during that period from 1996-2007 ranged from 14.6 +/- 0.04°C on week 20 to 22.6 +/- 0.04°C on week 29. Average water temperatures during the extent of the reproductive period within both study years ranged from 14.3 +/- 0.09°C (week 20) and 21.6 +/- 0.09°C (week 29) in 2007 and from 13.8 +/- 0.04°C (week 20) to 21.6 +/- 0.14 (week 29) in 2008. Average water temperatures were similar during the reproductive season between the 1996 to 2007 period (mean: 19.1 +/- 0.02°C) and the two-year study period (2007 and 2008; mean: 18.9 +/- 0.03°C). Shaded regions drawn in subsequent figures represent the calculated reproductive period (in weeks or months).

**General Characteristics of Tagged Fish**

Fifty-nine weakfish were tagged between 2007 and 2008, although only 53 fish were considered successful due to tag loss in six fish (Table 2.2). Acoustic tagging effort varied in duration across both study years, with tagging commencing earlier in 2007 (April) than 2008 (June) (Table 2.2). However, during both years peak tagging occurred in August (n=15 each year). Lengths of tagged fish ranged from 273 to 863 mm across both years, but did not differ significantly between years (U_{0.05(2),29,24}, P=0.98) (Table 2.2; Figure 2.5). Modal lengths, however, varied between years (Figure 2.6). In 2007, the greatest number of tagged fish was smaller (n=12; 301-400 mm) than in 2008 (n=13; 401-500 mm). Tagging locations within the study area were similar across years, but tagging intensity differed based on local availability of weakfish (Figure 2.6ab). In 2007, the largest number of fish (42%; n=10) were tagged in Main Marsh Thorofare during two
tagging events in July and August, while no fish were tagged in this location in 2008 (Figure 2.5). The highest percentage of fish (38%; n=11) were tagged at the mouth of the Mullica River in 2008 (Figure 2.5). Limitations based on tag and fish size allowed for the deployment of only seven multi-year tags in 2007 (29% of total) and 14 multi-year tags in 2008 (48% of total) (Table 2.2). Reporting of weakfish recaptures was rare during the study period, as well as in subsequent years. Two acoustically tagged fish (8%) were recaptured in 2007 in close proximity to their original tagging site. Both fish were caught in early September, roughly 1 to 1.5 month post-capture. No recaptures were reported as 2008. Variation in the number of active telemetry detections between years was due to decreased sampling effort (Table 2.2; Figure 2.2). In contrast, passive telemetry contacts were correlated with the amount of time fish spent within the listening range of stationary hydrophones. Therefore, the differences in residency patterns of fish, as well as a change in hydrophone deployments, contributed to a variation in the number of hydrophone contacts between years (Table 2.2; Figure 2.2).

**Estuarine Residency/Emigration**

Tagged adult weakfish were resident within the study area before, during, and after the calculated spawning period although variations in this pattern were observed between years (Figure 2.7). Residency time ranged from 0-4 months in both years (2007, n=24; 2008, n=26; mean: 1 month) and fish were present from April to November in 2007 and June to November in 2008. The weekly duration in residency time in 2008 was 0-18 weeks (n=26; mean: 6 weeks). Three fish (356-521 mm) in 2008 left the study area for 3-7 weeks (as determined through their last detection at inlet hydrophones) and returned briefly (less than one week) before final emigration. Of these three fish, two
were tagged during the spawning season and left following week 29. Emigration from the system was difficult to assess in 2007 due to the infrequency of sampling.

Timing of final emigration of weakfish from the estuary ranged from May to November in 2007 and June to November in 2008 and rates of emigration in both years followed similar annual patterns. During the reproductive periods, a small peak in emigrations in June was followed by the lowest emigration rates in July (0% in 2007; 18% in 2008; Figure 2.8). The two largest fish tagged during the study (864 and 838 mm TL; tagged weeks 19 and 24, respectively) made the earliest and quickest emigrations in spring 2007 (weeks 19 and 24). Two smaller fish (381-648 mm) were tagged in spring 2007 (weeks 18-20) and, in contrast to the larger fish, they remained resident in the estuary until a later period (weeks 25 to 32). No comparison could be made with 2008 data since no fish of that size were tagged during spring.

Water temperatures during the month of lowest emigration rates in both years (July) were 23.0 +/-0.03°C in 2007 and 22.2 +/-0.04°C in 2008 (Figure 2.8). All available tagged fish left the estuary by November of both years although the highest numbers of weakfish (n=8 in both years) were last detected during the month of August. Emigration in August coincided with peak mean water temperatures at emigration sites (2007: 24.4°C +/- 0.04; 2008: 23.7°C +/- 0.02) and November emigration with lower water temperatures of 10.0°C (+/- 0.04) in 2007 and 9.3°C (+/-0.06) in 2008 (Figure 2.8). Emigration of the second largest fish tagged (838 mm) in spring 2007 (week 24) took place when average water temperatures at SWMP buoy 126, near the likely emigration site, were 20.3 +/- 0.05°C. No SWMP data on estuarine water temperatures were
available for the emigration of the largest fish tagged in 2007 (week 19), but samples taken shortly after that period suggest lower average temperatures than week 24.

Emigration varied spatially during and across both study years. In 2007, 9 fish (41%) emigrated through Main Marsh Thorofare near hydrophone 13 and 8 fish (36%) most likely left through Little Egg Inlet. The remaining fish were either never detected at a hydrophone gate (n=4) or last detected during mobile tracking in Little Egg Harbor (n=1) and thus could have emigrated through Barnegat Inlet (approximately 40 km north of Little Egg Inlet). In 2008, the majority of fish (55%) were last detected at the Little Egg Harbor hydrophone gate, while 34% of fish were never detected as they emigrated. Only three fish (10%) emigrated through Main Marsh Thorofare.

**Estuarine Habitat Use**

While resident in the estuary, weakfish displayed patterns of seasonal habitat use characterized by frequent utilization of open bay and deeper subtidal creek habitats (Figure 2.4). No fish were ever detected above the lower Mullica River by either passive or mobile telemetry or in the vicinity of Little Egg Inlet during mobile tracking events in both years. The relative proportion of fish and their time spent in the “inlet” versus “estuarine” habitats varied seasonally (Figure 2.9). The proportion of fish (of those available) detected in the inlet increased after the conclusion of the spawning season, coinciding with fall emigration (Figure 2.9a). An earlier peak seen at inlet hydrophones in 2007 was due to spring emigration by fish tagged in May and June (Figure 2.9a). The proportion of fish seen at estuarine hydrophones was higher in 2007 than 2008 (Figure 2.9b). This may have been the result of a large number of fish tagged near an estuarine hydrophone (13) in August and the deployment of an additional estuarine hydrophone (5)
(Figures 2.2a, 2.4b). The average number of minutes spent per fish at inlet hydrophones was disproportionately less than at estuarine hydrophones (inlet: 108 min/fish (2007), 115 min/fish (2007); estuary: 759 min/fish (2007), 2291 min/fish (2008)), although a small peak occurred in the inlet during spring emigration of several weakfish in 2007 (Figure 2.9c and Figure 2.9d). The large peaks at estuarine hydrophones in 2007 and 2008 were due to the continuous presence of several fish in close proximity to hydrophone 13 at Main Marsh Thorofare.

On a smaller scale than detected by passive hydrophones, weakfish were found in similar habitats across years and the reproductive/post-reproductive seasons using mobile telemetry techniques, although the degree to which these habitats were utilized also varied between years and seasons (Figure 2.4). No fish were detected in Little Egg Inlet (region 1) in both study years or past the lower portion of the Mullica River (regions 9-13) in 2007 and 2008, respectively (Figure 2.4). The lower bay (near Little Egg Inlet), a section of Little Sheepshead Creek, and a small portion of Little Egg Harbor were not utilized during the reproductive season in both years, although fish were present in these areas during the post-reproductive seasons in 2007 and 2008 (region 2; Figure 2.4 and Figure 2.9). Several microhabitats within the utilized portion of the estuary (sometimes comprised of multiple regional quadrants) were consistently higher in fish densities. During the reproductive season, tagged weakfish most often utilized deep channels in the lower region near the mouth of the Mullica River (regions 6 and 7) in both years (Figure 2.4a and Figure 2.10a). In 2008, two groups of tagged fish used relatively shallow bay habitat and the subtidal thorofare Big Creek on the northern edge of Great Bay to great extents (regions 4 and 5; Figure 2.4a and Figure 2.10a) within the defined spawning
period. During the post-reproductive season in both years, tagged fish concentrated at the mouth of the Mullica River (region 6). The deeper channel running through Main Marsh Thorofare (on the southern edge of Great Bay; see Figure 2.1) was also used (region 3; Figure 2.4b and Figure 2.10b). Other habitats within region 3 also contributed to these higher densities. Weakfish located in Little Sheepshead Creek, another deep subtidal thorofare, split between regions 2 and 3 and fish were also detected in the Little Egg Harbor portion of the study area at Marshelder Channel (locally referred to as a “cut” due to its steep emergent banks; regions 2 and 3; see Figure 2.1) (Figure 2.4b and Figure 2.10b). Still another group of fish utilized regions 2 and 3 at a deep-water portion near the entrance to Great Bay (known as Grassy Channel; see Figure 2.1) (Figure 2.4b and Figure 2.10b). The shallower habitat within Great Bay held a high number of individual weakfish into the post-reproductive season in 2008, contributing to a seasonally increased density in region 5 (Figure 2.4b and Figure 2.10b). Weakfish utilized similar shallow bay habitat less substantially in 2007 (Figure 2.4b and Figure 2.10b).

In all years and seasons except the 2007 reproductive period ($\rho=0.55$, $P=0.054$), significant positive correlations between original capture location and regional fish densities were observed (2007 post-reproductive: $\rho=0.75$, $P=0.003$; 2008 reproductive: $\rho=0.63$, $P=0.02$; 2008 post-reproductive: $\rho=0.64$, $P=0.02$) (Figure 2.10). However, during the 2007 reproductive season a relatively high proportion of fish were tagged in Little Sheepshead creek (33%; $n=3$; region 2) and Marshelder Channel (33%; $n=3$; region 3) that did not contribute to higher densities in those regions during that season. Of those fish tagged in Little Sheepshead Creek, two were detected outside their original tagging region during subsequent mobile tracking in the spawning season, while one emigrated
from the system before redetection could occur. Fish tagging in Marshelder Channel occurred late in the spawning season (July 30); therefore, all fish were only detected during tracking events in the post-reproductive season. During the 2008 post-spawning season there was a regional density shift from region 5 (one of two peak tagging locations) to region 6 (Mullica River mouth) (Figure 2.10b). The peak in region 5 corresponded to an increase in tagging effort within Big Creek (25%; n=4) while the higher densities in region 6 were the result of weakfish maintaining residency at the mouth of the Mullica River (Figure 2.4b and Figure 2.10b), with no contribution from fish tagged in Big Creek. With the exception of two individuals, weakfish tagged in Big Creek (n=6) during both seasons were not redetected during any subsequent mobile tracking.

Weakfish choice of environmental variables was generally narrower than the wide range of available habitat and consistent with their spatial distribution. Utilization of water temperatures in the study area tracked seasonal changes (range: 10.9-28.3°C), although weakfish were found more often in the warmer available temperatures during the spawning season (Figure 2.11). Weakfish were frequently detected in higher salinities ranging from 19.8 to 34.0 (both years) although they were rarely detected in the inlet region (i.e. buoy 136) where higher salinities were more often available (Figure 2.11). Dissolved oxygen in the study area rarely fell to less than 4 mg/L, but weakfish were found within a wide range of dissolved oxygen levels (4.3-9.7 mg/L), sometimes greater than what was measured at the data loggers (Figure 2.11). Following the spawning season, weakfish were not found at the lower levels of D.O. (Figure 2.11) although fish were occasionally detected in these regions (i.e. Chestnut Neck; see Figure
Levels of pH varied from 5.1 to 9.0 but weakfish were only detected in the range of 7.5 to 8.4 (Figure 2.11). Weakfish generally utilized water depths greater than the average depth of the study area (<2 m) during both years (4.8 m in 2007; 5.2 m in 2008).

Although fish were not found in significantly different depths between seasons (both years combined) (reproductive season: n=14 fish, 5.6 m; post-reproductive season: n=31 fish, 4.7 m; \( U_{0.05(2),31,14}, P=0.11 \)), fish were found in marginally shallower depths during the post-reproductive season (see Figure 2.3 (inset), Figure 2.4, and Figure 2.12).

**Estuarine Movement**

Movement rates within the estuary generally increased following the end of the reproductive period in 2008 (Figure 2.13). Average individual minimum displacement per week (MDPW) during the reproductive months ranged from 0.08 to 1.9 km/wk and 0.09 to 5.8 km/wk during the post-reproductive season. Although individual MDPH varied greatly in October, the movement rates were highest overall during this month (mean: 2.2 km/wk). Movement could not be quantified during November due to a low sample size.

Observations of movement were confounded by the difficulty in relocating fish on a weekly basis in 2008. Mobile tracking events conducted in the early post-reproductive months were less successful in relocating tagged fish that had not yet emigrated from the study area. Two distinct periods where fish went unaccounted for occurred during weeks 34 (late August) and 38 (mid-September), where 47% and 56%, respectively, of available fish were not found during weekly mobile tracking (Figure 2.14). Furthermore, during 33% of the tracking events greater than 40% of tagged fish went undetected in the study area, all but one event occurring after the end of the defined spawning period (Figure
2.14). Only during 5 of the 23 (22%) consecutive weeks where tracking occurred were all available fish found.

**DISCUSSION**

**Reproductive Phenology**

Aspects of weakfish estuarine residency, habitat use, and movement may be influenced by reproductive phenology. However, as seen in previous studies of estuarine fish species (e.g. striped bass: Able and Grothues, 2006; Grothues et al., 2009), marked variation in weakfish behavior among and within individuals was high. Patterns were difficult to ascertain due to this variation, as well as non-uniform sampling between years, but an approach using multiple telemetry techniques proved useful in delineating some reproductive effects on weakfish habitat dynamics.

Seasonality of reproduction in weakfish has been well examined in the Mid-Atlantic Bight region using histology (Nye et al., 2008), gonado-somatic indices (Shepherd and Grimes, 1984), drumming muscle condition and weight (Connaughton and Taylor, 1994), and passive acoustics (Connaughton and Taylor, 1995). The defined spawning period used in the current study (mid-May to mid-July) corroborated the timing seen in the previous studies that found that spawning in the mid-Atlantic bight commenced in May with reproductive activity decreasing by late July. In those previous studies, metrics indicating spawning behavior declined dramatically by August; thus we feel confident in our interpretation of the spawning season. In addition, visual observations of weakfish gonad condition during tag implantation and from additional specimens (n>80) caught within the estuary showed more mature, ripe, and running individuals during the defined spawning season than in the months following (August and
September) (Jason Turnure, Rutgers University, New Jersey, pers. observations). The similarity in water temperatures between the twelve-year average and the two-year study period further justify use of the back-calculated reproductive period as a basis for comparison.

However, one aspect of weakfish reproduction seen in previous studies, bimodality in larval abundances, did not manifest itself in the data from larval sampling (Goshorn and Epifanio, 1991b; Lowerre-Barbieri et al., 1996b). Further, reproduction outside the estuary study area could not be accounted for using the data presented here, but previous works in the region provide evidence for coastal spawning. While weakfish larvae were present in both estuary and ocean sampling in a previous study in New Jersey, their abundances were higher at coastal sites, indicating offshore spawning (Able et al., 2006). Larval sampling in the surf zone and nearshore coastal habitats of northern New Jersey also found newly hatched weakfish, with relatively high densities and abundances in the latter habitat, presumably from offshore spawning events (Able et al., 2010). Nightly sound production (used as a proxy for spawning behavior) at an offshore observatory in New Jersey was detected from early June to late August, further evidence that spawning behavior occurs in the ocean adjacent to the study site (Mann and Grothues, 2009).

Residency/Emigration

Although considered facultative estuarine users (Able, 2005), especially for spawning purposes, some weakfish remained in the study area for extended periods during and following the reproductive season, suggesting that estuaries do play an important role in weakfish life history. Similar studies in the Great Bay-Mullica River
estuary have shown long-term patterns of residency in summer flounder (Sackett et al., 2008) and striped bass (Able and Grothues, 2007), but little is known about utilization of smaller estuaries by weakfish. A telemetry study in the urbanized Navesink River (New Jersey) estuary found that weakfish remained in the study area until early October and residency times averaged >30 days (Manderson et al., 2007). Residency times during the current study (approximately 1 month) were most likely confounded by the delay in tagging in early summer so as to underestimate their arrival into the system. However, estimates of residency times are useful when compared with fish tagged during the same period.

Recent evidence of natal homing (Thorrold et al., 2001) to larger estuarine spawning grounds (i.e. Chesapeake and Delaware Bays) could not be confirmed for smaller systems in this study since no fish were redetected in the study area following final emigration from the estuary during both years. Passive telemetry equipment and standardized mobile tracking were maintained into the 2009 season to redetect returning fish, but no fish with multi-year tags were recontacted in 2008 (potential n=7) or 2009 (potential n=21). This does not mean that weakfish generally do not return, since fish may have been recaptured without report, perished following emigration, or missed redetection by hydrophones. However, the suggestion that weakfish may not maintain similarly high fidelity rates to smaller estuaries should be considered.

The early emigration of the two largest tagged fish in spring 2007 suggests that temporal and size-related differences in spawning location may exist. Although annually variable, bimodal patterns of larval abundance (with peaks in June and July) have been seen in other east coast estuaries (Delaware Bay: Goshorn and Epifanio, 1991b; Rowe
and Epifanio, 1994; Chesapeake Bay: Lowerre-Barbieri et al., 1996b). Distinct size classes of weakfish entering the estuary at different times to spawn may contribute to the apparent bimodal pattern. In the New York Bight, there is evidence that the largest fish immigrate into estuaries earlier and leave before a second size class of smaller fish enters the estuaries to spawn (Shepherd and Grimes, 1984). These two large fish may represent such individuals, although no distinct bimodality in larval abundance was observed in the larval sampling data.

Higher water temperatures have been shown to correlate with increased reproductive condition and drumming in weakfish (Villoso, 1990; Connaughton and Taylor, 1994; Mann and Grothues, 2009). In this study, temperatures peaked during the month of greatest emigration from the system in August. However, the second highest monthly average temperature was in July during lowest emigration and within the defined spawning season. The pattern during both years shows that the cessation of the spawning season may not be related to peak water temperatures, although it is not known if fish are moving out of the estuary to spawn offshore or within a different estuary.

Weakfish emigration location differed between years, most likely due to a spatial variation in weakfish residency patterns within the study area (i.e. bay or lower river). These patterns, however, may also have been confounded by original capture location. In 2007, a higher percentage of fish left through an intra-estuary thorofare (Main Marsh Thorofare) when a large proportion of fish were tagged in that region, while a majority of fish left through an inlet (Little Egg) in 2008 when no fish were tagged near Main Marsh Thorofare. The high percentage of fish never detected at emigration suggests that weakfish may utilize unmonitored creeks within the estuary for estuarine emigration at
inlets north or south of the study site. Alternatively, these fish may have been recaptured by fishermen and never reported or equipment failure may have precluded their detection. A hydrophone placed inside Absecon Inlet for another study, approximately 14 km south of Little Egg Inlet, detected two emigrating weakfish during the same week in November (week 45). One fish (Tag #163) was last detected at Main Marsh Thorofare and the other (Tag #162) at hydrophone 2 (Little Egg Inlet). Both fish were last detected in the study area during week 45. The fish last detected at Main Marsh Thorofare likely utilized tidal creeks to reach Absecon Inlet and the circuitous nature of this emigration location suggests that weakfish may use alternative routes that afford better opportunities for feeding and/or protection from predators. With the traditional delineation of weakfish as “facultative estuarine users”, the current study suggests that extensive use of estuaries by mature weakfish, during the reproductive season or not, warrants further investigation into the importance of coastal habitats. Further comparative studies between broadly defined habitats (e.g. ocean versus estuary) are also warranted.

**Habitat Use**

Weakfish habitat use across the estuary varied by individual but it was clear that they utilized only a limited portion of the available habitat during both the reproductive and post-reproductive seasons. The modest use of inlet and riverine habitats during both seasons and years suggests that weakfish did not use either for reproductive or post-reproductive purposes. In general, the areas of highest weakfish densities, although confounded by tagging location, showed similarities in their physical attributes. With the exception of a group of fish found in the relatively shallow and open water of Great Bay in 2008, these locations were characterized by a close proximity to emergent (marsh
banks) and/or submergent edges. Although Little Egg Inlet is characterized by similar physical qualities (deep submergent edges and channels), weakfish preferred analogous features within the bay and river regions. Shifts in habitat use patterns between seasons were evident in individual fish that moved from deep channels within the Mullica River during the spawning season to open bay habitat, potentially utilizing this area as a feeding ground during the post-reproductive period. A high density of benthic invertebrates in this region (Kennish, 2004) may directly contribute to weakfish diets or they may take advantage of the trophic cascade that results from other organisms (juvenile fishes and crabs) that feed on these prey items. Further, a large proportion of weakfish were detected in monitored deep subtidal creeks and thorofares following the spawning season, suggesting utilization of these habitats for post-reproductive purposes (see “Movement” section below for further discussion on creek habitat use). Fine-scale utilization of estuarine habitats by adult weakfish is relatively understudied compared to other aspects of weakfish biology and ecology, especially in relation to reproduction. Luczcovich et al. (1999, 2008) and Connaughton and Taylor (1995) delineated weakfish spawning habitat preferences in North Carolina and Delaware Bay, respectively, using passive acoustics but could not observe behaviors following the spawning season. In their multi-species telemetry study in the Navesink River, Manderson et al. (2007) examined habitat dynamics in relation to environmental variables in weakfish, but comparisons between the spawning/post-spawning seasons were not made.

With the potential link between weakfish reproduction and water temperature (Epifanio et al., 1988; Villoso, 1990; Connaughton and Taylor, 1994), it is pertinent to note that adult weakfish (especially during the reproductive season) were found at higher
temperatures than those available in other portions of the study area. Luczcovich et al. (2008) noted that weakfish displayed higher drumming indices in warmer water temperatures (>23°C) in Pamlico Sound, North Carolina. In an earlier study in Pamlico Sound, weakfish utilized higher salinity regions (average salinity: 28.8) closer to inlets for spawning, which was determined through passive acoustics and egg sampling, but were rarely detected on the western side of the Sound where salinities were lower (average salinity: 7.4) (Luczcovich et al., 1999). The tagged weakfish in this study preferred salinities similar and sometimes higher to those found at inlet data loggers, but rarely utilized that inlet habitat, which shows a geographical preference within the estuary as opposed to one related strictly to the salinity gradient, as was seen in their preference for habitat with similar physical characteristics to those in the inlet. The proximity of weakfish to an inlet in Pamlico Sound may reflect bias resulting from sampling only two areas for spawning vocalizations (Bay River and Ocracoke Inlet) (Luczcovich et al., 2008). The area between these two sites may well have been suitable spawning habitat. Furthermore, the salinity gradient in the Great Bay-Mullica River, due to its smaller size, is spatially compressed in relation to Pamlico Sound, making it difficult to compare habitat use patterns between systems on the basis of physical features (i.e. inlets, river mouths, bay etc.). The effects of this could be seen in the dissimilarity in salinities between the Bay River study area in Pamlico Sound and the Mullica River mouth as well as the resulting difference in weakfish spawning habitat use between these areas (Luczcovich et al., 2008). The frequency of weakfish found in depths greater than the average depth of the study area (<2 m) during the reproductive months also agrees with the Luczcovich et al. (2008) conclusion that weakfish prefer deeper water during
spawning activity. A group of weakfish tagged in the Navesink River was observed in deeper channels during July while a second group moved to shallower upstream areas in August (Manderson et al., 2007). The authors suggest the shift may be due to decreases in water temperature within the estuary, but the effects of reproduction were not examined as a possible driver in the habitat shift.

In the analysis of weakfish habitat use, there was a high degree of correlation between original tagging location and fish density during both seasons and years indicative of site fidelity. While site fidelity was not fully examined, this behavior was observed during fine-scale tracking of individual tagged fish during a separate portion of the study (see Chapter 3) and may indicate the importance of small-scale habitats to weakfish reproduction. A slight variation in the strong correlation between tagging location and fish density occurred during both the spawning (2007) and post-spawning (2008) periods when there was a shift in regional density away from original tagging locations in Little Sheepshead Creek in 2007 and Big Creek in 2008. In both cases, fish originally tagged in subtidal creeks contributed to higher tagging densities in their respective regions, but those regions did not maintain those densities. This pattern could indicate a transient usage of subtidal creek habitats, whereby fish did not maintain a longer-term residency in those areas and either utilized portions of that habitat unmonitored by mobile tracking or left the habitat altogether. The former explanation seems to explain the behavior of fish tagged in Big Creek and not redetected elsewhere. An exception to these observations were fish tagged in Main Marsh Thorofare in 2007 that maintained close proximity to their original tagging site. While the physical characterizations of these two habitats are similar (deep channels flanked by emergent
marsh edges), other qualities may explain the differences in their utilization (i.e. water
flow, prey availability, etc.)

**Movement**

Movement is often tied to other aspects of habitat dynamics in fishes (such as
residency and habitat use), but was examined as a stand-alone metric during this study as
a means to delineate changes due to reproductive effects. Two broad patterns emerged
from the analysis of weakfish movement in 2008. For the subset of fish that were
redetected each week, the higher rates of movement correlated to the end of the
reproductive season and prior to emigration, whereby fish may have moved from the
spring-summer spawning grounds to other habitats within the study area. The trade-offs
between weakfish reproduction, predator avoidance, feeding, and physiology may have
played a part in the observed behavior. Once freed from the constraints of reproduction,
weakfish may begin to explore habitat space more conducive to other aspects of their
survival. A second pattern was seen in fish not redetected during consecutive weekly
tracking events in 2008 but that had not yet emigrated from the system. There are at least
several explanations for this pattern, such as (1) tagged fish went undetected because they
were outside the detection area of the sampling; (2) tagged fish were captured in the
recreational fishery and not reported; and/or (3) tagged fish were within the monitored
area but moving at rates that did not allow for mobile hydrophone detection. Due to the
pattern observed where fish were less frequently detected following the conclusion of the
defined spawning period than before, it is likely that present fish were missed due to a
shift to unmonitored habitats within the study area. The propensity for adult weakfish to
utilize creek systems is evidenced by their frequency of capture for tagging in these
habitats as well as previous net sampling in the study area (Rountree and Able, 1992; Able et al., 1996; Rountree and Able, 1997). In one particular examination of subtidal marsh creek systems, peak adult weakfish abundance correlated with late summer (August) peaks in the prey species Atlantic silverside (*Menidia menidia*) (Rountree and Able 1992). Further work on creek habitat utilization in weakfish will help to define the importance of these areas in relation to spawning and post-reproductive habitat use.

Several factors influencing weakfish population dynamics and reproduction, and therefore habitat dynamics, were not considered in this study. The nightly diel periodicity of spawning in weakfish has been well documented using passive acoustics (Connaughton and Taylor, 1995), egg-sampling (Ferraro, 1980) and histological techniques (Taylor and Villoso, 1994). Although passive telemetry was capable of detecting weakfish during the evening hours, when they are known to spawn, mobile tracking events occurred solely during the daytime and, therefore, it was not possible to make assumptions of weakfish habitat dynamics during the nighttime period. However, a concurrent study of nighttime movements indicated relatively small shifts from the daily ranges of most tagged fish (see Chapter 3). With the recent precipitous decline in the weakfish stock, the patterns observed in this study reflect dynamics associated with a low population size. Contingent structure in marine fishes has been attributed to density dependence and should be considered when evaluating data on habitat use and movement (Secor, 1999). The hypothesis that fish will utilize marginal habitats only when densities in prime habitats are great enough to negatively influence their quality (MacCall, 1990) has important significance in weakfish since the population is depleted enough to assume low densities Although factors such as interspecific competition most likely influence
habitat dynamics in weakfish, the current study may well be observing individuals within their preferred habitat distribution. Skewed demographics of the depleted weakfish population (towards younger, smaller fish) may also contribute to a shift in the timing of reproduction since a more robust population with older and larger adults may exhibit a more expanded and perhaps bimodal spawning season (Wright and Trippel, 2009).

While low population size may contract the geographic range of weakfish, localized and ocean-wide changes in water temperature regimes may also influence geographical range and timing of spawning (Perry, 2005; Rijnsdorp, 2009; Sydeman and Bograd, 2009). Evidence of latitudinal distribution shifts with warming water temperatures have already been documented in marine fish populations, such as in the pelagic species Atlantic herring (Clupea harengus; Toresen and Østvedt, 2000) and Atlantic mackerel (Scomber scombrus; Reid et al., 2001); cold-water species (Atlantic cod, Gadus morhua: Heath, 2007); and warm-temperate species (Atlantic croaker, Micropogonias undulatus: Hare and Able, 2007; various Northeast U.S. fish stocks: Nye et al., 2009). Changes in weakfish overwintering distribution due to warmer temperatures have most recently come into question (Weinstein et al., 2009). With the variable effects of environmental and fishery-related drivers, the interpretations of both current and future investigations of weakfish habitat dynamics should not assume that they remain static.
Table 2.1 Characteristics of acoustic tags deployed in weakfish during study period (2007 and 2008)

<table>
<thead>
<tr>
<th>Number of Fish Tagged (Year)</th>
<th>Tag Model</th>
<th>Average Transmitter Life (days)</th>
<th>Size (Diam. x L (mm))</th>
<th>Weight (g)</th>
<th>Frequency (KHz)</th>
<th>Burst Interval (s)</th>
<th>Power (dB re 1m P @ 1meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 (2007)</td>
<td>CAFT 11_3</td>
<td>229</td>
<td>11x46</td>
<td>8.4</td>
<td>76.8</td>
<td>5</td>
<td>150</td>
</tr>
<tr>
<td>15 (2008)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3  (2007)</td>
<td>CAFT 11_4</td>
<td>327</td>
<td>11x55</td>
<td>10.0</td>
<td>76.8</td>
<td>5</td>
<td>150</td>
</tr>
<tr>
<td>7  (2007)</td>
<td>CAFT 16_1</td>
<td>719</td>
<td>16x54</td>
<td>24.0</td>
<td>76.8</td>
<td>5</td>
<td>155</td>
</tr>
<tr>
<td>8  (2008)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1  (2007)</td>
<td>CAFT 16_3</td>
<td>675</td>
<td>16x97</td>
<td>39.3</td>
<td>76.8</td>
<td>5</td>
<td>161</td>
</tr>
<tr>
<td>10 (2008)</td>
<td>MS 16-25 (Dual-mode transmitter)</td>
<td>438</td>
<td>16x54</td>
<td>23.0</td>
<td>76.8</td>
<td>5 (5:1 CAFT;MAP transmissions)</td>
<td>155</td>
</tr>
</tbody>
</table>
Table 2.2 Characteristics of tagged weakfish and summary of telemetry detections during 2007 and 2008. Values in parentheses represent total number of weakfish originally tagged, including lost tags.

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Fish Tagged</td>
<td>24 (26)</td>
<td>29 (33)</td>
</tr>
<tr>
<td>Tagging Period</td>
<td>April 30 - August 31</td>
<td>June 11 - September 11</td>
</tr>
<tr>
<td>Mean Fish Size (mm TL)</td>
<td>431</td>
<td>401</td>
</tr>
<tr>
<td>Fish Size Range (mm TL)</td>
<td>292 - 864</td>
<td>273 - 591</td>
</tr>
<tr>
<td>Number of Fish Detected</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive Telemetry</td>
<td>18</td>
<td>22</td>
</tr>
<tr>
<td>Active Telemetry</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Number of Detections</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive Telemetry</td>
<td>71,961</td>
<td>98,563</td>
</tr>
<tr>
<td>Active Telemetry</td>
<td>25</td>
<td>118</td>
</tr>
<tr>
<td>Number of Fish Never Redetected</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Number of Lost Tags</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Number of Recaptures</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 2.1: Study area at Great Bay-Mullica River/Little Egg Harbor estuary, including the locations of ichthyoplankton sampling, stationary (passive) telemetry hydrophones, and JCNERR SWMP data loggers. The site lies within a portion of the Jacques Cousteau National Estuarine Research Reserve (JCNERR).

Figure 2.2: Yearly variation in both stationary and mobile telemetry efforts. (a) Annual variation in the deployment of passive telemetry hydrophones during 2007 and 2008. See Figure 2.1 for the location of each passive hydrophone. Hydrophone status signals were used as a proxy for sampling effort/deployment. Thick black lines indicate reception of a status signal (code 211) from the deployed hydrophone and thin lines represent times when hydrophones were not deployed or not functioning during deployment. Hydrophone 10 could not receive status signals so the time that the hydrophone was actively deployed and functioning properly was binned by day and used as the metric for effort. Mobile tracking effort was calculated as the percentage of total points completed for the (b) lower region of the study area (Great Bay and Little Egg Harbor; see Fig. 2.1) and the (c) Mullica River and its tributaries (see Fig. 2.1). The total number of potential tracking points (n=120) was based on the 2008 tracking protocol, which included the tributary Big Creek (see Fig. 2.1, Fig. 2.3). See Figure 2.1 for the location of each hydrophone.

Figure 2.3: Distribution map of standardized mobile telemetry sampling points in the study area. The number of sampling points varied over both study years due to an increase in the number points between 2007 (n=113) to 2008 (n=120). The additional points (in the Big Creek tributary) are represented as diamonds. Estuarine bathymetry (inset) was rasterized from NOAA soundings data.

Figure 2.4: Overall distribution of acoustically tagged weakfish during the defined (a) spawning and (b) post-spawning seasons in 2007 and 2008. Black rectangles represent equal-width (2 km) quadrants used to standardize weakfish spatial distributions by density.

Figure 2.5: Weakfish reproductive phenology as determined through weekly ichthyoplankton sampling within the study area from 1989-2007. (a) Bubble size indicates proportion of total weakfish larvae caught during a sampling week within a given year. The shaded region shows the estimated back-calculated spawning period based on the lengths of weakfish caught during the weeks of average peak larval density (weeks 28-30). (b) Indicates average larval weakfish densities (with standard error bars) by week.

Figure 2.6: Length frequencies of acoustically tagged weakfish captured in the Great Bay-Mullica River/Little Egg Harbor estuary during 2007 and 2008. Only successfully tagged weakfish are included.

Figure 2.7: Weekly detection history of individual acoustically tagged weakfish based on multiple telemetry techniques and dates of capture/recapture within the study area during 2007 and 2008. The shaded region indicates the spawning period (see Fig. 2.5).
Figure 2.8: Timing of weakfish emigration relative to the calculated spawning period (shaded region; see Fig. 2.5) and water temperatures at probable estuarine emigration sites. Water temperature data taken from JC NERR SWMP data loggers deployed at Buoy 136 and Buoy 139 (see Fig. 2.1).

Figure 2.9: Broad-scale habitat use of weakfish based on detections in the passive telemetry array within the Great Bay-Mullica River/Little Egg Harbor estuary. The number of weakfish detected as a proportion of those available (tagged and not yet emigrated from the study site) are indicated at (a) “inlet” (Little Egg Inlet; hydrophones 1-4) and (b) “estuarine” hydrophones (5, 7, 13), respectively. The average time (minutes) weakfish spent at (c) Little Egg Inlet and (d) estuary hydrophones, respectively. No fish were detected at the “river” hydrophone (Mullica River; 10) during both years. See Figure 2.1 for locations of stationary hydrophones. The shaded region represents the defined spawning period (weeks 20-29) based on Fig. 2.5.

Figure 2.10: Fine-scale habitat use of weakfish based on periodic mobile telemetry efforts in the Great Bay-Mullica River/Little Egg Harbor estuary during the (a) reproductive and (b) post-reproductive seasons. Fish density within a region (see Fig. 2.5) was standardized by the number of fish available and water surface area (km$^2$).

Figure 2.11: Yearly and monthly variation of four environmental parameters (water temperature, salinity, dissolved oxygen (D.O.), and pH) measured by four JC NERR SWMP data loggers within the Great Bay-Mullica River estuary during both study years with associated variables measured during mobile tracking of acoustically-tagged weakfish. Water quality parameters represent daily means at each of the four data logger sites (Buoy 136, Buoy 139, Chestnut Neck, and Lower Bank; see Fig. 2.1 for locations). For two environmental parameters (temperature and salinity) measured in 2007, there were 25 measurements represented by 16 individual weakfish. No data were taken on D.O. and pH in 2007. In 2008, temperature and salinity both had 118 measurements (n=20 individuals); D.O. had 95 measurements (n=20 individuals); and pH had 53 measurements (n=17 individuals). Shaded region represents the spawning period (see Fig. 2.5).

Figure 2.12: Depth utilization of acoustically tagged weakfish in 2007 and 2008. Black dots represent the water depth of an individual fish at detection during mobile tracking events.

Figure 2.13: Weekly movement rates calculated as a minimum displacement (kilometers) per week (MDPW) of acoustically tagged weakfish across the 2008 reproductive/post-reproductive seasons. A subset of fish with consecutive weekly contacts during mobile tracking was used for MDPW calculations. Numbers above each monthly value represent sample sizes. The shaded region represents the spawning period (see Fig. 2.5).
Figure 2.14: Number and proportion of undetected fish (of those available) found during weekly mobile tracking in 2008. Availability was defined as those tagged fish that had not yet emigrated from the study site.
Figure 2.2
Figure 2.3
Figure 2.4
Figure 2.5
Figure 2.6
Figure 2.7
Figure 2.8
Figure 2.9
Figure 2.10

(a) Reproductive Season (May-July)

(b) Post-Reproductive Season (August-November)

- Standardized Fish Density by Region (2007)
- Standardized Fish Density by Region (2008)
- Tagging Frequency by Region (2007)
- Tagging Frequency by Region (2008)
Figure 2.11
Figure 2.12
Figure 2.13
Weakfish Capture and Acoustic Tagging Data Sheet

Capture
Fish Name: Olga          Date: 5/9/07
Time: 19:15          Angler(s): Tag Turnure
Method of Capture: Hook & Line (Berkeley 60 lb Pink Mono)
General Location: CSAC sod bank
Latitude/UTM X: See GPS card, Longitude/UTM Y: See GPS card
Water Depth: Bank      Tide Cycle: Slack low
Weather Description: Fair, Cloudy & breezy 1 oonl
Temperature Surface/Bottom: See $1 data
Salinity Surface/Bottom: 
Oxygen Surface/Bottom: 

Tagging
Lotek Tag Model/Expected Tag Life: CAST II-4/327 days/5 sec. burst
Lotek Tag #: 149        Notes: 
External Tag #: 048 (yellow + bar)
Sex: 2 (not determined) Reproductive Status: Rigor (not knowing that I could tell)
Total Length: 34 in. (864.4 mm) Fork Length: 
Weight: 15 lbs. (bone grip) Spring Scale
Surgeon(s): Tag Turnure, Roland Hagen
Time in MS-222: 
Surgery Time: 18:55 ~ 20:08
Recovery Time: 7 min. Released: 20:15

Comments/Notes
Black Ethilon sutures (non-absorbable) - No scale sample
Chris Herbst
Bryan Cogniotti

Contact: Jason T. Turnure, (609) 296-5260 x255

Sample data sheet from Olga, Tag ID #149
CHAPTER 3

Small-scale estuarine habitat dynamics in adult weakfish: Seasonal and diel patterns of site fidelity

ABSTRACT

Movement towards a more holistic approach to fisheries has also pushed forward the implementation of various spatio-temporal management techniques, which should be utilized at ecologically relevant scales. With weakfish reproductive dynamics occurring on multiple temporal (seasonal and diel) and spatial (estuary and coastal) scales, management of the current stock is particularly susceptible to confusion over how to best define areas of essential weakfish resources, particularly small-scale habitats. In this study, patterns of adult weakfish site fidelity within the Mullica River-Great Bay estuary in 2007 and 2008 were examined at both the seasonal and diel scales using acoustic telemetry. These patterns were examined in relation to the reproductive and post-reproductive seasons, as well as to potential environmental (meteorological and water quality) and biological (spawning vocalizations) variables. The movement response of weakfish following initial tagging was also explored because of the influence that this behavior had on subsequent observations of site fidelity. At the seasonal scale, a majority of weakfish tagged in 2008 maintained fidelity to their original tagging location or established new “core areas” in other parts of the estuary. In both cases, fish were detected at these areas for the duration of their residency or made short- or long-term excursions before returning to their original core area, potentially related to storm events. At the diel scale, weakfish displayed movements of varying distances from their original...
tagging location beginning around sundown and returning around sunrise with no apparent correlation to an increase in spawning vocalizations. A potential “fall-back” response following tagging was observed in some individuals, which should be accounted for in future studies. The differential scales at which crucial life history characteristics occur in weakfish and the prevalence of small-scale dynamics in this, and other economically and ecologically important, species indicate that spatio-temporal scaling should be incorporated into the management of these fisheries.

**INTRODUCTION**

Movement towards a more holistic approach to fisheries has also pushed forward the implementation of various spatial management techniques (Agardy 1994; Murawski et al. 2000; Roberts et al. 2005) to protect over-exploited stocks and ecosystems. Successful management thus relies on appropriate data on the spatial dynamics of marine species. Therefore, information on the basic movement ecology (e.g. larval dispersal, Fogarty and Botsford 2007; adult spawning migrations, Guenette et al. 2000, Parsons and Egli 2005) of commercially and recreationally important species has become an increasingly warranted research goal (Pittman and McAlpine 2003). Depending on its scope, management could offer protections at multiple spatial levels (i.e. regional, estuary, tributary; Agardy 1993), making it necessary to understand fish movements at various spatial scales (Cowen et al. 2006; Pittman and McAlpine 2003; Botsford et al. 2009).

While small-scale movements and site fidelity have been examined extensively in terrestrial (Bright and Morris 1991; Costello 2010) and avian species (Hoppes 1987, Wakefield et al. 2010), improvements in our ability to track marine animals with greater
resolution, in both time and space, have shed light on similar behaviors (March et al. 2010). Studies of fine-scale movements in fishes has reflected their ability to home back to relatively small geographic areas (Mitamura et al. 2009), maintain restricted home ranges (McGrath and Austin 2009), and maintain true to particular habitats from daily (Humston et al. 2005) to yearly (Ng et al. 2007) time scales. Further complicating the development of spatial management techniques are comparable temporal shifts in fish behavior caused by seasonal (i.e. reproductive phenology) or daily (i.e. predator avoidance) effects (Naylor 2005). To account for the inherent temporal dynamism in fish behavior, management has both traditionally and more recently incorporated these shifts into plans for fish stock recovery, such as seasonal closures of fishing grounds that coincide with critical aspects of a fish’s life history (i.e. spawning; Murawski et al. 2000; Roberts et al. 2005) but an improved understanding of movements is still needed.

Concern over the decline of weakfish (Cynoscion regalis) justifies examination of similar aspects of their estuarine ecology. Weakfish are known estuarine and coastal spawners with a well defined spawning season (May through July) in the Middle Atlantic Bight (MAB) (Able and Fahay 2010; also see Chapter 2 section on Reproductive Phenology). Previous egg/plankton sampling (Ferraro 1980), reproductive histology techniques (Lowerre-Barbieri et al. 1996b; Nye et al. 2008), and gonado-somatic indices (Taylor and Villosso 1994) have also delineated weakfish as nightly diel spawners, generally commencing reproductive behavior around the evening crepuscular period. Both field and laboratory passive acoustic studies have utilized weakfish drumming of the swim bladder (i.e. dominant frequency), which generally occurs just prior to spawning, to better define the location (Luczkovich et al. 1999) and diel periodicity
(Connaughton and Taylor 1995) of their reproduction. Previous work also quantified the rate of philopatry (natal homing) to estuarine systems, suggesting that weakfish exhibit a high-degree of site fidelity to broad regional areas (i.e. Chesapeake Bay and Delaware Bay) (Thorrold et al. 2001). While current management defines only one coastal weakfish stock based on the lack of differentiation in genetic data (Cordes and Graves 2003), the evidence of site fidelity suggests that the weakfish stock consists of distinct subpopulations with likely variation in the degree of reproductive straying between estuarine systems (Thorrold 2001). Prior investigations of adult weakfish movements have been either too geographically coarse (Nesbit 1954; Bain et al. 1998) or limited in scope (Manderson et al. 2007) to interpret the degree of small-scale site fidelity within estuaries and its relevance to patterns of natal homing.

With weakfish reproductive dynamics occurring on multiple temporal (seasonal and diel) and spatial (estuary and coastal) scales, management of the current stock is particularly susceptible to confusion over how to best define areas of essential weakfish habitat and, ultimately, when and/or where to implement spatio-temporal management schemes for their protection. In an effort to elucidate these small-scale dynamics of adult weakfish in a MAB estuary, mobile and passive acoustic telemetry were utilized to examine patterns of site fidelity at both the seasonal and diel scales. To gain a better understanding of the processes behind weakfish site fidelity in an estuarine system, environmental (water quality and meteorological) and biological (sex and sound production) variables were also observed in relation to these patterns. Weakfish movements immediately following release (because of potential tagging effects) were considered in this study since subsequent observations were based on an individual’s
initial fidelity to their tagging area. Also, because weakfish may change habitat use as the result of reproduction, patterns of site fidelity were examined in relation to the reproductive and post-reproductive seasons.

**MATERIALS AND METHODS**

**Study Areas**

To examine aspects of seasonal and diel site fidelity in weakfish, as well as initial movements after release, several sub-study areas were utilized within the primary area of study in southern New Jersey (Figure 3.1). For the initial tagging movement and seasonal site fidelity components, the study site encompassed both the Great Bay-Mullica River estuary and a smaller portion located in the adjacent Little Egg Harbor estuary (Figure 3.1A). Although adjacent, these estuaries differ in their physico-chemical properties. The Mullica River-Great Bay system is characterized as a relatively small and salt marsh-dominated drowned river valley with a relatively shallow average depth (<2 m) (Kennish 2004). With the majority of the watershed flowing through undeveloped habitat, namely the Pinelands National Reserve, it is considered to be one of the least anthropogenically disturbed estuaries in the northeastern United States (Good and Good 1984; Psuty et al. 1993; Kennish and O’Donnell 2002). The Little Egg Harbor estuary is also a relatively shallow system (<2 m), but is characterized as a barrier island estuary with significantly less freshwater inputs than the Mullica River-Great Bay system (Kennish 2001; Kennish 2004). While the Mullica River is characterized by low pH (4-6) due to tannic leachate from the surrounding pine/oak-dominated watershed, less acidic conditions prevail in the Little Egg Harbor estuary. Further, extensive development in Little Egg Harbor has manifested in water quality problems (i.e. eutrophication and
hypoxia) and habitat modification (i.e. bulkheading) not seen in the adjacent estuary (Kennish et al. 2007). Seasonal variability in the water temperatures of both systems are typical of temperate estuaries, ranging from <0 C in winter to >30 C in summer (Kennish 2004). Because of their unique ecological status, the National Oceanic and Atmospheric Administration (NOAA) have delineated both estuaries as part of the Jacque Cousteau National Estuarine Research Reserve (Kennish 2004). A second, more spatially constrained part of the study of seasonal site fidelity included the area around Main Marsh Thorofare, a deep subtidal thorofare that connects Great Bay with Absecon Bay to the south (Figure 3.1B). For the diel portion of the study, several smaller regions within the Mullica River estuary were monitored: the lower portion of the Mullica River (Deep Point, Figure 3.1C), as well as limited areas in Little Sheepshead Creek, a subtidal thorofare (Figure 3.1D), and the northeastern edge of lower Great Bay (Figure 3.1E).

**Acoustic Telemetry**

*General Tagging Procedure*

All adult fish (>250 mm; Nye et al., 2008) examined for patterns of site fidelity in 2007 and 2008 were captured using hook-and-line and subsequently tagged by abdominal implantation of individually coded acoustic transmitters (Lotek Wireless, Inc., St. John’s, Newfoundland) following both Bridger and Booth (2003) and Able and Grothues (2007). Before surgical implantation, fish were anesthetized in a diluted solution of MS-222 in ambient seawater (0.05 g/L; Sigma, Inc.) In 2008, visual inspection of the gonads during surgery was made for sex determination and incisions were sutured using Ethilon® absorbable monofilament PDS-II sutures. Immediately following either surgery or recovery (ability to maintain upright posture) in a bath of ambient seawater, fish were
delivered the broad-spectrum antibiotic oxytetracycline (0.1 mL/kg fish; Liquamycin, Pfizer, New York) to guard against latent infection. After full recovery, fish were released within 100-m of their original site of capture.

Patterns of movement after initial tagging were evaluated in fish tagged over the two-year study period in 2007 and 2008 (n=53). Seasonal site fidelity patterns, both before and after reproduction, were observed in the movements of only acoustically tagged fish in 2008 (n=29), as well as a subsample of fish tagged in 2007 at Main Marsh Thorofare (n=10). To examine patterns of fidelity to their original tagging site at the daily time scale and across seasons, another subsample of fish in 2008 were monitored in the lower Mullica River during the summer (n=9) and within Little Sheepshead Creek during the fall (n=4). The battery duration of the deployed acoustic transmitters (CAFT and MS series, Lotek Wireless, Inc.) for both the seasonal and diel components of the study ranged from 229 to 719 days, allowing for monitoring of fish up until final emigration from the study area in the fall.

**Passive Telemetry Array**

Within Great Bay-Mullica River/Little Egg Harbor, a passive and gated array of stationary hydrophones (WHS-1100, Lotek Wireless, Inc.) were deployed along the salinity gradient and at locations designed to maximize fish detection during estuary emigration or immigration (Figure 3.2a; see Chapter 2 “Passive Telemetry” section for further details on the array; Grothues et al., 2005). In this particular study, seasonal site fidelity was evaluated in 2007 at a smaller spatial scale at a single hydrophone located at Main Marsh Thorofare (Figure 3.1). Observations were made during both years on movement from release location immediately following tagging whereby all available
hydrophones were utilized for fish detection. Due to various constraints, deployment of stationary hydrophones varied between and among study years (Figure 3.3a).

**Mobile Telemetry**

Mobile telemetry was utilized at both the seasonal and diel scales to examine patterns of site fidelity in 2008. In general, mobile tracking took place from a small boat using a directional hydrophone (LHP_1, Lotek Wireless, Inc.) attached to an on-board signal processor (SRX-400, Lotek Wireless, Inc.) At sampling locations (Figure 3.2B), the hydrophone was lowered approximately 3 meters underwater and turned in 90° increments to full rotation. When fish were audibly detected, the boat was positioned to maintain close proximity (signal power > 115dB and gain <15) and then fish location was recorded using a hand-held global positioning system (GPS) unit, together with the tag identification number, signal power (dB), and gain. Although variable due to ambient weather conditions and inherent loudness of the acoustic transmitter, the mobile hydrophone’s minimum listening range averaged 500 meters. For further discussion of the general mobile tracking procedure, see Ng et al. (2007) and Sackett et al. (2007).

**Seasonal Tracking** - During every calendar week from May 19 to December 4, 2008 (except the week of November 17 due to weather), 120 predetermined locations covering a majority of the Mullica River-Great Bay system were sampled during daylight hours (07:00-19:00) as described above (Figure 3.2B). For most of the tracking events, both the “bay” and “river” were sampled on different days (see Figure 3.2B for bay/river designations).

**Diel Tracking** - Mobile diel tracking occurred during summer 2008 from June 30 to July 31 and fall 2008 from October 1 to October 14 (Figure 3.3B). During the
summer, nine predetermined sampling points were visited on a rotating basis during each tracking event (Figure 3.2B). Following detection of a(n) individual(s) at a tracking point, the subsequent locations would be visited until all nine points were completed (Figure 3.2B). Upon finishing, the nine point rotation would repeat at point 1 until the daily sampling event was over (Figure 3.2B). The duration between consecutive contacts of a single individual was highly variable (12-382 minutes) based on the abundance of fish at sampling points and the time it took to return to the location of a previous detection. Additionally, if fish left the tracking area for extended periods, subsequent redetection was delayed. To determine the effect of the crepuscular and nighttime periods on weakfish site fidelity, tracking frequently occurred during and after sun-down (Figure 3.3B). During fall tracking, several different locations were visited throughout October (Figure 3.2B). If tagged fish were detected, location information was recorded every 9 to 58 minutes depending on the difficulty of relocating the fish. Due to various constraints, the frequency of sampling during both the summer and fall varied greatly (Figure 3.3B). During the fall tracking, in particular, fish were difficult to relocate on a consistent daily basis due to the increase in movement observed during these months (see Chapter 2 “Movement” results section).

**Passive Acoustics**

In addition to individual fish location, information on weakfish drumming activity was assessed at every location that a fish was detected during the summer diel tracking period. Recordings were made using an unbaffled underwater hydrophone (HTI-96-Min, High Tech, Inc., Gulfport, Mississippi) placed at the end of a 3 meter PVC extension linked to a mobile digital audio recorder (Microtrack II, M-Audio, Avid Technology,
Sound was monitored in real-time through stereo headphones (K-55, AKG, Harman Intl. Industries, Inc., Vienna, Austria) and recorded to a flash memory card. Based on a previously developed drumming index (DI) (Connaughton and Taylor, 1995; Luczcovich et al., 2008), drumming was assigned a qualitative measure of activity (0=no drumming; 1=one individual sporadically drumming; 2=at least one individual drumming throughout recording; 3=multiple individuals (aggregation) heard throughout recording). All recordings were post-analyzed in the laboratory by listening to the raw audio without manipulation to the original sound properties.

**Environmental Measures**

Measures of environmental variability were used during both components (seasonal and diel) of the study to assess whether site fidelity could be explained by abiotic factors. The JCNERR System-Wide Monitoring Program (SWMP) provided data on estuary-wide water quality (Kennish and O’Donnell, 2002; see Chapter 2 section “Environmental Measures”) and local meteorological data (Figure 3.2a). Meteorological data, collected at the JCNERR at Richard Stockton College Field Station at Nacote Creek (Figure 3.2a), were sampled every 5 seconds and averaged or totaled by 15-minute time bins. Variables used in this study were average air temperature (°C), average wind speed (m/s), average wind direction (°), total precipitation (mm), average barometric pressure (mb), and total photosynthetically active radiation (PAR) (mmoles/m^2) (NERRS 2007; Mills et al. 2008). For analysis purposes, only data from Buoy 139, located on the southwestern portion of Great Bay (Figure 3.2A), were used to assess general trends in water quality variables within the study site. SWMP data collection was infrequently
interrupted due to weather or equipment malfunction. Water quality was also measured during mobile tracking when/where fish were detected using a hand-held YSI (Model 85, Yellow Springs Instruments, Inc., Yellow Spring, OH). Refer to Chapter 2 (“Mobile Tracking” section) for a detailed discussion on methodology and water quality variables sampled.

**Data Analysis**

In most of the quantitative analyses where pseudoreplication was of concern, the sampling unit (n) was defined as an individual tagged fish. Unless noted, variables used in analyzing site fidelity were averaged for each individual. Analysis techniques and the metrics utilized varied for each component of the study; therefore, their descriptions will be treated separately and are as follows:

*Movement After Tagging* – To understand the immediate influence of tagging on weakfish movement, individuals were analyzed for broad patterns of movement within the first week (seven days) after release. Mobile tracking could not provide the temporal resolution needed to observe immediate post-tagging movements and, therefore, only location and duration of detections at hydrophones were utilized. If fish were tagged within a relatively short distance (<1 km) of a stationary hydrophone, detections at that location would not be counted.

*Seasonal* - Analysis of seasonal site fidelity consisted of data from two sampling programs: mobile and passive telemetry. For fish detected during weekly mobile tracking in 2008, site fidelity was defined as two or more consecutive detections at a site that was less than 500 meters from the previous contact. If fish showed limited movement from their original tagging location, the distance was measured from their
tagging site. If fish relocated to an area greater than 500 m from their tagging site, but then showed fidelity to the second site over two subsequent detections (based on the standard described above), the site was defined as a new “core area”. If fish were either never redetected after release or redetected only once, they were characterized as not displaying fidelity. Environmental data variation in average daily water quality (water temperature, salinity, dissolved oxygen, pH, depth) and meteorological (barometric pressure, wind speed, wind direction, total precipitation) variables during the study period was reduced to its major synthetic trends using principal components analysis (PCA) (CANOCO v. 4.5 software; Braak and Smilauer 1998) with day of the year as the sampling unit. Differences among sexes were also examined in relation to general patterns of site fidelity.

Due to the greater frequency of sampling by the passive array hydrophones, fish detected near their original capture site (near hydrophone 13) were assessed for site fidelity more continuously. Metrics for this hydrophone were based on the proportion of detections received on a daily basis across seasons and the proportion of days (while resident in the estuary) detected.

*Diel* – Variations in sampling protocol during the summer and fall tracking periods made it necessary to evaluate diel site fidelity using different methods. During both seasons, distance of fish from their original tagging location or core area was measured on an hourly scale to observe diel effects. When applicable in analyses, night was defined as the period one-hour before sundown to one-hour before sunrise (19:30 - 4:29), to account for potential behavioral changes (i.e. reproductive) during the dusk and dawn periods seen previously in weakfish (Connaughton and Taylor 1995). Daytime was
defined as the period from 4:30 to 19:29. Crepuscular and nighttime movements, however, were only examined during the summer season. Differences between distances from the tagging site during day and night samples were evaluated with the non-parametric Mann-Whitney U test to avoid concerns over non-normality of the data. To examine environmental correlates to an individual’s distance from their tagging or core area, multivariate analysis (PCA) (CANOCO v. 4.5 software; Braak and Smilauer, 1998) was conducted using water quality (water temperature, salinity, dissolved oxygen, depth) and meteorological (Total PAR) variables. Drumming indices were pooled by hour of the day and averaged to investigate correlations with fish distance from tagging site. In fall 2008, fidelity could only be assessed for the daytime period when sampling occurred.

RESULTS

General Characteristics of Tagged Fish

During both study years, a total of 53 adult weakfish were successfully tagged with acoustic transmitters (see Chapter 2 section on General Characteristics of Tagged Fish). In this study, subsamples of those fish were analyzed for various components of site fidelity. For inspection of seasonal site fidelity, 29 adult weakfish were successfully tagged, but only 20 fish were redetected sufficiently often during mobile tracking to be used in subsequent analyses (Table 3.1). Several characteristics, such as time of tagging (June 11 - September 11), capture, and length (273-591 mm TL) varied between fish, but sex ratio maintained a relatively even distribution (0.81 male:female) (Table 3.1). A subsample of fish tagged at Main Marsh Thorofare (Figure 3.1) in 2007 (n=10) for further examination of seasonal site fidelity ranged from 292 to 434 mm TL, with 9 of 10 fish tagged on the same day (August 1) and one fish tagged several weeks earlier on July
19 (Table 3.2). Observations were made on only eight of these fish (80%) because two tagged individuals were not redetected following release.

Diel site fidelity was examined in a subsample of fish in summer (n=9) and fall (n=4) 2008 (Table 3.3). However, one fish was detected only once during the summer diel tracking period and was removed from subsequent analyses (Table 3.3). Fish tracked in the summer were all tagged at Deep Point in the Mullica River, but tagging location varied for fish tracked in the fall (Figure 3.1; Table 3.3). Lengths for weakfish monitored in the summer ranged from 337 to 540 mm TL and from 279 to 432 mm TL in the fall (Table 3.3). During both seasons, weakfish were predominantly female and only one fish was examined during both the summer and fall tracking periods (fish ID 64) (Table 3.3).

Response to Tagging

In both 2007 and 2008, several stationary hydrophones (2, 3, 4, 5, 7, and 13; see Figure 3.1 for locations) detected movement 1 to 7 days after tagging (n=12 fish; 23% of all tagged fish), but the most distinct pattern was seen in eight weakfish (15% of all fish tagged) that made upriver runs to the area around hydrophone 7 for short periods following release (Figure 3.4). With minimum swimming distances varying from 6 to 22 kilometers (mean: 8 km), individual weakfish were detected at this location 1 to 7 days following release (63% within three days) and detection duration ranged from 1 to 18 days. Six fish were recontacted on consecutive days and for the two fish not seen consecutively, only one day separated their detections. On a daily scale, individual weakfish were detected for an average of 20% (+/- 7%) of the time at hydrophone 7 and two individuals spent over 40% of their time in the region. The movement of fish to the locations of other stationary hydrophones following release (n=7) took place to a lesser
degree than for hydrophone 7 and included three fish that also showed upriver movement. With all hydrophones (except 7) pooled, the average proportion of time spent by individual weakfish was less (9% +/- 2%) than for the upriver hydrophone 7 and duration of detection ranged from 2 to 4 days. Furthermore, distances traveled were not as extensive as those that moved to hydrophone 7 because most fish were tagged within closer proximity to a stationary hydrophone. Of the twelve fish that were detected at stationary hydrophones greater than 1 km from their release site, five (42%) emigrated from the study area within 1 to 7 days post-release based on their detection history.

**Seasonal Fidelity Patterns**

**Mobile Telemetry** - For fish detected using mobile telemetry, two broad patterns emerged in weakfish that exhibited fidelity (n=15; 52% of all tagged fish) during their residency within the estuary. One group of fish remained at their original tagging locations for at least some time (n=7), while another group exhibited fidelity within new core areas (n=7) (Table 3.1). For both groups, the duration of fidelity varied from short-term site affinity (0.9-1.6 weeks) to greater than a month (3.7-4.9 weeks) (Table 3.1). One individual (Fish 137) maintained more than one core area, moving from its original tagging site to another core area later in the season (Table 3.1). A difference in site fidelity related to sex was observed whereby all male weakfish (n=6; 40% of fish displaying fidelity) were observed to establish new core areas while only one female (7%) showed similar behavior. A large number of other female weakfish (n=7; 47% of fish displaying fidelity) remained at their tagging site and only one female displayed both fidelity patterns (7%). Additionally, the time of day of initial capture may have influenced the subsequent patterns of fidelity seen in tagged fish. All but one fish (Fish
that remained at their release site were captured during the late morning or afternoon daylight hours (n=6; 86%; 09:15-17:40) while only two fish that moved to new core areas were captured during mid-day (29%; 11:00-11:16).

Within each group, two additional patterns were detected. Several fish were never redetected outside their original tagging site (n=5; 33% of fish displaying fidelity; Figure 3.5ab) or new core area (n=3; 20% of fish displaying fidelity; Figure 3.6a-c) until later in the season (just prior to emigration from the study area). Other fish made excursions of varying durations from their tagging site (n=2; 13% of fish displaying fidelity; Figure 3.7a,b) or new core areas (n=4; 27% of fish displaying fidelity; Figure 3.8a-c) but were redetected in the vicinity of their previous core area during subsequent tracking events. One tagged individual (fish 62; 7%) displayed a slight variation from this pattern of excursions from its core area (Figure 3.7c). This individual never met the criteria for site fidelity at its tagging area but established a new core area before being relocated at its tagging site shortly thereafter. Therefore, this fish was not characterized as displaying either pattern.

The location of new core areas varied within the group displaying that fidelity pattern. Three individuals (Fish 102, 137, and 162) established new core areas and displayed excursion behavior in the southwest portion of Great Bay and were within close proximity to each other (two individuals shown in Figures 3.8a,b). However, when excursions were not observed, the location of the established core area was different for all three fish (Figure 3.6a-c). All the fish that established new core areas in southwest Great Bay were originally tagged at Deep Point (lower Mullica River), while only one
individual (Fish 103) that maintained fidelity at a different location was originally tagged in that area (Figure 3.6c).

The magnitude and duration of movements varied between and among fish displaying patterns of site fidelity. For most fish that maintained fidelity solely to their original tagging site, their final detection was at a large distance from that region during final emigration from the estuary (Figure 3.9a). Excursions consisted of short- and long-term movements from the core area, which sometimes exceeded 5 kilometers, but were followed by a return to the original tagging site (Figure 3.9b) or new core area (Figure 3.9c). In some cases, these returns may have been influenced by episodic weather events. During early October, three fish were redetected at their core area after excursions lasting from 9 to 16 weeks (Figure 3.9c). A multivariate analysis of the environmental and meteorological conditions from June through November in 2008 (Figure 3.10a) shows a relatively strong coastal storm that occurred in late September (Figure 3.10b) and resulted in high on-shore winds (northeast), coastal flooding, and heavy rainfall followed by a significant input of freshwater run-off into Great Bay several days later. The three weakfish were detected at their core area 2 to 9 days following the peak decrease (September 29) in bay salinity, dissolved oxygen, and pH (Figure 3.9c; Figure 3.10b). A significant decrease in average barometric pressure, usually associated with storm events, occurred approximately one week after the storm on October 1.

Site fidelity across the reproductive/post-reproductive periods was variable and few fish were detected throughout most of the spawning season to make comparative observations. However, a general trend of increased distance from tagging sites (Figure 3.9a) and new core areas (Figure 3.9c) after the defined spawning period (May-July) was
noted. The furthest excursions took place after July in three of the four individuals who established fidelity at new core areas (Figure 3.9c). Returns to the new core area did not occur until early October prior to the storm event in late September (see above). The other tagged fish (Fish 162) was last detected in early August, after the end of the reproductive season. Of those individuals that maintained fidelity to their tagging sites, two fish (40%) were last seen (prior to emigration) in late August, although three others remained close to their tagging sites throughout the post-spawning season before emigration in the late fall (Figure 3.9a).

Of the 29 weakfish that were successfully tagged in 2008, a total of 14 were either never redetected (n=9; 31% of all fish tagged) or did not fit the criteria for site fidelity (n=5; 17% of all fish tagged). Unlike those fish that exhibited site fidelity, the majority of these fish (71%) were tagged later in the season (August to September) when movement generally increased in tagged fish (see “Movement” section in Chapter 2) or within subtidal creeks (50%; Little Sheepshead Creek and Big Creek), which may have made subsequent detection more difficult. A smaller portion of fish that exhibited site fidelity were tagged after July (n=6; 40%) and in subtidal creek habitats (n=6; 40%). Further, a majority of these fish (06:02-09:00; n=9; 64%) were initially captured during the early morning hours suggesting that time of capture may have negatively influenced their detection because fish may exhibit diel-scale movement behaviors that preclude their subsequent detection (i.e. they may maintain fidelity in an unmonitored region within or outside the study area).

**Passive Telemetry** - Fidelity examined across seasons at Main Marsh Thorofare indicated similar variation in the amount of time spent within the vicinity of the original
tagging site, including fish that were never redetected following release (n=2; 20%) (Table 3.2). Three fish were redetected at the hydrophone site greater than 70% of the days after release (Table 3.2). However, a majority of fish (n=5) were redetected only 23% to 35% of the days (Table 3.2). Of those fish that maintained some degree of fidelity, the number of days detected revealed relatively long residency times within the area (22-84 days), with the exception of one fish that was detected for only six days post-release (Table 3.2). A closer examination of the proportion of time weakfish spent at hydrophone locations by day indicates that daily residency varied greatly, with many fish not detected for long periods between redetections (Figure 3.11a). Further, a low average proportion of detections per day (0.10 +/- 0.012) pooled across all fish tagged on August 1 indicate that many fish utilized the area for only short periods of time before leaving the study area (Figure 3.11a). The majority of fish (>60%) spent less than 10% of their day near their original tagging site (Figure 3.12). The single weakfish tagged in mid-July (fish 103) displayed a different pattern of fidelity, evidenced by a greater average daily proportion of detections (0.44), as well as more consecutive days contacted, Main Marsh Thorofare (Figure 3.11b). Movement from hydrophone 13 in Main Marsh Thorofare could be seen in fish that were detected at other hydrophones within the array either during emigration (Figure 3.13a) or during their residency (Figure 3.13b), although these detections lasted for relatively short periods of time (Figure 3.11a).

*Diel Fidelity Patterns*

Weakfish displayed daily patterns of fidelity to their tagging sites or new core areas during both the summer and fall. During summer, eight weakfish (n=154 total contacts) were detected on more than one occasion during diel tracking (code 100 was
detected only once and not included in subsequent analyses) and most fish exhibited a
diel periodicity of daytime fidelity to their original tagging site followed by nightly
movements beginning around sundown (Table 3.3; Figure 3.14). Weakfish maintained
fidelity less than 0.5 km from the tagging site (mean: 0.30 km) during the day and moved
significantly further from that site during dusk and nighttime (mean: 1.37 km; $U_{0.05(2),8,6}$,
P=0.002) although distances varied between individuals (Figure 3.15). No weakfish were
ever detected within 0.5 km of their tagging site after 22:30 throughout the study period.
The highest peaks in drumming occurred during the early morning and mid-afternoon
periods and were not directly associated with an increase or decrease in distance from the
tagging site (Figure 3.15). In general, fish were found in shallower depths during
nighttime sampling, although other environmental variables (temperature, salinity,
dissolved oxygen) were higher during that time (Figure 3.16).

During fall tracking, four weakfish were tracked (n=58 total contacts) with one
weakfish (Fish 50) detected during multiple tracking events in Little Sheepshead Creek
and three fish detected on only one occasion (Table 3.3). All fish remained within close
proximity to either their original tagging site or newly established core area during the
day (mean: 0.47 km), with the exception of code 64 (also tracked during the summer)
who was detected at a site (mean distance from tagging site: 1.24 km) not previously
occupied (see “Seasonal Fidelity Patterns” section) (Table 3.3). Although crepuscular
and nighttime movements were not observed in the fall, one individual (Fish 50) was
tracked moving into a shallow intertidal creek in Little Sheepshead Creek around
sundown but detection could not be maintained due to shallow water depths. Although
anecdotal, these movements suggest a similar day-night shift in the fall months.
DISCUSSION

With the exception of extensive work on juvenile weakfish, intra-estuarine movements of adults has been less understood, especially at smaller spatial scales and within smaller estuarine systems. Although site fidelity has been observed in other fish species, as well as on a regional scale for weakfish, these results represent new evidence to the affinity of weakfish to specific estuarine habitats. In addition, the reproductive phenology of weakfish may be an important factor in when/where/how weakfish utilize those fine-scale habitats.

Response to Tagging

A primary assumption when conducting any field telemetry study is that tagging does not affect natural fish behavior (Jepsen et al. 2008). In this study, weakfish behavior may have been modified in some individuals based on their rapid upriver movement to and the short residency times at hydrophone 7 in the Mullica River. With the overall limited use of upriver habitat seen in weakfish during this study (see Chapter 2 section on Habitat Use), the timing and duration of these movements suggests a post-tagging response. While this behavior was only observed in several individuals, the approach (passive telemetry) used to assess fish response to tagging limited the scope of observation to areas where hydrophones were present, possibly missing movements of other tagged fish. The high percentage of these fish that left the system permanently suggests that tagging may influence fish behavior beyond just smaller scale estuarine movements and could affect the residency patterns of tagged fish. Post-tagging movements have previously been noted in anadromous fishes (alosids: Olney et al. 2006; salmonids: Bernard et al. 1999) and are generally characterized by “fall-back” behavior
(directed movement downstream during an upriver spawning run). Unfortunately, the parsing of tagging effects from natural behavior is experimentally difficult to conduct (Frank et al. 2009) and the argument could be made that fish would display these observed behaviors independent of tagging (e.g. as they were normally moving upstream). One method to reduce uncertainty of tagging influences is to censor data from fish for a short period of time following release (Rogers and White 2007). In this study, mobile telemetry sampling occurred on a weekly basis, naturally increasing the time between release and first contact and censoring potentially biased data. In any case, these results indicate that the influence of tagging should remain a primary concern for researchers studying animals, including weakfish, using telemetry methods and further work should be done to elucidate the presence and/or degree of these effects.

**Seasonal Site Fidelity**

Both methods used to assess seasonal site fidelity suggest that weakfish exhibit varying degrees of close association with small-scale estuarine habitats during both the reproductive and post-reproductive seasons. An increase in weekly movements after the reproductive season was seen in fish tracked with mobile telemetry, although individual variation was apparent and several fish remained highly localized following the spawning season. Further, the single fish tagged at Main Marsh Thorofare (Fish 103) in July 2007 and monitored using passive telemetry showed a higher degree of site fidelity to its tagging area than all the fish tagged in August when the reproductive season was over. With such a low sample size (n=1), however, it is difficult to determine what influenced this difference. It is also problematic to describe fine-scale spatial dynamics when utilizing only one stationary hydrophone. For those fish tagged in the vicinity of
hydrophone 13 at Main Marsh Thorofare, it is probable that detection rates were low for most individuals because their core area was just outside the listening range of the hydrophone. An advantage to using presence/absence at a stationary hydrophone over weekly mobile telemetry was that it allowed a finer-scale temporal resolution of fidelity to the tagging area. The low, but persistent, number of detections seen at hydrophone 13 may indicate a more realistic picture of how weakfish used their core areas. The “snapshot” of site fidelity provided by weekly mobile telemetry does not account for the extent of movements between detections.

Little previous work has been done on intra-estuarine movements and site fidelity of adult weakfish, although a multi-species acoustic telemetry study conducted in a northern New Jersey estuary showed evidence of localized movements and establishment of home ranges in a smaller number (n=15) of tagged weakfish (Manderson et al. 2007). Unlike the Mullica River-Great Bay system, the study area (Navesink River) was characterized as a narrow (maximum 1.5 km wide) tributary to the Raritan estuary and, therefore, a more urbanized and impacted system. Because of these divergent characteristics, comparisons between the two systems were difficult to make; however, some similarities were noted. Although detections in the present study were made on a weekly scale, individual variation was similarly high to the variation in mean daily ranges of upstream/downstream movements (approximately 0.25 to 3.4 km) seen among tagged weakfish in the Navesink River. Episodic events, such as storms, may also influence movements in weakfish. On a daily to weekly scale, weakfish in the Navesink River shifted (>2.5 km) to new home ranges or returned to previous ones following an increase in freshwater discharge, a predictor of salinity. Similar movements to previously
established core areas were observed in tagged individuals in the Mullica River-Great Bay after a storm event in late September 2008. While weakfish sex was an indicator of movement patterns in the Mullica River-Great Bay system, the relationship could not be established by Manderson et al. (2007) because sex data was not available. A difference in analysis techniques also confounds a thorough comparison between these two studies. Quantifying the breadth of movements in animals has traditionally been accomplished by calculating home ranges, as seen in Manderson et al. (2007). A proper analysis of home range could not be undertaken in this study, however, because of a lack of consecutive detections in tagged weakfish which would have increased uncertainty in the estimations of home range (Rogers and White 2007).

In the previous chapter, weakfish movements were analyzed in relation to the reproductive period. Observations indicated that weakfish had the lowest redetection rates in August following the end of spawning. In the context of the site fidelity patterns observed in this portion of the study, periods of non-detection were sometimes followed by returns to core areas. Although analyses did not account for these periods of non-detection, it should be noted that weakfish might have made longer excursions from their core areas than reported due to the inability to detect individuals on a weekly basis. As mentioned previously, further investigation into subtidal creek habitat use may shed light on these periodic movements.

Although sample sizes were too low to evaluate the mixed effects of sex and season/location/time of day of capture, the observed patterns suggest that singular relationships between these variables and seasonal site fidelity patterns may exist. The most striking variation was seen in the high proportion of male weakfish that established
new core areas, while most females remained at their original tagging site. The majority of male weakfish established new core areas near the end of or after the spawning season, suggesting that the shift may have been related to reproduction. However, few of these fish were observed for long periods during the spawning season, making comparisons difficult. For the fish that were observed to shift to new core areas in late July, the impetus for movement may have been related to a search for new spawning grounds. Otherwise, changes in habitat, home range, and core areas not related to ontogenetics (life-cycle changes) are generally made in response to unfavorable environmental conditions and potentially density dependent intra- or inter-specific interactions (Pittman and McAlpine 2003). The time of day of capture also appeared to influence subsequent seasonal fidelity patterns. With the diel observations of fidelity observed in this study (see section below), it is probable that the capture location of weakfish during the early morning or evening hours may inaccurately reflect their daily core area. If fish were captured while still within a nighttime excursion or en route to daytime habitat, an observed shift in core areas may simply be a function of a natural return to their true core area. In further studies of small-scale weakfish habitat dynamics, especially site fidelity, variables such as these should be noted and, potentially, accounted for.

Seasonal or long-term site fidelity to small-scale habitats has been evident in a number of freshwater (e.g. arctic grayling: Buzby and Deegan 2000), marine (e.g. blue trevally: Holland et al. 1996), and estuarine (e.g. red drum: Dresser and Kneib 2007) fish species. Others exhibit temporal site fidelity during specific life history events, such as reproduction (plaice: Solmundsson et al. 2005; common snook: Adams et al. 2009). With evidence that weakfish display similar fidelity during a portion of their spawning period,
more work should be done to delineate the mechanisms surrounding this behavior. One step would be to reexamine the previous model of natal homing in adult weakfish (Thorrold et al. 2001) at smaller spatial scales.

In the Mullica River-Great Bay system, prior investigations of habitat dynamics in striped bass (Ng et al. 2007) and summer flounder (Sackett et al. 2008) revealed both intra- and inter-annual attachment to fine-scale habitats. In both studies, fish were tagged with multi-year transmitters allowing for detection the following season and found to home back to areas within 0.55 km of their previous locales in the study area. On the other end of the spectrum, bluefish were also examined using similar telemetry methods but did not display site fidelity at either the estuary-scale (between years) or the small-scale (within years) (Grothues and Able 2007). The long-term spatial memory needed to enable a fish to return ("home") back to relatively small areas (Fukumori et al. 2010) on a yearly basis was not observed in weakfish (see Chapter 2), but a similar ability to relocate core areas within a season was evident in several individuals.

Diel Site Fidelity

A broad base of prior work has assessed the diel nature of weakfish behavior, largely due to their conspicuous drumming behavior, but few studies have combined individual fish movements at the diel scale. In this study, a distinct pattern of diurnal movement was observed in the subset of tagged weakfish during both the summer and fall study periods. In the fall, the limited movements of weakfish during the daylight hours suggest that they may maintain similar small-scale temporal fidelity to their core areas throughout residency within the estuary. This was made more apparent in the diel tracking of one fish when small-scale movements were limited during both seasons.
Although movements increased, on average, in fish after the reproductive season (see Chapter 2 section on Movement), at least some individuals maintained highly localized core areas. In the summer, which coincided with the last part of the spawning period (July), weakfish exhibited nightly movements from their daytime core area. Initiation of movement from the core area seemed to relate to lower light levels and, more specifically, the nighttime crepuscular period, which is also the period when peak weakfish spawning has been shown to occur (Taylor and Villosolo 1994). While an increase in drumming behavior of male weakfish has been used as a proxy for peak nighttime spawning in several diel studies (e.g. Connaughton and Taylor 1995), a similar peak was not seen in the drumming indices during this study. The two largest peaks in drumming (early morning and late afternoon) did not coincide with the onset of movement during sundown but rather during periods when fish were maintaining fidelity to their daytime core area. The traditional understanding that weakfish may use drumming as a method to attract other males and females to spawning aggregations (Connaughton and Taylor 1996) seems to contradict the present data where drumming activity was highest when groups were already aggregated. Other studies confirm some of the observations of movement during the sundown period. In an evaluation of diel weakfish reproductive condition in Delaware Bay, Connaughton and Taylor (1994) noted that fish were frequently caught in gill-nets during the early evening hours with their heads facing inshore (presumably pre-spawning) and in the later evening (presumably post-spawning) with their heads facing offshore indicating direction of movement at capture. Although inshore/offshore movements are relative to the study area in question, weakfish in the current study were seen in shallower depths following movement after
sundown, which may serve a similar purpose. Furthermore, the authors noted that few fish were caught during the early morning and early afternoon, likely the time when weakfish decreased their movements. Related to these observations, Connaughton and Taylor (1995) also examined the drumming pattern of weakfish in relation to the inshore-offshore spectrum and consistently noted the highest level of spawning vocalizations inshore. The nightly movement of weakfish in this study to shallower (inshore) depths corroborates their findings, but the pattern of drumming does not. Therefore, further delineation of these behaviors should be sought. The only other investigation of daily movements in adult weakfish took place within the Navesink River (Manderson et al. 2007), where weakfish exhibited a varying pattern of tidal- and diel-influenced movements. Although individual variation was high, the authors noted a pattern of directed downriver movement from their daytime home range at night followed by a return during the daylight hours. Reproductive behavior was not included in their analyses, so the timing of movements in relation to the crepuscular period cannot be addressed here.

The limited spatial sampling at night prohibited any assumptions about nocturnal fidelity patterns. Although a high percentage of fish left the diel study area at night and were not detected until the following daytime sampling event, several individuals were redetected in small areas following movement away from the tagging site and this may suggest a shift to new nightly core areas. Alternatively, the movement of some fish outside the study area may indicate non-directed foraging behavior, in contrast to aggregative spawning groups, that did not result in the establishment of new areas of fidelity. A previous investigation of nighttime utilization of subtidal creeks in the study
area by weakfish hinted at the possible use of these habitats for nighttime feeding excursions on high tides (Rountree and Able 1997).

The recognition of a diel pattern of movement and site fidelity places weakfish within the spectrum of a wide-range of fishes exhibiting similar, although variable, behavior. Two distinct groupings of diel fish movements are prevalent in the literature: 1) fish increase their activity space and movements at night (Ackerman et al. 2000; Luo et al. 2009) or 2) fish increase their activity space and movements during the day (Topping et al. 2005; Dresser and Kneib 2007; March et al. 2010). In some cases, individuals within a species displayed both patterns (Abecasis and Erzini 2008; Ortega et al. 2009). With evidence that weakfish fall into the first category, it is important to understand the mechanisms behind this behavior. While this study was not designed to explore causal relationships, it can be hypothesized that the movements may be related to reproductive and/or foraging behavior, but further work in this area is warranted.

In sum, patterns of site fidelity at multiple temporal scales (seasonal and diel) revealed that weakfish maintain close habitat associations at more than just the regional level observed in other studies (Thorrold et al. 2001). The differential scales at which crucial life history characteristics occur in weakfish and the prevalence of these small-scale behaviors in other economically and ecologically important species within the same study area (i.e. striped bass and summer flounder) indicates that 1) fisheries management should directly address the implications of small-scale behaviors in the regulatory process and 2) subsequent scientific investigations should explore these behaviors further, especially accounting for the influence of scale (temporal and spatial) in study designs.
Table 3.1  Weekly detection history and characteristics of seasonal site fidelity in weakfish acoustically tagged in the Great Bay-Mullica River estuary during 2008 for the seasonal site fidelity component of the study.  See Figure 3.1 for tagging locations. SE=standard error of the mean.

<table>
<thead>
<tr>
<th>Fish ID</th>
<th>Length (mm TL)</th>
<th>Sex</th>
<th>Date Tagged</th>
<th>Capture Time</th>
<th>Tagging Location</th>
<th>First Detection</th>
<th>Last Detection</th>
<th>Time Between Tagging and First Detection (Weeks)</th>
<th>Number of Weeks Detection</th>
<th>Proportion of Weeks Detected</th>
<th>Number of Core Areas (1=include original tagging location)</th>
<th>Duration in Core Areas (Works)</th>
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Table 3.1 (continued)  Weekly detection history and characteristics of seasonal site fidelity in weakfish acoustically tagged in the Great Bay-Mullica River estuary during 2008 for the seasonal site fidelity component of the study. See Figure 3.1 for tagging locations. SL=standard error of the mean.

<table>
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<th>Tagging Location</th>
<th>First Detection</th>
<th>Last Detection</th>
<th>Time Between Tagging and First Detection (Weeks)</th>
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<th>Number of Core Areas (T=include original tagging location)</th>
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<td>418</td>
<td>M</td>
<td>6/30/2008</td>
<td>09:00</td>
<td>Deep Point</td>
<td>6/10/2008</td>
<td>8/13/2008</td>
<td>0.0</td>
<td>7.9</td>
<td>7</td>
<td>0.76</td>
<td>1</td>
<td>0.9</td>
<td>7</td>
</tr>
<tr>
<td>163</td>
<td>406</td>
<td>F</td>
<td>9/11/2008</td>
<td>03:23</td>
<td>Marshfield Channel</td>
<td>9/28/2008</td>
<td>11/4/2008</td>
<td>2.1</td>
<td>5.6</td>
<td>4</td>
<td>0.67</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>704</td>
<td>457</td>
<td>F</td>
<td>6/25/2008</td>
<td>00:00</td>
<td>Deep Point</td>
<td>7/1/2008</td>
<td>7/1/2008</td>
<td>0.9</td>
<td>0.0</td>
<td>1</td>
<td>1.00</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Range</td>
<td>253 - 591</td>
<td></td>
<td>6/11/2008 -</td>
<td>06:00 - 5/00</td>
<td>-</td>
<td>6/25/2008 - 7/1/2008</td>
<td>0 - 4.9</td>
<td>0 - 10.1</td>
<td>0 - 13</td>
<td>0.00 - 1.00</td>
<td>0 - 2</td>
<td>0.9 - 4.9</td>
<td>2 - 6</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>401 +/- 15 (SE)</td>
<td></td>
<td>6/11/2008 -</td>
<td>06:00 - 5/00</td>
<td>-</td>
<td>6/25/2008 - 7/1/2008</td>
<td>1.1 +/- 0.2 (SE)</td>
<td>6.7 +/- 0.8 (SE)</td>
<td>1 +/- 1 (SE)</td>
<td>0.5 +/- 0.0 (SE)</td>
<td>2.3 +/- 0.3 (SE)</td>
<td>1 +/- 0.1 (SE)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3.2: Detection history and characteristics of individual weakfish acoustically tagged at Main Marsh Thorofare near Hydrophone 13 (see Fig. 3.7A) during summer 2007 for the seasonal site fidelity component of the study. All fish, unless indicated (*), were caught and released during the same tagging event on August 1, 2007. SE=standard error of the mean.

<table>
<thead>
<tr>
<th>Fish ID</th>
<th>Length (mm TL)</th>
<th>First Detection</th>
<th>Last Detection</th>
<th>Duration (Days)</th>
<th>Number of Detections</th>
<th>Proportion of Days Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>134</td>
<td>311</td>
<td>8/1/2007</td>
<td>8/6/2007</td>
<td>6</td>
<td>765</td>
<td>1.00</td>
</tr>
<tr>
<td>144</td>
<td>330</td>
<td>8/1/2007</td>
<td>9/26/2007</td>
<td>57</td>
<td>4416</td>
<td>0.35</td>
</tr>
<tr>
<td>145</td>
<td>405</td>
<td>8/1/2007</td>
<td>8/22/2007</td>
<td>22</td>
<td>802</td>
<td>0.23</td>
</tr>
<tr>
<td>146</td>
<td>324</td>
<td>8/1/2007</td>
<td>10/15/2007</td>
<td>76</td>
<td>8984</td>
<td>0.71</td>
</tr>
<tr>
<td>148</td>
<td>292</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>193</td>
<td>298</td>
<td>8/1/2007</td>
<td>9/29/2007</td>
<td>60</td>
<td>2498</td>
<td>0.28</td>
</tr>
<tr>
<td>194</td>
<td>311</td>
<td>8/7/2007</td>
<td>10/29/2007</td>
<td>84</td>
<td>2914</td>
<td>0.29</td>
</tr>
<tr>
<td>200</td>
<td>349</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>208</td>
<td>381</td>
<td>8/1/2007</td>
<td>9/19/2007</td>
<td>50</td>
<td>1245</td>
<td>0.32</td>
</tr>
<tr>
<td>103*</td>
<td>434</td>
<td>7/19/2007</td>
<td>9/2/2007</td>
<td>46</td>
<td>49779</td>
<td>0.98</td>
</tr>
<tr>
<td>Mean</td>
<td>344 +/- 14 (SE)</td>
<td>-</td>
<td>-</td>
<td>50 +/- 9 (SE)</td>
<td>8888 +/- 59731 (SE)</td>
<td>0.52 +/- 0.17 (SE)</td>
</tr>
</tbody>
</table>
Table 3.3 Detection history and characteristics of acoustically tagged weakfish tracked during the diel component of the study. See Table 3.1 for locations of tagging sites (C,D,E); Figure 3.1 for map of locations where weakfish were tracked; and Figure 3.2B for locations of mobile tracking points at Deep Point (lower Mullica River). Mobile tracking in the summer took place from 6/20/2008 to 7/31/2008 and in the fall from 10/1/2008 to 10/14/2008. Fish with no more than one detection (*) during the study periods were not used in subsequent analyses. SE=standard error of the mean.

<table>
<thead>
<tr>
<th>Fish ID</th>
<th>Length (mm TL)</th>
<th>Sex</th>
<th>Tagging Location</th>
<th>First Detection</th>
<th>Last Detection</th>
<th>Number of Tracking Events Detected</th>
<th>Total Day/Night Contacts</th>
<th>Mean Distance (km) from Tagging Site (Day/Night)</th>
<th>Location Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>496</td>
<td>M</td>
<td>Deep Point</td>
<td>7/22/2008</td>
<td>7/31/2008</td>
<td>5</td>
<td>14/1</td>
<td>0.20/1.24</td>
<td>Deep Point - C</td>
</tr>
<tr>
<td>54</td>
<td>337</td>
<td>F</td>
<td>Deep Point</td>
<td>7/17/2008</td>
<td>7/31/2008</td>
<td>6</td>
<td>20/4</td>
<td>0.21/1.10</td>
<td>Deep Point - C</td>
</tr>
<tr>
<td>100*</td>
<td>413</td>
<td>F</td>
<td>Deep Point</td>
<td>7/22/2008</td>
<td>-</td>
<td>1</td>
<td>0/1</td>
<td>-/1.36</td>
<td>Deep Point - C</td>
</tr>
<tr>
<td>103</td>
<td>571</td>
<td>M</td>
<td>Deep Point</td>
<td>6/30/7068</td>
<td>7/30/7068</td>
<td>5</td>
<td>75/1</td>
<td>0.40/7.77</td>
<td>Deep Point - C</td>
</tr>
<tr>
<td>136</td>
<td>540</td>
<td>F</td>
<td>Deep Point</td>
<td>7/17/2008</td>
<td>7/31/2008</td>
<td>6</td>
<td>19/6</td>
<td>0.30/1.49</td>
<td>Deep Point - C</td>
</tr>
<tr>
<td>151</td>
<td>502</td>
<td>F</td>
<td>Deep Point</td>
<td>7/10/2008</td>
<td>7/31/2008</td>
<td>8</td>
<td>24/11</td>
<td>0.28/0.86</td>
<td>Deep Point - C</td>
</tr>
<tr>
<td>167</td>
<td>438</td>
<td>M</td>
<td>Deep Point</td>
<td>6/30/7068</td>
<td>7/10/2008</td>
<td>2</td>
<td>7/0</td>
<td>0.55/-</td>
<td>Deep Point - C</td>
</tr>
<tr>
<td>204</td>
<td>497</td>
<td>F</td>
<td>Deep Point</td>
<td>6/30/2008</td>
<td>-</td>
<td>1</td>
<td>10/0</td>
<td>0.44/-</td>
<td>Deep Point - C</td>
</tr>
</tbody>
</table>

**Range**
- 337-540
- 6/30/2008 - 7/10/2008

**Mean**
- 461 +/- 24 (SE)
- 6/30/2008 - 7/10/2008

**FALL**

<table>
<thead>
<tr>
<th>Fish ID</th>
<th>Length (mm TL)</th>
<th>Sex</th>
<th>Tagging Location</th>
<th>First Detection</th>
<th>Last Detection</th>
<th>Number of Tracking Events Detected</th>
<th>Total Day/Night Contacts</th>
<th>Mean Distance (km) from Tagging Site (Day/Night)</th>
<th>Location Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>305</td>
<td>F</td>
<td>Little Sheephead Creek</td>
<td>10/1/2008</td>
<td>10/14/2008</td>
<td>3</td>
<td>31/0</td>
<td>0.31/1.0</td>
<td>Little Sheephead Creek - D</td>
</tr>
<tr>
<td>54</td>
<td>337</td>
<td>F</td>
<td>Deep Point</td>
<td>10/17/2008</td>
<td>-</td>
<td>1</td>
<td>6/0</td>
<td>1.24/-</td>
<td>Deep Point - C</td>
</tr>
<tr>
<td>75</td>
<td>279</td>
<td>F</td>
<td>Little Sheephead Creek</td>
<td>10/7/2008</td>
<td>-</td>
<td>1</td>
<td>10/0</td>
<td>0.16/-</td>
<td>Little Sheephead Creek - D</td>
</tr>
<tr>
<td>138</td>
<td>432</td>
<td>M</td>
<td>Little Sheephead Creek</td>
<td>10/9/2008</td>
<td>-</td>
<td>1</td>
<td>11/0</td>
<td>0.19/-</td>
<td>Lower Great Bay - F</td>
</tr>
</tbody>
</table>

**Range**
- 279-432
- 10/1/2008 - 10/14/2008

**Mean**
- 338 +/- 33 (SF)
- 10/17/2008

- 2 +/- 1 (SF)
- 15 +/- 6 (SF)/0
- 0.47 +/- 0.76 (SF)/-
Figure 3.1: Location of sub-areas within the Mullica River-Great Bay estuary for the seasonal (A,B) and diel (C,D,E) components of the study in 2007 and 2008. Estuarine bathymetry data was rasterized from NOAA soundings data.

Figure 3.2: Sampling locations within the Mullica River-Great Bay estuary for the post-tagging movement and seasonal/diel study components in 2007 and 2008. A) Locations of stationary (passive) telemetry hydrophones used to evaluate movement after tagging (2007 and 2008), including hydrophone 13 at Main Marsh Thorofare (see inset) where seasonal site fidelity was monitored in 2007. The sites of both the JCNERR SWMP water quality data loggers and meteorological station are depicted. B) Locations of standardized distribution (mobile) telemetry sampling points (n=120; bay and river points are delineated) used in the seasonal site fidelity study during 2008 and the sub-sites (square boxes) used to evaluate diel movement in both the summer and fall of 2008. The inset of Deep Point in the lower Mullica River shows locations of standardized points visited for the summer diel tracking study.

Figure 3.3: Variation in passive and mobile diel tracking telemetry efforts. A) Yearly variation in stationary hydrophone deployment during 2007 and 2008 (see Fig. 3.2A for locations of stationary hydrophones). Hydrophone status signals were used as a proxy for sampling effort/deployment. Thick black lines indicate reception of a status signal (code 211) from the deployed hydrophone and thin lines represent times when hydrophones were not deployed or not functioning during deployment. Hydrophone 10 could not receive status signals so the time that the hydrophone was actively deployed and functioning properly was binned by day and used as the metric for effort. B) Seasonal (summer and fall) and daily variation in effort during mobile diel tracking (see Fig. 3.1 for tracking locations represented by letters on the y-axis). Circled times denote samples that overlapped with the nighttime period (19:30-04:29).

Figure 3.4: Representative movement plot of an individual weakfish (code 79) detected in the vicinity of hydrophone 7 shortly following release (April 30, 2007) (see Fig. 3.1 for locations of all deployed stationary hydrophones). Circles represent the number of contacts within a 15-minute time bin. For scaling purposes, hydrophone 13 was assigned the number 4.5 shown on the y-axis.

Figure 3.5: Mobile telemetry detections of weakfish displaying seasonal site fidelity to their original tagging locations (with no intermediate relocations outside 0.5 km) at A) Deep Point (lower Mullica River) and B) the western side of Little Sheepshead Creek (n=2 fish) (see Fig. 3.1 for locations and interpretation of bathymetry contours). Stars represent tagging sites (see Table 3.1 for release dates) and solid circled contacts are detections that fit the criteria for site fidelity.

Figure 3.6: Mobile telemetry detections of weakfish displaying seasonal site fidelity to newly established “core areas” (with no intermediate relocations outside 0.5 km) at A) Main Marsh Thorofare; B) Big Creek; and C) the lower Mullica River (see Fig. 3.1 for locations and interpretation of bathymetry contours). Stars represent tagging sites (see
Table 3.1 for release dates) and solid circled contacts are detections that fit the criteria for site fidelity.

Figure 3.7: Mobile telemetry detections of weakfish making excursions from original tagging sites to A) the Mullica River; B) Marshelder Channel; C) and various locations within the lower Mullica River and Great Bay (see Fig. 3.1 for locations and interpretation of bathymetry contours). Fish 62 (shown in A) was the only fish that did not fit the criteria for site fidelity at its tagging site but movement to a new core area (circled) was followed by a detection at the original tagging area. Stars represent tagging sites (see Table 3.1 for release dates) and solid circled contacts are detections that fit the criteria for site fidelity.

Figure 3.8: Mobile telemetry detections of weakfish making excursions from new core areas to various locations within Great Bay (A,B,C). Fish 137 (shown in B) had also previously established site fidelity at its original tagging location at Deep Point (lower Mullica River) (see Fig. 3.1 for locations and interpretation of bathymetry contours). Stars represent tagging sites (see Table 3.1 for release dates) and solid circled contacts are detections that fit the criteria for site fidelity. Dashed circles encompass all other detections outside the established core area.

Figure 3.9: Variation in seasonal movement from core areas (shown as distance in km; June-November 2008) for individual fish that A) maintained fidelity to tagging site and made excursions from their B) tagging location or C) new core area. The first point for each individual weakfish line plot are initial distances (0 km) from either the original tagging site (A,B) or the median date of all consecutive contacts within the new core area (C). The area below the horizontal gray line (dashed) indicates distances (<0.5 km) within the defined core area.

Figure 3.10: Principal components analysis (PCA) of select water quality and meteorological variables during the extent of tagged weakfish residency in the study area (June 15-November 15, 2008). A) Biplot of axis 1 and axis 2 principal components. B) Seasonal variation in PCA scores (axes 1 and 2). Arrows show distinct peaks in PCA scores occurring during late September associated with a coastal storm event. Water quality variables were from the JCNERR Buoy 139 data logger in Great Bay and meteorological variable were from the JCNERR meteorological station at the Richard Stockton College of New Jersey (see Fig. 3.2A for locations).

Figure 3.11: Daily variation in the proportion of contacts from individual weakfish tagged in the vicinity of hydrophone 13 (near Main Marsh Thorofare on A) August 1 and B) July 19 in 2007. Cross symbols represent proportion of pooled contacts at all other stationary hydrophones in the study area (see Fig. 3.2A for all hydrophone locations).

Figure 3.12: Frequency (as a proportion of total) of the daily proportion of detections at hydrophone 13 for weakfish tagged near hydrophone 13 (Main Marsh Thorofare) on August 1 (n=7 fish) (See Fig. 3.2A for hydrophone location).
Figure 3.13: Representative movement plots of weakfish displaying two patterns of movement (to other stationary hydrophones) from their tagging site near hydrophone 13 (Main Marsh Thorofare). (A) Weakfish (fish 208) showing intermediate detection at hydrophone 13 with movement to hydrophone 4 (Grassy Channel) before final emigration from the study area. (B) Weakfish (fish 146) showing consistent detections at hydrophone 13 with short-duration excursions to hydrophone 4. Final emigration from the study area was likely through Main Marsh Thorofare. See Fig. 3.1 and 3.2A for locations. Circles represent the number of contacts within a 15-minute time bin. For scaling purposes, hydrophone 13 was assigned the number 4.5 shown on the y-axis.

Figure 3.14: Cumulative mobile telemetry detections of tagged individual weakfish at Deep Point (lower Mullica River) during the day (n=119) and night (n=35) periods from June 30 to July 31, 2008 (see Fig. 3.1 for interpretation of bathymetry contours and Fig. 3.2B for sampling locations).

Figure 3.15: Hourly variation in distance from tagging site and drumming index for individual weakfish tracked using mobile telemetry for diel component of study. All weakfish (n=8) were originally tagged at Deep Point (lower Mullica River) and distances (km) were pooled and averaged by hour for each fish. Drumming indices were pooled and averaged across individuals. Light gray boxes represent dawn (04:30-05:30) and dusk (19:30-20:30) periods, and dark gray boxes depict the sundown to sunrise periods (20:30-04:30). See Fig. 3.2B for sampling locations. The area below the horizontal gray line (dashed) indicates distances (<0.5 km) within the defined core area.

Figure 3.16: Principal components analysis (PCA) biplot (axes 1 and 2) of environmental variables and distance (km) from tagging site for individual weakfish detected during mobile diel tracking events in summer 2008 (June 30-July 31) at Deep Point (lower Mullica River) (n=112 total samples). Total photosynthetically active radiation (PAR) was included as a supplementary variable and does not influence the PCA scores. White circles represent daytime (04:30-17:29) samples and black circles represent nighttime (17:30-04:29) samples. See Fig. 3.2B locations.
Figure 3.2
Figure 3.3
Figure 3.5

A

Fish 151
7/2/2008 - 8/5/2008

B

- Fish 50
- Fish 75
8/22 - 9/3
9/18 - 9/23
9/18 - 10/8

0.5 Km

0 0.1 0.2 Km
Figure 3.6
Figure 3.7
Figure 3.8
Figure 3.9
Figure 3.10
Figure 3.11
Figure 3.12
Figure 3.13
Figure 3.14
Figure 3.15
Figure 3.16
Weakfish caught near Great Bay, New Jersey (July 28, 1899)

(Courtesy of the Tuckerton Historical Society)
These findings represent new insights into the interactions of adult weakfish with their environment. Overall, the study elucidated several important aspects of weakfish habitat ecology: 1) estuaries play a role in the life history of adult weakfish during and after the spawning season; 2) restricted spatial use of estuaries may indicate a narrow tolerance to particular habitat types; 3) shifts in habitat use may occur with regard to the reproductive season (i.e. movement in subtidal creeks); 4) small-scale site fidelity in weakfish (at the seasonal and diel scale) may indicate the importance of microhabitats in weakfish.

Although this study was one of the first attempts to quantify various aspects of adult weakfish habitat dynamics, more work should be done to make these results clearly applicable to future management plans. Emigration, residency, and movements, as well as delineation of preferred habitats, are important parts of weakfish ecology that could influence how they are subsequently managed, especially in the context of ecosystem-based management plans. For instance, timing of movement and emigration from the estuary could influence our perception of the health of the weakfish population because stock assessment surveys usually occur during relatively constricted time periods (i.e. Fall) and in spatially restricted areas (i.e. inner continental shelf). If a majority of fish either moved from or still remain within estuary habitats during these periods, a quantitative assessment of the population may show varying results (Sackett et al. 2007). Another facet of weakfish ecology, site fidelity, could also enhance our ability to understand weakfish population dynamics. With the high incidence of weakfish site
fidelity to small-scale habitats seen in this study, individual turnover rates at these sites appears to be low, making localized depletion of these fish more likely. In the case of larger, more fecund fish, this localized depletion could manifest itself in more profound at the population level.

Although patterns were observed between and among years for both components of the study, a high degree of individual variation was seen in tagged fish. Therefore, these results suggest that undertaking a weakfish telemetry study may require thorough control of a multitude of intrinsic (sex, size) and extrinsic (date/time/location/season of tagging) factors to better elucidate habitat dynamics. While this study did not account for all of these variables, the results suggest that some of the variation seen may be due to confounding factors such as these. The results also suggest that a prior understanding of scale (both temporal and spatial) is necessary to formulate proper research questions about weakfish residency, habitat use, movements, and site fidelity.

This study also demonstrates that weakfish are amenable to acoustic telemetry techniques utilizing the tagging and tracking methods previously discussed. The observed tag loss (from either mortality or shed tags) in these fish was relatively low (<10%), although the loss of tags following the study could not be determined. In addition, a greater number of tagged fish (9 out of 59) were never redetected following their release, which could indicate tag loss in unmonitored portions of the study area.

Previous mark-recapture studies of weakfish have proven relatively unsuccessful due to apparent shedding of external tags (i.e. t-bar; John Clark, DNREC, pers. comm.). Similar problems may have occurred in this study because very few fish were reported as recaptured based on visual identification of the external marker tag. However, the two
fish that were reported in 2007 had both shed their external tags and were identified by the acoustic transmitter within their stomach cavity. Based on these observations, traditional mark-recapture studies may be limited by weakfish’s ability to shed tags easily rather than mortality associated with tagging. Therefore, the ability to successfully implant acoustic receivers in adult weakfish and track them for relatively long periods of time (>3 months) is encouraging for future work studying weakfish movements.

In sum, the recent concern over the health of the Atlantic coast weakfish stock (ASMFC 2009) should be an impetus to fill the basic knowledge gaps in the life history of this economically and ecologically important species. Without doubt, the effects of directed fishing, and perhaps natural mortality (Kahn et al. 2006), should be a management priority in recovering weakfish stocks. As a coastal species, however, weakfish are directly affected by the rapid environmental change occurring along coastal habitats, specifically estuaries. Both significant and minor changes in how, when, and where weakfish utilize habitats effects how both fisheries and humans interact with the species. When temporal changes in habitat dynamics are a result of reproductive phenology, the outcome could have an even more significant impact on the health of the species. Beginning to understand the importance of estuarine habitat in general and habitat dynamics within estuaries in particular will likely lead to better long-term management practices and weakfish stock health.
LITERATURE CITED


