Movement Patterns and Catch-and-Release Impacts of Striped Bass in a Tidal Coastal Embayment in Massachusetts

Heather M. Tyrrell

University of Massachusetts Amherst

Follow this and additional works at: https://scholarworks.umass.edu/theses

Part of the Aquaculture and Fisheries Commons, Marine Biology Commons, and the Terrestrial and Aquatic Ecology Commons


Retrieved from https://scholarworks.umass.edu/theses/1205
MOVEMENT PATTERNS AND CATCH-AND-RELEASE IMPACTS OF STRIPED BASS IN A TIDAL COASTAL EMBAYMENT IN MASSACHUSETTS

A Thesis Presented

by

HEATHER MARIE TYRRELL

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

MASTER OF SCIENCE

February 2014

Intercampus Marine Science Graduate Program
MOVEMENT PATTERNS AND CATCH-AND-RELEASE IMPACTS OF STRIPED BASS IN A COASTAL TIDAL BAY IN MASSACHUSETTS

A Thesis Presented

By

HEATHER MARIE TYRRELL

Approved as to style and content by:

__________________________, Chair

Andy Danylchuk

__________________________, Member

Stephen McCormick

__________________________, Member

Greg Skomal

__________________________________________________

Curt Griffin, Department Head

Environmental Conservation
ACKNOWLEDGEMENTS

Without the help of key individuals, this project would not have been possible. A special thank you is in order for Andy Danylchuk, Stephen McCormick, and Greg Skomal for serving on my committee and providing scientific and mental support. Utmost thanks are also in order to Jeff Kneebone, for his patient guidance throughout the entire study and allowing me to pepper him with questions.

I would like to express thanks to the Duxbury Yacht Club, and in particular Jon Nash, as well as, Steve O’Brien for their fishing expertise and excitement about the project. I am very grateful to the Massachusetts Division of Marine Fisheries for providing a boat and the majority of the receiver array. Thank you to the Conte Anadromous Fish Research Lab, especially Amy Regish, for patiently teaching me how to run cortisol and ion assays. I would also like to thank all of those who provided detection data.

Thank you in no particular order, to John Chisholm, for help in the field, Heather Marshall, for helping me to run my blood samples, as well as, Erin Snook and Cristina Kennedy. Lastly, thanks to all of my family and friends for their love, support, and for tolerating my life-long obsession with marine life.
Striped bass (Morone saxatilis) are highly migratory, anadromous fish spending much of the summer in New England estuaries. Due to their large size and good fighting qualities, striped bass are highly targeted by recreational anglers and are an important source of revenue for the sport fishing industry. An investigation into the spatial ecology and effects of catch-and-release angling on the physiology and behavior of striped bass was conducted. Fine-scale behavior was assessed by tagging fish with acoustic transmitters equipped with pressure and tri-axial accelerometer sensors and tracking them within a fixed array (n=34 receivers) in a Massachusetts estuary. Activity space changed significantly over the course of the season and increased with water temperature. Striped bass most frequently exhibited low levels of locomotory activity representing 67% of total activity measurements (slow swimming or hovering in place), with occasional high activity and burst swimming, often within the upper 3 m of the water column. Depth distribution of striped bass remained shallower when temperatures peaked at over 21 °C. Diel vertical migration was present with shallowest depths observed during the day and greatest depths during high tide. To investigate catch-and-release consequences, 102 striped bass were angled and blood sampled between July and November 2011. A subsample of 35 striped bass (July n=11, August n=11, September n=13) were
implanted with tri-axial acoustic accelerometers to assess relative behavior and survival post-release. Results from principle component analyses produced five factors describing 72.7% of the variance for blood physiology parameters, total length, and water temperature. Subsequently, only eigenvalues from PC1, with high loading for blood lactate, plasma sodium and chloride, and total length, were significantly correlated with fight time. Eight individual fish were detected within 12 hours of release and exhibited their greatest mean daily activity space estimate within that time (1.5 km$^2$ ± 0.6, 50%; 5.6 km$^2$ ± 2.2, 95%). Depth ranged from 0-6.15 m (1.89±1.3 m) and acceleration ranged from 0.095-3.51 ms$^{-2}$ (0.95±0.33). In summary, no observed mortality suggests that fish were able to recover from the physical and physiological impacts of angling. This thesis has increased the understanding of striped bass ecology and will help promote future conservation and management initiatives for striped bass and facilitate additional research.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xi</td>
</tr>
<tr>
<td>CHAPTER 1. GENERAL INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Species Background</td>
<td>1</td>
</tr>
<tr>
<td>Atlantic Striped Bass Fisheries</td>
<td>2</td>
</tr>
<tr>
<td>Commercial</td>
<td>2</td>
</tr>
<tr>
<td>Recreational</td>
<td>3</td>
</tr>
<tr>
<td>Management and conservation</td>
<td>4</td>
</tr>
<tr>
<td>Focus of Recreational Sector</td>
<td>5</td>
</tr>
<tr>
<td>Movement Patterns</td>
<td>6</td>
</tr>
<tr>
<td>Striped bass migration and activity within estuaries</td>
<td>6</td>
</tr>
<tr>
<td>Fine-scale movement using accelerometers</td>
<td>8</td>
</tr>
<tr>
<td>Physiology related to catch-and-release</td>
<td>10</td>
</tr>
<tr>
<td>Catch-and-release endpoints</td>
<td>10</td>
</tr>
<tr>
<td>Physical Trauma</td>
<td>11</td>
</tr>
<tr>
<td>Physiological stress response</td>
<td>12</td>
</tr>
<tr>
<td>Primary effects</td>
<td>12</td>
</tr>
<tr>
<td>Secondary effects</td>
<td>13</td>
</tr>
<tr>
<td>Tertiary effects</td>
<td>13</td>
</tr>
<tr>
<td>Post-Release Behavior and Mortality</td>
<td>15</td>
</tr>
<tr>
<td>Purpose of Thesis</td>
<td>16</td>
</tr>
<tr>
<td>Chapter Outline</td>
<td>17</td>
</tr>
<tr>
<td>Chapter 2 – Movement and activity patterns of striped bass in a tidal coastal embayment in Massachusetts measured using tri-axial accelerometer transmitters</td>
<td>17</td>
</tr>
<tr>
<td>Chapter 3 – Physical injury, physiological stress, and post-release activity patterns on striped bass in PDK following catch-and-release recreational angling</td>
<td>18</td>
</tr>
</tbody>
</table>
Chapter 4: Synthesis and Conclusions ................................................................. 18
References ........................................................................................................................ 19
Figures and Tables ............................................................................................................ 27

2. MOVEMENT AND ACTIVITY PATTERNS OF STRIPED BASS IN A TIDAL COASTAL EMBAYMENT IN MASSACHUSETTS MEASURED USING TRI-AXIAL ACCELEROMETER TRANSMITTERS ............................................................ 29
   Abstract ............................................................................................................................. 29
   Introduction ...................................................................................................................... 30
   Materials and Methods .................................................................................................... 33
      Study site ...................................................................................................................... 33
      Receiver Array ........................................................................................................ 33
      Capture and tagging ............................................................................................... 34
      Data Analysis ........................................................................................................ 36
   Results ............................................................................................................................... 39
      Space Use and Site Fidelity .................................................................................. 40
      Activity pattern (Depth and Acceleration) ........................................................... 41
   Discussion ......................................................................................................................... 42
      Activity space and site fidelity ............................................................................. 44
      Activity patterns- Depth and acceleration ........................................................... 45
   References ........................................................................................................................ 48
   Figures and Tables ............................................................................................................ 53

3. PHYSICAL INJURY, PHYSIOLOGICAL STRESS, AND POST-RELEASE ACTIVITY PATTERNS ON STRIPED BASS A MASSACHUSETTS ESTUARY FOLLOWING CATCH-AND-RELEASE RECREATIONAL ANGLING ........................................................................................................................... 66
   Abstract ............................................................................................................................. 66
   Introduction ...................................................................................................................... 67
   Materials and Methods .................................................................................................... 69
      Study Site ...................................................................................................................... 69
      Capture ................................................................................................................... 70
      Physical Trauma ...................................................................................................... 70
      Physiological Profiling ............................................................................................ 71
      Reflex Assessment ................................................................................................... 72
      Receiver deployment and acoustic monitoring ...................................................... 73
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. Summary of 2011 Atlantic striped bass recreational regulations by state</td>
<td>27</td>
</tr>
<tr>
<td>2.1. Summary of telemetry data from 35 striped bass tagged with acoustic tri-axial accelerometers in PKD Bay</td>
<td>54</td>
</tr>
<tr>
<td>2.2. Summary of total and weekly activity space estimates, including the results of GLM (looking at relationship between size and 50% and 90% total activity space) and GAMM (generalized additive mixed models) models (TL, average wk temp, time on 50 and 95% weekly activity space)</td>
<td>57</td>
</tr>
<tr>
<td>2.3. Summary of mean weekly depth and acceleration, including results from GAMM (looking at relationship between size, mean weekly temperature, week, WAS 50% and WAS 90%)</td>
<td>60</td>
</tr>
<tr>
<td>2.4. Summary of mean hourly depth and acceleration (acc), including results from GAMM (investigating relationship between size, tide stage, zone, temp, photoperiod)</td>
<td>61</td>
</tr>
<tr>
<td>3.1. Summary of physiological characteristics measured in 102 striped bass in PKD Bay</td>
<td>98</td>
</tr>
<tr>
<td>3.2. Summary of results from principle components analysis. Table shows principle components with eigenvalues greater than 1 (PC1-PC5) and the variance explained</td>
<td>99</td>
</tr>
<tr>
<td>3.3. Summary table of reflex impairments. Table shows number of fish with impairments for each reflex test (operculum, mouth, gag, dorsal, and body flex)</td>
<td>100</td>
</tr>
<tr>
<td>3.4. Summary of post-release activity data for all tagged striped bass (n=35). Activity space, depth, and acceleration (mean ± sd) were all limited to two days post-release</td>
<td>101</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1. Study area in the Plymouth, Kingston, Duxbury (PKD) Bay along the east coast of Massachusetts including the 34 receiver locations (receivers with temperature loggers are underlined)</td>
<td>53</td>
</tr>
<tr>
<td>2.2. Proportion of detections of tagged striped bass for each month (July, August, September, and October) across zones (1-4) within PKD Bay</td>
<td>56</td>
</tr>
<tr>
<td>2.3. Estimates of striped bass 95% activity space across months of study period (July, August, September, and October) and total activity space</td>
<td>58</td>
</tr>
<tr>
<td>2.4. Mean weekly activity spaces (95% and 50%) for 2011 (17 weeks) ± 1 standard deviation. Dark gray circles represent 95% activity space and light gray squares represent 50% activity space</td>
<td>59</td>
</tr>
<tr>
<td>2.5. Frequency histogram of wild striped bass acceleration (m s(^{-2}))</td>
<td>62</td>
</tr>
<tr>
<td>2.6. Diel patterns in average depth (top), acceleration (middle), and temperature (bottom) binned by hour of day (0 – 23 hrs)</td>
<td>63</td>
</tr>
<tr>
<td>2.7. Seasonal patterns of mean weekly depth (top), acceleration (middle), and temperature (bottom)</td>
<td>64</td>
</tr>
<tr>
<td>2.8. Mean depth (top) and mean acceleration (bottom) for day (6AM-6PM) and night are displayed for each tidal stage, ebb, flood, high, and low</td>
<td>65</td>
</tr>
<tr>
<td>3.1. Study area in the Plymouth, Kingston, Duxbury (PKD) Bay along the east coast of Massachusetts including the 34 receiver locations (receivers with temperature loggers are underlined)</td>
<td>97</td>
</tr>
<tr>
<td>3.2. Changes in movement and activity post-release for the first 14 days. Mean 95% activity space (top), 50% activity space (middle), and acceleration (bottom)</td>
<td>103</td>
</tr>
<tr>
<td>3.3. Changes in mean depth for the first 14 days post-release (G1=July, G2=August, G3=September)</td>
<td>104</td>
</tr>
</tbody>
</table>
CHAPTER 1
GENERAL INTRODUCTION

Species Background

Striped bass (Morone saxatilis), also known as rockfish or stripers, are an anadromous species of the Order Perciformes, Family Percichthyidae, native to the Eastern North American coast from the St. Lawrence River in Canada to St. John’s River in Florida, as well as the Gulf of Mexico through Louisiana (Clark 1968; Karas 1993). Being a popular game fish, Atlantic striped bass have also been introduced to inland lakes and reservoirs (Jackson and Hightower 2001), in addition to the Western United States, where they can now be found from Mexico to the British Columbia (Karas 1993). Striped bass are a slender, silver fish getting their name from distinctive narrow, dark, continuous stripes (usually seven or eight) along the sides of the body. Their dorsal fins show discrete separation, and the fish have a pronounced forked caudal fin (Werner 2004). Their main prey items include a large variety of fishes, crustaceans, squids, mussels, and worms (Karas 1993). Striped bass can range up to 1.5 meters and are considered a fairly long-lived species (up to 30 years) (Merriman 1941, Mansueti 1961). Individuals can spawn several times during their lifespan (Carmichael et al. 1998, Secor 2000). Female striped bass reach sexual maturity as early as four years, while males mature between two and three years of age. At full reproductive productivity (approximately eight years old), a female can carry 700,000 eggs (Werner 2004).

Atlantic striped bass migrate from coastal waters to freshwater rivers to spawn (Clark 1968; Karas 1993; Werner 2004). Much of the Atlantic striped bass stock spawns in three key freshwater systems along the North American east coast: the Chesapeake Bay, Delaware River, and Hudson River (Mather et al. 2009). Juveniles typically remain in estuaries for two to four years and then migrate out to the Atlantic Ocean. Striped bass spend the majority of their adult
life in coastal estuaries or the ocean (Clark 1968; Karas 1993). In the spring season, there is a large coastal migration northward toward New England and parts of Canada. In the fall, most of the striped bass journey south and return to warmer waters for the winter months, ranging from Virginia and the Carolina capes to as far south as Florida (Clark 1968; Berggren and Liberman 1978). After their spring spawning, many of the fish utilize New England non-natal estuaries throughout the summer and fall, as this is an important period for food acquisition (Kohlenstein 1981; Waldman and Fabrizio 1994; Mather et al. 2009). This annual migration supports major recreational and commercial fisheries for striped bass along the northeastern United States (Karas 1993).

**Atlantic Striped Bass Fisheries**

**Commercial**

Historically, overfishing and poor environmental conditions caused the collapse of Atlantic striped bass stocks in the late 1970’s (Karas 1993). Since then, listing the species as federally protected coupled with strict management regulations have aided in the striped bass stock recovery and allowed the fishery to grow extensively to be one of the most targeted species along the northeastern coast of the U.S. (US Fish and Wildlife Service 2008). Commercial harvest increased from 140,000 pounds in 1987 to 5.9 million pounds in 1997 and remained relatively stable likely due to quota restrictions (Atlantic States Marine Fisheries Commission 2011). In 2010, the striped bass commercial fishery landed an estimated 7 million pounds and was valued at over $17 million (US Fish and Wildlife Service 2011). Gillnets are the most dominant gear type, followed by hook and line. In fact, since the 1940s, it has been illegal to commercially fish for striped bass with anything but hook and line in Massachusetts (Karas
Other less popular gear types used in commercial fishing include pound nets, seines, and trawls (ASMFC 2011).

**Recreational**

Recreational angling is a very popular leisure activity worldwide and in the United States (Cooke et al. 2002, Arlinghaus et al. 2007). Recreational anglers globally are responsible for 12% of all sport fish landed each year, which is equivalent to an estimated 47.1 billion fish (Cooke and Cowx 2004). In the U.S., over 21% of all males and 7% of females 16 years and older went fishing in 2011 (U.S. Fish and Wildlife Service 2012). In the New England region alone (Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, and Connecticut), there were 1.25 million angling participants bringing in 1.5 billion dollars in fishing expenditures to the local economy (U.S. Fish and Wildlife Service 2012). Recreational anglers support fisheries management, conservation efforts, and outdoor recreation through excise taxes and purchasing fishing licenses. This pastime also promotes environmental appreciation, relaxation, and time spent with family and friends. Some even refer to fishing as having a ‘healing’ quality (Arlinghaus et al. 2007). A healthy fishing industry is fundamental to the nation, especially in coastal regions, bringing both social and economic benefits with its popularity. As a result, it is necessary to understand, successfully manage, and conserve sport fish stocks.

Due to their large size and good fighting qualities, striped bass are regarded as an excellent gamefish, are highly targeted by recreational anglers, and are an important source of revenue for the sport fishing industry (Werner 2004). In 2006, more than 75% of recreational anglers fishing in saltwater along the coast of Massachusetts (approximately 225,000 individuals) were specifically targeting striped bass, and spent in excess $350 million (U.S. Fish and Wildlife Service 2008). Historical periods of population declines (U.S. Fish and Wildlife Service 2008) and the importance of marine recreational angling for striped bass (Diodati and
Richards 1996) lead fisheries management in Massachusetts, as well as other coastal states, to employ bag limits and size restrictions to reduce the recreational harvest, thus, resulting in mandatory catch-and-release. There is also a growing trend among recreational anglers targeting striped bass to practice catch-and-release voluntarily as a conservation measure (Cooke and Cowx 2004; Arlinghaus et al. 2007).

Management and conservation

During colonial times, striped bass were considered a very abundant species (Karas 1993). The fishery increased in popularity during the early twentieth century until an alarming decline in striped bass stocks in the 1970s; commercial harvest dropped from 15 million pounds landed in 1973 to 140,000 pounds in 1986 (ASMFC 2011). At that point, it was widely agreed that management on the species was hindered by the lack of biological, ecological, and fisheries data (Karas 1993).

Congress enacted an Emergency Striped Bass Act in 1979, calling for a study to be initiated to assess the size of the migratory stocks, investigate the causes of the decline, calculate its economic importance and recommend measures for restoration (NMFS and USFWS 2005). Scientists discovered that over exploiting striped bass allowed for the species to become much more susceptible to natural stresses and pollution, including temperature fluctuations at spawning grounds and PBCs. Conclusions indicated that reducing the fishing pressure would lead have an immediate positive effect by enabling females with eggs to spawn (Karas 1993). Thus, the Interstate Fisheries Striped Bass Management Plan was implemented in 1981 to ensure that the harvest will be maintained below a specific rate to conserve the striped bass spawning stock (Karas 1993; NMFS and USFWS 2005).

In 1984, the Atlantic States Marine Fisheries Commission (ASMFC) management plan set size and catch limits under the Atlantic Striped Bass Conservation Act (ASMFC 1984). This act
placed the Secretary of Commerce and Secretary of the Interior as the authority to set a federal suspension on striped bass fishing in states that fail to comply with the ASMFC’s Interstate Fishery Management Plan. The Secretaries must also provide biennial reports to Congress and the Commission on studies of the Atlantic striped bass resource (NMFS and USFWS 2005).

When looking specifically at striped bass, management currently is handled by individual states (Maine through North Carolina) with support and coordination from the ASMFC (ASMFC 2011). Restrictions vary greatly and, within each state or province, can be quite complicated. In state waters for commercial and recreation fishers, there are catch quotas, size limitations, gear restrictions, fishing seasons, bycatch monitoring, and research programs studying catch-and-release. Federal waters (> 3 miles offshore) remain closed to all fishing for Atlantic striped bass (Karas 1993).

**Focus of Recreational Sector**

Maintaining the sustainability of the fishing industry has not always been effective and, recently, recreational fishing has been shown to be linked to the declines in fish stocks (Post et al. 2002; Coleman et al. 2004, Cooke and Cowx 2004). Today, angling is the largest source of fishing mortality for some species (Coleman et al. 2004; Arlinghaus and Cooke 2008; Lewin et al. 2006). In 2001, it was estimated that over 440 million fish were landed by anglers in the United States coastal waters, of which 187 million were retained for personal consumption (US Department of Commerce 2003). To prevent overfishing by the recreational sector, strict state management laws and limits have been implemented (Table 1.1). In many areas, anglers must obtain fishing licenses and adhere to bag limits, size restrictions, and fishing seasons to limit the removal of fish from the population (Hilborn and Walters 2003). If an individual fish does not meet the requirements for harvest, it is mandatory that it be released. Although many anglers fish for personal harvest, voluntary catch-and-release is a growing trend to aid in fish
conservation and sustainability (Policansky 2002). However, less is known about how angling effects stress levels and recovery of released striped bass.

**Movement Patterns**

Quantifying movement patterns is an important step to understanding of fish ecology and management (Lowe et al. 2003, Cooke et al. 2004). Identifying fine-scale movement patterns of aquatic animals allows researchers to identify life history characteristics, resource utilization, and essential habitats such as nurseries, feeding grounds, shelter, and over-wintering habitat (Lowe and Bray 2006). For example, Danylchuk et al. (2011) used tri-axial acoustic accelerometers to discover bonefish spawning grounds off the coast of Eleuthera, The Bahamas. Kneebone et al. (2012) was able to identify sand tiger shark nursery habitat in a Massachusetts estuary with acoustic telemetry. Ng et al. (2011) also demonstrated important dynamics in habitat use, site fidelity, and estuarine movements in striped bass in New Jersey using mobile telemetry. With the added detail from fine-scale movement and activity patterns, it is possible to reveal where and when anglers are likely going to encounter striped bass. This is key in linking natural spatial ecology to catch-and-release consequences, and has the potential to support future effective management decisions.

**Striped bass migration and activity within estuaries**

It is well known that a large percentage of striped bass follow a seasonal migration route (Clark 1968), while some remain within a particular estuary, migrating up and down river only (Carmichael et al. 1998, Wingate and Secor 2007). Other landlocked striped bass, many of which were introduced, can remain in freshwater reservoirs for their entire lifespan (Karas 1993; Jackson and Hightower 2001). Coastal migratory stocks travel north to spawn and spend much
of the summer in New England estuaries where there is an abundance of seasonal prey species (Kohlenstein 1981; Waldman and Fabrizio 1994; Mather et al. 2009).

There has been a great deal of research regarding striped bass movement and distribution using external tagging methods (reviewed in Clark 1968, Kohlenstein 1981; Boreman and Lewis 1987; Dorazio et al. 1994; Waldman and Fabrizio 1994; Mather et al. 2009). Technological developments such as acoustic telemetry have aided studies in examining movement and migration within rivers such as Roanoke River (Haeseker et al. 1996; Carmichael et al. 1998) and within landlocked reservoirs in Virginia through North Carolina (Jackson and Hightower 2001; Hightower et al. 2001; Thompson et al. 2010). Acoustic telemetry has also been used to observe coastal migrants within the Hudson River, a popular spawning location (Wingate and Secor 2007), and within other non-natal estuaries across New England (Mather et al. 2009; Pautzke et al. 2010). One study focused on the diversity of striped bass movements within a New Jersey estuary (Able and Grothues 2007). Able and Grothues (2007) used ultrasonic transmitting tags in striped bass (n=65; 508-978 mm TL) and observed movement with wireless hydrophones deployed at four gates inside the entrance as well as upstream. Although this study showed less-complex patterns than earlier studies, they were able to successfully monitor movements in and out of the bay showing a relatively high (58%) seasonal return (Able and Grothues 2007).

Recent developments in acoustic telemetry have lead to the ability to measure and transmit (to remote receivers) other variables related to spatial ecology of species (such as striped bass) and has the potential to add a great amount of detail to the current knowledge base (O’Toole et al. 2010, Cooke et al. 2004, Cooke et al. 2012). The ability to track (Lucas and Baras 2000) and assess the physiology, bioenergetics, and behavior (Cooke et al. 2004, Ropert-Coudert and Wilson 2005) in free-swimming fishes has greatly improved with the advent of
increasing technology. Methods of studying fish ecology and biology has expanded to include tools such as: passive integrated transponder (PIT) tags, electromyogram, heart rate, radio and acoustic telemetry, satellite tags, and archival, biologging devices (Lucas and Baras 2000, Cooke et al. 2004, Ropert-Coudert and Wilson 2005).

Fine-scale movement using accelerometers

Past studies have broadly examined striped bass ecology, including their seasonal movement patterns (Wingate and Secor 2007, Pautzke et al. 2010), site fidelity and habitat use (Ng et al. 2007), spawning behavior (Hocutt et al. 1990, Douglas et al. 2009), and responses to temperature and drought (Baker and Jennings 2005). Acoustic telemetry is a tool that has been increasingly used to assess post-release behavior and survival of marine organisms (Cooke et al. 2002; Donaldson et al. 2008). Biotelemetry studies applied to wild animals, including marine species, are increasing in number due to recent developments in technology allowing detailed analysis of behavior and movement patterns, spatial ecology, and survivorship (Jacoby et al. 2012).

Although there are different varieties of telemetry tags, most share a similar feature of transmitting presence and absence data with a time stamp and location for each individual fish in a time series (Jacoby et al. 2012). Acoustic tri-axial accelerometers specifically transmit and/or record (depending on transmitter type) a time-series of presence/absence data with alternating readings of pressure and acceleration. Accelerometers can be logging tags, which are attached to the individual animal to be retrieved later, or transmitting tags that use a stationary array to retrieve and record the data as a tagged individual swims within the range of the receiver (Murchie et al. 2009). The accelerometer tag allows for a more detailed view of localized fine-scale activity and cyclical movement patterns related to general behavior and can also help identify changes related to human impacts (Murchie et al. 2009; Jacoby et al. 2012).
Transmitting accelerometers have broad applications for future research in behavior ecology of free-ranging marine species (Cooke et al. 2004, O’Toole et al. 2010). Several studies in Eleuthera, The Bahamas have successfully used tri-axial accelerometry to study spatial ecology, activity, metabolic rates, etc. of several native species such as the great barracuda and bonefish (e.g. Danylchuk et al. 2011; Murchie et al. 2011; O’Toole et al. 2011). One such study demonstrating the use of accelerometry focused on using tri-axial accelerometry coupled with respirometry to quantify the activity patterns and field metabolic rates of free-swimming bonefish (n=10, 527 ± 36 mm TL). Although much of the study focused on the development of bioenergetics models for bonefish, Murchie et al. also discussed the opportunities and limitations of tri-axial accelerometer transmitters for marine fisheries research (2010).

O’Toole et al. (2010) documented adult great barracuda (*Sphyraena barracuda*) in Bahamian coastal habitats using acoustic tri-axial accelerometers (n=13 barracuda, 62-120 cm TL). This study focused on locomotory activity and depth utilization across habitat types and diel periods, thereby illustrating the application of accelerometers in a remote receiver array (n=53 receivers). Although O’Toole et al. was unable to find differences in acceleration or depth across habitats or diel periods, evidence of movement into shelf habitat during mid-day (occupying >10m) was found. This was claimed to be one of the first reports of the use of telemetered acceleration values from free-swimming fish and will aid in similar future studies (O’Toole et al. 2010).

Another study, Landsman et al. (2011), used transmitting accelerometers to study the behavioral ecology of muskellunge (*Esox masquinongy*) in the Rideau River in Ontario. The free-ranging swimming behavior of eight muskellunge was assessed using tri-axial acceleration and pressure sensing acoustic transmitters recorded by nine underwater hydrophones. Landsman et al. (2011) found depth to increase during a waxing lunar phase and decreased for large fish
during the warmest hours of the day. Acceleration activity was shown to be highest during a waxing lunar phase and was low during periods of warm temperatures (Landsman et al. 2011). These types of observations have the potential to also contribute to a greater understanding of the activity levels and depth use patterns of ecologically and recreationally important sport fish, such as the striped bass.

**Physiology related to catch-and-release**

**Catch-and-release endpoints**

Due to a growing awareness that recreational angling can influence post-release survival, catch-and-release studies have been increasing in number and contributing to the development of new research methods and analyses (Cooke et al. 2012). A great deal of literature suggests that substantial mortality can occur after catch-and-release events despite the fish appearing to be in good condition (Thompson et al. 2002; Cooke and Philipp 2004). Even low levels of post-release mortality can be biologically significant to fish populations of long-lived species with high ages at maturity (Schroeder and Love 2002). Recent studies on catch-and-release angling have shown that all angling events elicit physiological stress in individual fish (reviewed in Thompson et al. 2002; Cooke and Suski 2005; Arlinghaus et al. 2007). Much of the literature published has focused on post-release hooking mortality related to catch-and-release (many centering on one or two aspects of hook type; Bartholomew and Bohnsack 2005). Although studies on post-release mortality have been conducted, little is still known about the sublethal tertiary effects of catch-and-release, where the possible endpoints of an angling event are highly dependent on a number of different factors (e.g. fish time, gear, angler skill and intention, and environmental factors) (Arlinghaus et al. 2007). Studies focusing specifically on striped bass are also limited; most have been related to hooking mortality and the
physiological impacts of angling for striped bass in freshwater systems. Due to the diadromous nature of striped bass, it is important to quantify the impacts of catch-and-release in freshwater, marine, and estuarine environments where fish encounter large predators, greater temperature differences, and strong tidal changes.

Many assume that catch-and-release conserves fish populations (Lucy and Studholme 2002) and, in theory, common sense suggests that this practice promotes biological, economic, and social sustainability (Policansky 2002). However, some fish unavoidably are fatally injured from the event, while other fish can experience sublethal effects leading to delayed mortality, disease, infection, decreased fitness/reproductive success, and/or behavioral changes (Cooke et al. 2002; Arlinghaus et al. 2007; Skomal et al. 2007). Due to the high number of variables that can affect a fish during an angling event (e.g. angler experience/skill, gear used, and environmental factors), mortality prior to release can be as low as one percent or as high as 90 percent (Muoneke and Childress 1994).

With up to 90% of the 12.5 million striped bass being released in the United States annually and relatively little knowledge about the fate of released fish (Millard et al. 2003), post-release activity and mortality are essential to quantify. Delayed mortality and even sublethal consequences can potentially lead to population declines and trophic cascades (Arlinghaus et al. 2007). To effectively manage recreational fisheries and minimize the impacts of angling on valuable fish populations, it is necessary to gain a better understanding of how anglers and angling influences individual fish and their ultimate fate.

**Physical Trauma**

During an angling event physical injury (both external and internal) can affect the fish. Minor injury to an individual fish is inevitable (Arlinghaus et al. 2007) due to the nature of hooking the fish and reeling them to the side of the boat or up the beach/jetty. Major injuries
can also occur, such as foul hooking or hooking the fish in the gut/gills, which can lead to substantial blood loss and immediate mortality (Diodati and Richards 1996). Studies suggest that variables such as hooking location, hook type, and angler experience can show significant differences in mortality levels of striped bass (Diodati and Richards 1996; Nelson 1998). Fish brought up from deeper waters too quickly can show signs of barotrauma and have equilibrium problems upon release (Schreck et al. 1997).

**Physiological stress response**

Stress can be defined as a deviation from a physiological homeostatic state (Barton and Iwama 1991, Barton 2002). Fish have adapted abilities to meet the demands of the working muscles and respond to stress during exhaustive exercise (Barton 2002, Suski et al. 2012). Physiological responses during and angling event can be very similar to the stress associated with exhaustive exercise. In both, a suite of physiological changes occurs, including depletion of energy stores and disturbances in hormone and ion levels (Wood 1991, Suski et al. 2004, Arlinghaus et al. 2007). To quantify stress associated with exhaustive exercise, it is necessary to comprehend these mechanisms.

**Primary effects**

The process of fighting a fish during an angling event has the potential to cause physiological stress to that individual (Cooke et al. 2002, Arlinghaus et al. 2007). In fish, the primary stress response to exhaustive exercise or a potential threat involves alterations in neurotransmitter activity (Barton 2002). This includes increases in corticosteroid and catecholamine hormones (Skomal and Mandelman 2012). The release of stress hormones involves the primary corticosteroid, cortisol, aiding in the mobilization of energy reserves (Suski et al. 2007). In most fishes tested, cortisol levels tend to peak between 0.5-1 hr post-stress, thereby reducing the short-term effectiveness of the immune system and white blood cells.
(Barton and Iwama 1991). For example, plasma cortisol concentrations for juvenile Chinook salmon (*Oncorhynchus tshawytscha*) peaked after one hour from the final stressor (Barton et al. 1986). Davis and Parker (1990) reported that striped bass have a robust cortisol response that was temperature sensitive.

**Secondary effects**

The secondary responses to stress include physiological and biochemical changes, largely due to the primary response of the fish (Skomal and Mandelman 2012). These responses are usually evaluated in the blood and muscle tissue and are mostly dependent on the nature and duration of the stressor(s) (Barton 2002, Skomal and Mandelman 2012). Biochemical changes include the rapid mobilization of glucose to the blood to meet energetic demands (causing hyperglycemia) and increased production of lactate in white muscle (Wood 1991; Wang 1994). The adrenaline produced in exercise disturbs the individual’s natural osmoregulation and ionic balance (Moyle and Cech 1996, Arlinghaus et al. 2007). Primary responses may also lead to increases in the permeability and gill-diffusing capacity to aid in oxygen demands, therefore a stress response could include the loss of water and gain of ions across the gills (O’Toole et al. 2010). Plasma acidification occurs as pH decreases in the blood stream leading to increases in Cl$^{-}$ ions to buffer pH disturbances (Thompson et al. 2002). Potassium is important in regulating the activity of nerves and muscles and can increase due to ion permeability and cellular leakage (Vanlandeghem et al. 2010). Rising levels of hormones also cause an increase in red blood cells released from the spleen for the uptake of Na$^{+}$ and Cl$^{-}$ ions to aid in increasing O$_2$ delivery throughout the fish’s body during the angling event (Pickering and Pottinger 1998).

**Tertiary effects**

Aspects of whole-animal performance occur as a result of the stressors and have a variety of potential outcomes depending of duration and magnitude of the stress (Barton 2002).
There can be decreased fitness and overall resistance to disease, decreased somatic growth, changes in metabolic scope for activity, and reduced survivability (Barton 2002; Arlinghaus et al. 2007). Lowerre-Barbieri et al. (2003) reported that the reproductive output and quality of common snook could potentially be impacted by angling-related stress. It has been observed that angling events and related stress can leave individual fish disoriented and have difficulty maintaining equilibrium (Cech et al. 1996), suggesting that there could also be changes in post-release behavior during the recovery period that may be permanent (Cooke et al. 2004, Cooke et al. 2005, Cooke et al. 2008, Davis 2010).

In most species, physiological changes due to exhaustive exercise induced by catch-and-release events will return to resting control levels within a 2-24 hour period (Wang 1994; Suski et al. 2007). However, problems can occur due to the fish having to exchange long-term health for short-term energy bursts. Related striped bass physiological research has been focused in riverine systems where there is a lack of predators. For striped bass studied in a freshwater reservoir, Tomasso and Isely (1996) noted significantly higher physiological indicators (cortisol, glucose, lactate, and osmolality) of stress following angling. Fatal consequences were also observed proportional to increased fight time during the summer months when the temperatures are higher, which also happens to coincide with increase fishing demand (Tomasso and Isely 1996). Cooke and Phillip (2004) reported high mortality in bonefish within 30 minutes of release when sharks were present. Danylchuk et al. (2007) also found similar mortality associated with marine predators, even while angling. Exhaustive exercise from the angling event can lead to sub-lethal consequences (Cech et al. 1996; Tomasso and Isely 1996) that could ultimately disrupt normal behavior post-release (i.e. feeding behavior), increase susceptibility to disease, decrease fitness, become more vulnerable to attack from predators, and lead to post-release mortality (Muoneke and Childress 1994, Arlinghaus et al. 2007). These
factors could make coastal embayments and marine environments potentially dangerous since they are abundant in predators targeting weak or injured fish like the striped bass.

**Post-Release Behavior and Mortality**

There are few studies focusing specifically on how angling affects striped bass post-release survival and behavior (Young and Isely 2006; Graves et al. 2009). Young and Isely (2006) conducted a study performed in a large freshwater reservoir using acoustic telemetry to quantify the post-tournament survival of striped bass. They also assessed the effectiveness of live holding systems for transport of fish to weigh-in sites. These live holding systems are rarely used by non-tournament anglers targeting striped bass; therefore, their results may only apply to a relatively small proportion of striped bass. Their study did produce a post-release survival rate of 87% after 120 days of monitoring; however, the physiological stress response was not measured, making it difficult to understand the reasons behind the mortalities (Young and Isely 2006).

Graves et al. (2009) conducted a mortality assessment of caught-and-released coastal striped bass using pop-up satellite archival tags during the winter, pre-spawning aggregation near the mouth of Chesapeake Bay. The pop-up tags allowed measurements to be taken for 30 days prior to their detachment, including temperature, pressure, and light levels as an indicator of location to assess movement patterns and potential mortality. No mortality was observed. The tagged striped bass spent more than 90% of their time at depths less than 10m and in temperatures of 6 – 9°C, demonstrating no significant diel differences in depth or temperature (Graves et al. 2009). There was also evidence of weak periodicities in vertical movement consistent with daily and tidal cycles. A limited sample size (n=8) precluded statistical comparisons between hook types (Graves et al. 2009). It has been shown that higher water temperatures have the potential to exacerbate the effects of angling stress (Thompson et al. 2006).
therefore, the study by Graves et al. (2009) during the winter months potentially excluded effects related to temporal differences.

Another study, Schreck et al. (1997), noted that behavioral changes in predator avoidance, movement patterns, migration, food acquisition, and reproduction could be indicative of decreased survivability. Within the first few hours or days after release, some biotelemetry studies have observed increased movement activity (Sundstrom and Gruber 2002; Gurshin and Szedlmayer 2004; Thorstad et al. 2004), however, decreased movement activity has also been observed, although less frequently (Holland et al. 1993). Reasons for altered post-release behavior could be related to individual physiological condition and environmental factors (Shepard et al. 2008). Reduced activity may simply be a result of fatigue from the angling event, whereas increased activity could result from an escape response to avoid areas that are unfavorable (Arlinghaus et al. 2007). Minor changes in behavior may be adaptations to increase survivability or can be reflective of how the fish senses and responds to its environment, while significant alterations in normal patterns could lead to decreased probability of survival (Schreck et al. 1997). Due to the popularity of recreational angling targeting striped bass, it will be important to gain a better understanding of the physical and physiological consequences, as well as, the behavioral and movement changes associated with catch-and-release. This information will aid in improving catch-and-release techniques and management.

**Purpose of Thesis**

The purpose of this research is to conduct a thorough investigation into the spatial ecology and effects of catch-and-release angling on the physiology and behavior of striped bass in coastal waters of Massachusetts. The first segment of my research quantified the spatial ecology and activity patterns of coastal striped bass using acoustic transmitters equipped with
pressure and tri-axial acceleration sensors. The second part will examine physical injury, physiological stress, and post-release activity patterns of striped bass following catch-and-release in a coastal tidal bay. This study is one of the first to use accelerometer transmitters to quantify activity levels in striped bass, a tool that might prove useful for also understanding the link to physiological stress and impacts related to catch-and-release angling of coastal striped bass. Results from this research have the potential to aid in improving the ability to effectively manage fish stocks and increase the sustainability of the valued striped bass fishery for Massachusetts and throughout the United States Atlantic coastline.

Chapter Outline

Chapter 2 – Movement and activity patterns of striped bass in a tidal coastal embayment in Massachusetts measured using tri-axial accelerometer transmitters

Though it is general knowledge that striped bass have an annual migration and spend the summer months in New England, there are limited empirical data on the detailed movements and activity patterns of coastal striped bass in tidal bays. Transmitting acoustic accelerometers provide detailed information that can be collected from remote receivers. To my knowledge, this is the first time accelerometers have been used to look at movements of coastal striped bass, making this study unique. The objective of the present study was to examine residency, movement patterns, and activity levels of striped bass in the coastal waters of Plymouth, Kingston, Duxbury (PKD) Bay in Massachusetts using accelerometers. A large-scale acoustic telemetry array was deployed across a range of habitat types and fish were monitored for up to 160 days.
Chapter 3 – Physical injury, physiological stress, and post-release activity patterns on striped bass in PDK following catch-and-release recreational angling

Understanding how angling can influence physiology, survival, and post-release behavior of individual coastal striped bass is beneficial for future assessments and is important to ensure that the benefits of catch-and-release, when used as a conservation and management tool, are not overestimated. The goal of this study was to quantify physical injury, physiological stress, and post-release activity patterns of striped bass following catch-and-release in a Massachusetts coastal tidal bay. First, I examined the physical consequences and physiological stress response of coastal striped bass exposed to catch-and-release angling and those elements of the angling event that influenced measurements. Secondly, I used acoustic transmitters with pressure and tri-axial accelerometer sensors for a subset of angled striped bass to measure post-release movement and activity levels.

Chapter 4: Synthesis and Conclusions

In this final chapter, a summary and synthesis of the study's main finding will be included with comments regarding future implications. Future research recommendations based on this research will also be discussed. These data will strengthen the general knowledge of the striped bass species and should assist in creating more effective management of the recreational and commercial fisheries.
References


### Figures and Tables

Table 1.1: Summary of 2011 Atlantic striped bass recreational regulations by state (ASMFC 2012)

<table>
<thead>
<tr>
<th>State</th>
<th>Size Limits</th>
<th>Bag limit</th>
<th>Other</th>
<th>Open Season</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME</td>
<td>20 - 26&quot; OR ≥ 40&quot;</td>
<td>1 fish</td>
<td>Hook &amp; line only</td>
<td>All year, except spawning areas are closed 12.1-4.30 and catch-and-release only 5.1-6.30</td>
</tr>
<tr>
<td>NH</td>
<td>1 fish 28-40&quot; &amp; 1 fish &gt;28&quot;</td>
<td>2 fish</td>
<td>No netting; no gaffing; must be landed with head and tail intact; no culling</td>
<td>All year</td>
</tr>
<tr>
<td>MA</td>
<td>28&quot; min</td>
<td>2 fish</td>
<td>Hook &amp; line only</td>
<td>All year</td>
</tr>
<tr>
<td>RI</td>
<td>28&quot; min</td>
<td>2 fish</td>
<td></td>
<td>All year</td>
</tr>
<tr>
<td>CT</td>
<td>28&quot; min, except Connecticut River Bonus Program: 22-28&quot;</td>
<td>2 fish, except CR Bonus: 1 fish</td>
<td>CR Bonus Quota: 4,025 fish</td>
<td>All year, except CR Bonus 5.4-6.30 (limited to I-95 bridge to MA border)</td>
</tr>
<tr>
<td>NY</td>
<td>Ocean Private: 1 fish 28-40&quot; &amp; 1 fish &gt;40&quot;; Ocean Charter: 28&quot; min; Hudson River: 18&quot; min; DE River: 28&quot; min</td>
<td>Ocean: 2 fish; Hudson R.: 1 fish; DE River: 2 fish</td>
<td>Angling or spearing only</td>
<td>Ocean: 4.15 - 12.15; Hudson River: 3.16 - 11.30; Delaware River: All Year</td>
</tr>
<tr>
<td>NJ</td>
<td>28&quot; min</td>
<td>2 fish, plus 1 additional through Bonus Program</td>
<td>Bonus program quota 321,750 lb.; No netting. Non-offset circle hooks required 4.1-5.31 in DE River if using natural bait.</td>
<td>All year, except 1.1-2.28 in intra-coastal waters plus 4.1-5.31 in lower DE River</td>
</tr>
<tr>
<td>PA</td>
<td>Non-tidal DE River: 28&quot; min; Delaware Estuary: 28&quot; min. except 20-26&quot; from 4.1 - 5.31</td>
<td>2 fish</td>
<td></td>
<td>All year</td>
</tr>
<tr>
<td>DE</td>
<td>28&quot; min. except 20-26&quot; from 7.1-8.31 in Del. River, Bay &amp; tributaries</td>
<td>2 fish</td>
<td>Hook &amp; line, spear (for divers) only. Circle hooks required in spawning season.</td>
<td>All year except 4.1 - 5.31 in spawning grounds (catch &amp; release allowed)</td>
</tr>
<tr>
<td>State</td>
<td>Species &amp; Regulations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-----------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MD</strong></td>
<td>Chesapeake Bay Trophy: 28” min; Chesapeake Bay Regular: 18” min with 1 fish &gt; 28”; Ocean: 28” min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF:</td>
<td>1 fish; Chesapeake Bay Trophy: 1 fish; Chesapeake Bay Regular: 2 fish; Ocean: 2 fish</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF: non-off set circle hook if baited hooks &amp; hap&gt;0.5’’; Chesapeake Bay Quota: 2,956,463 lbs (part of Baywide quota; includes Susquhanna Flats harvest, excludes trophy harvest)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SF:</td>
<td>3.1-5.31; catch &amp; release only 3.1-5.3; Chesapeake Bay Trophy: 4.18-5.15 (most tribs closed); Chesapeake Bar Regular: 5.16-12.15 (most tribs closed until 6.1); Ocean: All year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PRFC</strong></td>
<td>Trophy: 28”; Regular: 18” min with 1 fish &gt; 28”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trophy:</td>
<td>1 fish; Regular: 2 fish</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quota:</td>
<td>683,967 lbs. (part of Baywide quota; excludes trophy harvest)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trophy:</td>
<td>4.18-5.15; Regular: 5.16-12.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>DC</strong></td>
<td>18” min 1 fish &gt; 28”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 fish</td>
<td>Hook &amp; line only</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.16-12.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VA</strong></td>
<td>Bay/Coastal Trophy: 32” min (28” Potomac tribs); CB Spring: 18 - 28”, 1 fish &gt; 32”; CB Fall: 18-28”, 1 fish &gt;34”, Potomac Tribs: 18-28”, 1 fish &gt;28”; Ocean: 28”</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bay/Coastal Trophy:</td>
<td>1 fish; CB Spring: 2 fish; CB Fall: 2 fish; Potomac Tribs: 2 fish; Ocean: 2 fish</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hook &amp; line, rod &amp; reel, hand line only; Chesapeake Bay Quota: 1,538,022 lbs in 2010 (part of Baywide quota, excludes trophy harvest)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bay Trophy:</td>
<td>5.1-6.15 (open 4.18 Potomac tribs); Coastal Trophy: 5.1-5.15; CB Spring 5.16-6.15 (no fish &gt;32” in spawning areas); CB Fall: 10.4-12.31; Potomac Tribs:5.16-12.31; Ocean: 1.1-3.31, 5.16-12.31</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NC</strong></td>
<td>Roanoke River: 2 fish 18-22” OR 1 fish 18-22” and 1 fish &gt;27”; Albemarle Sound: 18” min; Ocean: 28” min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roanoke River:</td>
<td>2 fish; Albemarle Sound: 3 fish; Ocean:2 fish</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roanoke River quota: 137,500 lbs.; Albemarle Sound quota: 137,500 lbs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roanoke River:</td>
<td>3.1-4.30 (single barbless hook required 3.1-6.30 from Roanoke Rapids dam downstream to US 258 bridge); Albemarle Sound: Spring 1.1-4.30, Fall 10.1-12.31; Ocean: All year</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 2

MOVEMENT AND ACTIVITY PATTERNS OF STRIPED BASS IN A TIDAL COASTAL EMBAYMENT IN MASSACHUSETTS MEASURED USING TRI-AXIALACCELEROMETER TRANSMITTERS

Abstract

Striped bass (*Morone saxatilis*) are a popular sport fish among recreational anglers along the Atlantic coastline. Although there is a good understanding of their seasonal migration patterns, less is known about the short-term movements of striped bass once they have reached New England coastal embayments frequented during the summer months. It is important to understand striped bass movement patterns and behavioral ecology to make the most educated management decisions. Fine-scale movement and activity were assessed by tagging 35 striped bass (38.5-80.5 cm TL) with acoustic transmitters equipped with pressure and tri-axial accelerometer sensors and tracking them within a fixed array (n=34 receivers) in Plymouth, Kingston, Duxbury (PKD) Bay, MA. Activity space was significant over the course of the season and increased with water temperature. Striped bass most frequently exhibited low levels of locomotory activity representing 67% of total activity measurements (slow swimming or hovering in place), with occasional high activity and burst swimming, often within the upper 3 m of the water column. Depth distribution of striped bass ranged from 0 - 14.95 m and fish remained at shallower depths when temperatures were over 21 °C. Diel vertical migration was observed with shallower depths during the day and greatest depths during high tide.
**Introduction**

Striped bass (*Morone saxatilis*) are highly targeted by recreational anglers along the Atlantic coastline and are an important source of revenue for the sport fishing industry (Werner 2004). Historically, overfishing and poor environmental conditions caused the collapse of Atlantic striped bass stocks in the late 1970's (Karas 1993). Since then, listing the species as federally protected coupled with strict state management regulations have aided in the striped bass stock recovery and allowed the fishery to grow extensively to be one of the most targeted species along the northeastern coast of the U.S. (US Fish and Wildlife Service 2008). Striped bass, even today, face management issues when they are on summer grounds including habitat loss, lack of prey, angling, mycobacteria, and pollution (Karas 1993). A healthy fishing industry is fundamental to the nation, especially in coastal regions, bringing both social and economic benefits with its popularity (Cooke and Cowx 2004; Arlinghaus et al. 2007). As a result, it is necessary to understand, successfully manage, and conserve sport fish stocks.

Native striped bass (*Morone saxatilis*) are anadromous and highly migratory fish found along the Atlantic coast (Walter et al. 2003; Mather et al. 2009). A large percentage of striped bass follow a seasonal migration route (Clark 1968), traveling south in the fall and north in the spring to spawn (Karas 1993). For coastal striped bass, estuarine dependency during early life stages is obligate and remains important throughout the life of the fish (Secor 2000). Coastal migratory stocks spend much of the summer in New England estuaries where there is an abundance of seasonal prey species (Kohlenstein 1981; Waldman and Fabrizio 1994; Mather et al. 2009). Past studies have broadly examined striped bass ecology, including their seasonal movement patterns (Wingate and Secor 2007, Pautzke et al. 2010), site fidelity and habitat use (Ng et al. 2007), spawning behavior (Hocutt et al. 1990, Douglas et al. 2009), and responses to temperature and drought (Baker and Jennings 2005).
Quantifying movement patterns is an important step to our understanding of fish ecology and management (Lowe et al. 2003, Cooke et al. 2004). There has been a great deal of research regarding striped bass migration and distribution using external tagging methods (reviewed in Clark 1968, Kohlenstein 1981; Boreman and Lewis 1987; Dorazio et al. 1994; Waldman and Fabrizio 1994). Interestingly, however, still not much is known about striped bass movement patterns or ecological behavior while on their summer grounds in New England coastal estuaries. With recent recreational striped bass catches in Massachusetts being the largest observed along the east coast (Nelson et al. 2006), a large portion of the Atlantic population is believed to reside along the coast and estuaries of Massachusetts during the summer months (Nelson et al. 2006; Mather et al. 2009). It is also believed that these estuaries provide important foraging grounds for striped bass before their annual migration (Nelson et al. 2006; Pautzke et al. 2010) and that striped bass have strong site fidelity to non-natal estuaries (Ng et al. 2007; Able et al. 2012). Recent acoustic tagging studies within the natal Hudson River (NY; Wingate and Secor 2007) and non-natal Mullica River – Great Bay (NJ; Able and Grothues 2007; Ng et al. 2007; Grothues et al. 2009) and Plum Island Estuary (MA; Pautzke et al. 2010) estuaries provide the first examples of multiple-detection movement data for individual coastal striped bass. Many environmental cues may drive movement and behavior including temperature (Able and Grothues 2007). Further documentation of these free-ranging marine species in space and time is important to understanding the fundamentals of their natural history, ecological interactions, and habitat requirements (Cooke et al. 2008; O’Toole et al. 2010) to aid in effective management and conservation efforts.

Free-ranging marine predators, like the striped bass, live in a three-dimensional environment where they are able to move in both horizontal and vertical planes (Vianna et al. 2013). Although there are different varieties of telemetry tags, most share a similar feature of
providing presence and absence data with a time stamp and location for each individual fish in a
time series (Jacoby et al. 2012). Recent technological developments in acoustic telemetry have
lead to the ability to measure and transmit (to remote receivers) other variables related to
spatial ecology with great learning potential (O’Toole et al. 2010; Cooke et al. 2012). This allows
data to be transmitted to a stationary array (or hydrophone) as a tagged individual swims within
the range of the receiver (Murchie et al. 2009). This is beneficial because there is no need to
recapture the fish, however it is necessary to have good coverage of the study area to detect the
tag (Cooke et al. 2004). Specifically, acoustic transmitting tri-axial accelerometers send out a
time-series of presence/absence data with the potential of also measuring additional detail
including depth and acceleration. The accelerometer tag allows for a more detailed view into
localized fine-scale activity and cyclical movement patterns related to general behavior and can
also help identify changes related to human impacts (Murchie et al. 2009; Jacoby et al. 2012).
Although there has been no use of transmitting accelerometers in coastal striped bass studies,
these new developments have broad applications for insight into detailed short-term movement
patterns and behavioral ecology of free-ranging marine species (Murchie et al. 2010; O’Toole et
al. 2010).

The objective of my study was to quantify the movement and activity patterns of striped
bass in a New England bay. To do so, I capitalized on the use of acoustic transmitters with
pressure and tri-axial acceleration sensors within a large-scale fixed array deployed across a
range of habitat types. I predicted that striped bass would exhibit strong fidelity to PKD Bay
over the extent of the summer and that activity and depth patterns would correlate to
temperature of the bay.
Materials and Methods

Study site

The primary study area included the Plymouth, Kingston, and Duxbury (PKD) Bay (42°42′41.59″ N, 70° 47′41.89″ W), approximately 50 km south of Boston, Massachusetts. This coastal embayment, and surrounding area, serves as a popular fishing destination for recreational anglers targeting striped bass. In 2006, more than 75% of the recreational anglers fishing in saltwater along the coast of Massachusetts (approximately 225,000 individuals) were specifically targeting striped bass (U.S. Fish and Wildlife Service 2008). PKD Bay (20,362 acres) is dominated by geographical features such as two barrier beaches that together form a 1.6 km wide inlet, connecting the embayment to the much larger Cape Cod Bay. PKD Bay contains one small residential island, Clarks Island, in the northern portion providing rocky outcroppings and grass bed habitat. There are also several important inflows, including Jones River in Kingston and Eel River in Plymouth. PKD Bay is relatively shallow, averaging 2-3 meters and ranging from several centimeters to 20 meters in boating channels. Characteristics of PKD Bay include large channels surrounded by sand and mud flats, salt marshes, and tidal creeks that can be exposed at low tide (Kneebone et al. 2012).

Receiver Array

An array of 34 fixed acoustic receivers (VR2W, Vemco Division, AMIRIX Systems Inc., Halifax, Nova Scotia) was deployed the first week of May 2011 through October 2011 (Figure 2.1). Receivers were deployed either along the estuary floor, each receiver attached to a short length of rebar cemented into a cinder block, or were attached to existing navigational markers. Receivers were arranged to maximize coverage in the bay while creating nodes that corresponded with transitions between habitat types (e.g., shallow flat to deep channel). The configuration of the study site has only one small inlet; therefore, a curtain of receivers was
deployed across the mouth to capture immigration and emigration from the bay. Receivers were downloaded and cleaned monthly during the deployment period. Given that water temperature can greatly influence the habitat selection and movement of fish (Thompson et al. 2011) several water temperature loggers (n=13; model HOBO Pendant, Onset Computer Corporation, Onset, MA) were deployed at pre-determined receiver locations throughout the estuary (Figure 2.1). The loggers were programmed to record temperature readings (°C) every 30 minutes with an accuracy of ±0.7 °C (range -20 to 70 °C).

Acoustic detection limits were tested on a subset of receivers positioned at various depths and substrates (e.g. tidal flats and channels; as in Kneebone et al. 2012). During each trial, a stationary control tag was tested at 50, 100, 200, 300, 400, and 500 m from the receiver in all four cardinal directions and the number of detections monitored for 5 minutes. The detection radius of receivers ranged from ~ 100 m in water depths <3 m to ~ 350 m in water depths >5 m. Also, the receivers positioned in ‘deep’ (>3m at low tide) channels did not show a symmetrical detection range in all cardinal directions; the range was much greater along the axis of the channel and reduced in shallower water along each side of the channel. Although the overall detection range for some receivers was reduced during low tide, striped bass were mostly restricted to deeper channels during these periods (much of the submerged area goes dry at low tide), were the detection range remained high. Thus, striped bass could be detected throughout the entire tidal cycle and data correction to account for receiver range was unnecessary.

**Capture and tagging**

Striped bass were caught by recreational anglers using a variety of common fishing techniques and gear across a range of habitats that act as popular fishing spots throughout the PKD Bay. Anglers employed conventional striped bass angling methods (including spinning and
fly fishing. A variety of artificial lures, including soft plugs and fly lures, were used at the anglers’ discretion, ranging in size from 5-15 cm with 1-3 barbed hook points. Cut bait (mainly mackerel) was also used when available. All striped bass were angled in less than 5 m of water.

Tri-axial acoustic accelerometer transmitters (Model V9AP-1L, 9 mm diameter, 46 mm long, 6.3 g in air, 50 m depth range, min and max delay times 60 and 180 s, accelerometer parameters 5 samples/sec with a 25 sec sample time, 160 day battery life, Vemco Inc., Halifax, NS) were implanted in 35 striped bass (3 separate periods during 2011: early-June, mid-July, and mid-September). Once landed, each fish was removed from the water, hook removed, and a non-lethal blood sample was collected as part of a related study (Chapter 3). Fish were anesthetized in a MS-222 bath and transferred to a V-shaped surgery table lined with pre-wetted neoprene with continuous fresh seawater running over the gills. Transmitters were implanted in the body cavity through a small (2-3 cm) abdominal incision on the ventral side of the fish, and the incision closed with 2-3 interrupted sutures (Ethicon 3-0 PDS II, Johnson and Johnson, New Jersey). Immediately following surgery, striped bass were measured (total length, fork length, and girth to the nearest cm) and held in a floating mesh holding pen (1.2 m x 1.2 m x 1.2 m, 1.5 cm mesh, Memphis Net & Twine Co., Memphis TN) alongside the boat until the fish was actively swimming (< 20 min). All surgeries were performed by the same trained surgeon.

The accelerometer transmitters were calibrated for the raw readings of acceleration in a holding tank at Jones River Landing in Kingston, MA. Six striped bass were angled in the PKD Bay near the Jones River and then transported (< 30 min) in aerated onboard coolers (110-L x -48-W x 46-H) to the holding tank. After a 24-hour acclimation period, individual fish were implanted with accelerometer transmitters in the same fashion listed above and given an hour to recover in the tank. A manual hydrophone (VR100 receiver, Vemco Division, AMIRIX Systems Inc., Halifax, Nova Scotia) was used to record raw acceleration readings given by the implanted
accelerometer. These readings were visually compared with striped bass behavior: categorized as resting on the bottom, swimming in water column, and fast-paced swimming (by chasing fish in tank twice for 2 min). The individual fish were euthanized by cerebral percussion to also observe readings associated with a dead fish.

**Data Analysis**

Prior to analysis, all transmitter data were examined individually and false detections rejected using criteria established by Vemco (Pincock 2012). Only fish detected for more than one day, on more than one receiver, and with more than 50 detections were used in the analysis. Detections within the first 24 hours of tagging were excluded to account for potential impacts from the angling event and surgery (O’Toole et al. 2010). In subsequent analyses, means are reported as ± 1 standard deviation where appropriate.

**Residency**

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

**Space use and Site Fidelity**

To determine the extent of site fidelity within the bay, four zones were created (Figure 2.1) by grouping the receivers into similar habitat types and/or location within the bay to look at
relevant factors that potentially drive specific movement/behavior of tagged striped bass, including activity levels and temporal patterns (depth distribution, acceleration peaks). Total number of detections was tallied for each receiver during the study period. To correct for uneven receiver deployment times, the number of detection per receiver per day was calculated as the total number of detections for the entire study period divided by the number of days each receiver was deployed where fish was still detected within the array (Kneebone et al. 2012).

To determine the site fidelity of striped bass in PKD, a residency index was calculated for each individual by dividing the total number of days spent in each zone by the total number of days spent within the whole array. Values ranged from 0 (no residency) to 1 (residency only in that zone); a value of 0.5 was set as the lower limit for ‘strong’ site fidelity within a zone.

**Center of Activity**

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

Conventional estimators of animal home range and activity space (such as MCP and kernel analysis) were not suitable given the irregular boundaries, presence of islands and salt marshes, and the deployment pattern of the acoustic receivers in PKD Bay (Kneebone et al. 2012). A latticed-based estimator (Barry and McIntyre 2011) was used instead to generate 2-dimensional activity space estimates for all tagged fish. A common approach to defining a home range is to find the smallest area that contains a given proportion of the density (Barry and
McIntyre 2011) and activity space estimates were chosen at 50% and 95% of the density for each individual (Kneebone 2012). Activity spaces (50% and 95%) were calculated weekly (17 weeks; July 3 to October 30) and for the entire season (total activity space) for all tagged fish to assess any changes. Only striped bass detected for at least three days in a given week could be included in this analysis. Experimental estimation of the optimal smoothing parameter (k) using unbiased cross-validation was problematic due to the dispersal of the COA positions (i.e. many positions in the same location and/or in very close proximity). A fixed k value was used instead (Kneebone et al. 2012). All lattice-based estimates of activity space were obtained using the latticeDensity package in R (Barry 2011).

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

**Movement patterns and activity**

To investigate cyclical (i.e. diel, tidal) activity patterns in striped bass movements, spectral analysis was utilized. All detections were binned into hourly intervals (0-23). Photoperiod was used to investigate how environmental cues, including tidal stage, Day/Night (day defined as between 6AM and 6PM), and temperature influenced weekly and hourly
acceleration and depth of individuals; generalized additive mixed models were again used with striped bass incorporated as a random effect. Significant relationships were accepted at p<0.001 (Zuur et al. 2009).

Results

The 35 striped bass implanted with transmitters ranged in size from 38.5-80.5 cm TL with a mean body size of 55.75 ± 12.54 cm. There was no difference in body size of striped bass among the three sampling periods (p= 0.8, ANOVA). Of the 35 fish tagged, 33 were detected over 50 times on multiple receivers (Table 2.1). The two fish not included in the analysis were observed leaving the bay within 2 days of tagging. There were a total of 70,654 reliable detections (35,231 acceleration and 35,423 depth) for the 33 striped bass. During the study, striped bass were detected by 32 out of the total 34 receivers deployed. R16, on the northern point of Clarks Island (Figure 2.1), had the most visits per day deployed, detecting 23 unique fish. Individual striped bass exhibited minimal residence times ranging from 6 to 75 days (mean 30 ± 19 days), and there was a significant relationship between residence time and TL ($r^2=0.287$, df=31, p=0.001) with minimum residence time decreasing with size.

A total of 32 striped bass (97%) were last detected on receivers at the mouth of PKD, with 15% (n=5) being detected between September 5th and September 18th and 76% (n=25) being detected between October 3rd and October 29th. An individual fish (TL=40.1 cm) was last detected on the last day receivers were in the water on R1 (Figure 2.1), therefore emigration could not be confirmed. Of the emigrated striped bass, 67% (n=22) were detected on other receiver arrays south of PKD Bay, including Connecticut, Long Island, and Sandy Hook, NJ. One individual fish (ID= 5804/5805, TL= 40.1cm) was not confirmed to have left the bay before
receivers were hauled (last detected in the northern most marshes within PKB Bay, receiver 1) and was not detected on any of the southern arrays.

**Space Use and Site Fidelity**

Individual receiver detections per day ranged from 0.32 (R33, visited by 6 unique fish) to 231.75 (R2) detections/day (18.88 ± 41.25 detections/day). Tagged striped bass show high site fidelity (Figure 2.2) to zones 1 and 2 (zone 1= 41.93%, zone 2= 25.81%) and less fidelity to zones 3 and 4 (zone 3=19.36%, zone 4=12.9). Six of the tagged striped bass (19.35%) showed residency spread among zones 1, 2, and 3. Only one striped showed high site fidelity in zone 4 (residency in zone 4=0.53), while the majority of the fish (91%) spent less than 10% of their time in zone 4. Spatial use patterns of PKD Bay also change monthly (Figure 2.2), with the greatest proportion of detections found to be highest in zone 1 over the course of the monitoring period. During the month of August, all tagged fish showed restricted movement and were detected only within zones 1 (98% of detections) and 2 (2% of detections). All zones (including zone 4) were utilized only during September and October.

According to the lattice-based home range analysis, striped bass were shown to make use of the range of habitats within PKD Bay (Figure 2.3). Although space use differed among months, striped bass consistently used core habitat in the northern region of the bay (near a large wooden bridge and tidal marshes) and also by Clarks Island. Total activity space varied among individuals, but was there was no significant relationship between body size of the fish and 50% (df=32, t=-0.488, p=0.629) or 95% (df=32, t=1.502, p=0.143) activity space estimates for the 2011 monitoring period (Table 2.2).

Mean weekly activity space varied greatly over the season, ranging from 0.05 to 6.68 km$^2$ (1.7 ± 1.12) 50% and 0.13 to 26.36 km$^2$ (7.78 ± 5.02) 95% (Table 2.2). As the season progressed, there was a noticeable increase in weekly activity space (Figure 2.4). During the
week of August 7 – 13th, mean weekly activity space was at its lowest, and steadily increased in the following weeks. The greatest increases in mean weekly activity space occurred during the month of October, reaching a maximum in the final two weeks of the monitoring period. The results of GAMM analyses (Table 2.2) indicated that both 50% and 95% weekly activity space estimates were significantly related to mean weekly water temperature and week of study. Lower mean water temperatures yielded higher weekly activity space estimates.

**Activity pattern (Depth and Acceleration)**

Laboratory calibration trials indicated that ‘still’ (or dead) fish acceleration readings had mean acceleration readings of $0.076 \pm 0.02 \text{ m/s}^2$. Observations associated with ‘low’ locomotory activity, ranged from $0.17 – 0.88 \text{ m/s}^2$ ($0.48 \pm 0.19 \text{ m/s}^2$) and were generally associated with fish swimming in place or slowly around the tank. Higher levels of observed swimming varied from $1.63 \text{ m/s}^2$ (fast swimming around the tank), $2.02 \text{ m/s}^2$ (some burst swimming - chased), and $3.7 \text{ m/s}^2$ (mostly burst swimming - chased) during the tag’s sampling period of 25 seconds. These values allowed me to estimate fish behavior associated with recorded acceleration readings within PKD Bay.

Wild striped bass acceleration values ranged from $0.081 \text{ m/s}^2$ to $4.901 \text{ m/s}^2$ ($0.8 \pm 0.508 \text{ m/s}^2$) during the study period. Individual mean acceleration readings were within the range of ‘low’ activity and were consistent with laboratory observations (Figure 2.5). Overall, tagged striped bass mainly exhibited low locomotory activity, spending approximately 67% of the time swimming slowly or swimming in place. Analyses of mean weekly acceleration using GAMM showed no significant difference between acceleration and TL of individuals (df=214, p=0.005); Zuur et al. (2009) recommended using $p<0.001$ to confidently choose significant relationships. However, there was a significant relationship for acceleration across the season (df=214,
F=28.47, p<0.001), with acceleration values increasing during periods of higher mean water temperatures (df=214, F=28.32, p<0.001; Table 2.4; Figure 2.6).

Depth distribution of striped bass ranged from 0 -14.95 m (1.96 ± 1.44 m). Mirroring weekly acceleration, mean weekly depth values (Figure 2.6) were found to also be significant across the season (df=214, F=68.04, p<0.001) and for mean weekly water temperature (df=214, F=68.69, p<0.001; Table 2.4). Individuals remained at shallower depths from July 31st through August 13th as well as September 4th through the 10th, when temperatures peaked at 24.3 and 22.4 °C, respectively.

Activity patterns in mean hourly depth and acceleration also showed significant relationships to environmental cues within PKD Bay (Table 2.4). Both were found to be significantly associated with mean hourly water temperature, photoperiod (day vs. night), and zone (see Table 2.4). Body size was not found to be a significant factor for mean hourly depth or acceleration (depth: F=0.47, p=0.49; acceleration: F=4.8, p=0.02). Hourly acceleration was not related to tidal stage (F=12.27, p=0.04; Table 2.4). Greater mean hourly depths and higher acceleration rates occurred during daylight hours (6AM – 6PM), when the temperatures are generally warmest. Acceleration and depth values showed the greatest changes during sunrise and sunset (Figure 2.7). Fish used greater water depths during high and flood tidal stages, and were significantly shallower at night across all tidal stages (Figure 2.8). Acceleration showed no difference between tidal stage, but individuals had reduced acceleration rates at night.

**Discussion**

This telemetry study identified striped bass short-term movement patterns in a non-natal estuary using acoustic transmitting accelerometers. Overall, the majority of tagged striped bass (38.5-80.5 cm TL) took up residency within PKD Bay for the summer months before
emigrating from the bay for potential migration. It is typical of large juveniles (<46cm) and adults to show residency seasonally, particularly during the spring and fall (Able et al. 2012, Able and Grothues 2007, Grothues et al. 2009). Patterns involving residency duration as well as migratory timing within coastal estuaries vary along the east coast of the United States (Able et al. 2012) and a large portion of the Atlantic striped bass population is believed to reside along the coast and estuaries of Massachusetts temporarily during the summer months (Nelson et al. 2006, Mather et al. 2009). It has been previously suggested that these estuaries provide important nursery habitat for juvenile fish (Able et al. 2012), but residency could also be dependent on the presence of important prey species targeted by striped bass (Nelson et al. 2006, Pautzke et al. 2010).

Prior tag-recapture studies observed coastal migration patterns during the fall months (e.g. Boreman and Lewis 1987, Waldman et al. 1999). The present study showed a large portion of striped bass emigrating from PKD Bay and the majority of these fish were also detected on southern arrays (in Connecticut and New Jersey). Consistent with Wingate and Secor (2011) that showed that tidal Hudson River striped bass emigrated from the area at a mean temperature of 15 ± 4 °C, most (69.7%) of the striped bass in our study emigrated from the PKD as the average weekly temperature dropped below 16 °C during the last two weeks of the monitoring period (October 16th – 29th). Only two individuals left the bay prior to September 5th and could have been responding to an unknown potential stressor (i.e. being targeted by a predator, Cooke et al. 2004), or responding to prey availability. However, as these were larger fish (74.9 and 80.5 cm TL), it is not uncommon for them to move offshore earlier than smaller, juvenile fish (Clark 1968). One individual fish (ID= 5804/5805, TL= 40.1cm) was not confirmed to have left the bay before receivers were hauled (last detected in the northernmost marshes within PKB Bay on the last date the receivers were in) and may have been a year round resident.
of this estuary. Able and Grothues (2012) found that small juvenile fish (<46cm) were full time residents of non-natal estuaries in New Jersey. I briefly touch on emigration data in this study; however, further documentation and a more detailed look into coastal migration cues and fine-scale movement patterns during southern movement are needed.

**Activity space and site fidelity**

High survival allowed me to track fish for up to 5 months, documenting seasonal movements and activity space use within PKD Bay. Previous studies have shown that striped bass tend to be associated with habitat providing diverse, vertical relief (such as banks, sandbars, bridges, channel markers and other submerged structures) (Harding and Mann 2003, Ng. et al. 2007). In this study, nearly half of the tagged striped bass in PKD Bay were detected by receivers deployed in areas with a mosaic of habitat types. The striped bass spent the majority of their time within zones 1 and 2 (Figure 2.1), accounting for 88.8% of all detections. Zone 1 includes a variety of submerged structures (such as suspended oyster farms), Powder Point Bridge, a small residential island (Clarks Island), and many sandbars and eelgrass beds. Zone 2 is comprised of deep channels, rock structures, and similar natural features to zone 1. Throughout the study, zone 4 consistently had the lowest proportion of detections and activity space estimates. Although the number of receivers was low in Zone 4 (n=2), they were deployed in channels where striped bass, if present, would likely be detected. Zone 4 is similar to each of the other zones within PKD Bay and contains comparable natural features and habitat variability; however, it is in close proximity to Plymouth Harbor. Plymouth Harbor is a relatively large commercial and recreational boating port with an abundance of anthropogenic activity. Other top predators, such as sand tiger sharks, have been suggested to avoid Plymouth Harbor due to high activity in the area (Kneebone et al. 2012), and striped bass may be also displaying avoidance behavior.
Weekly activity space changed significantly across the study period decreasing throughout the month of August and increasing prior to emigration from the estuary. Significant relationships were also observed between weekly activity space within PKD Bay and mean weekly water temperature. This could potentially explain the decreased activity during the month of August when corresponding higher water temperatures were observed (19.8± 1.5 °C across the bay). A New Jersey study, Ng et al. (2007), also observed a decrease in detection of tagged fish in August, followed by an increase in movement rates during October. They credited the increase in movements to cooler water temperatures and migration from the estuary (Ng et al. 2007). Increases in activity space by striped bass during the end of the season may have also been related to increase foraging prior to emigration from the bay (Pautzke et al. 2010). Menhaden schools were observed to be highly abundant during the season (also documented by Kneebone et al. 2012) and were most likely targeted by tagged individuals. Striped bass typically forage heavily on forage fish, including Atlantic menhaden (*Brevoortia tyrannous*), before migration (Raney 1952; Graves et al. 2009). Ecologically, factors such as water temperature and prey availability could drive striped bass distribution within New England estuaries and could be confirmed by further detailed studies.

**Activity patterns- Depth and acceleration**

Generally, striped bass locomotory activity ranged from stationary holding to bursting activity, although the majority of acceleration rates among individuals demonstrated low locomotory activity typical of striped bass swimming slowly or swimming in place. Although these results may have been influenced by the nature of the transmitting accelerometers (averaging over a 25 second sampling period), other studies focusing on marine species capable of high swimming speeds generally spent most of their time at low, energy efficient speeds (i.e. Wheils 1984; Block et al. 1992; O’Toole et al. 2010; Murchie et al. 2011). Striped bass are
voracious feeders and, according to stomach content analysis, consume almost anything edible in their environment, including marine worms, shrimp, crabs, and prefer forage fish such as menhaden, silversides, and anchovies (Karas 1993; Tupper and Able 2000). Schools of striped bass typically feed on balls of baitfish when available (Karas 1993) and therefore, display higher swimming and burst activity to capture their prey items. Occasionally high locomotory activity (and burst swimming) was observed potentially in pursuit of prey and/or predation avoidance (such as sharks).

Seasonal changes in depth distribution could be linked to changes in foraging behavior (Meyer and Holland 2005; Whitney et al. 2007; Thompson et al. 2011). For instance, Thompson et al. (2011) showed that prey availability is generally found to correspond to depth. In our study, striped bass changed their depth distribution over the course of the study from 0 to 14.95 m. Prey could also be an influencing factor effecting diel increased activity and shallower depth distribution (Thompson et al. 2011). Personal observations of fish feeding and best fishing times (according to local anglers) were early in the morning between 6 and 8 AM and later in the evening between 5-7 PM, which is consistent with observed highest acceleration peaks and shallow depths (Figure 2.6). Future studies could provide further analysis to quantify foraging activity in order to understand the linkage between striped bass movement patterns and their prey.

Individuals remained at shallower depths during the first two weeks of August and first week of September, when temperatures peaked (from 22.4 - 23.2 °C). Water temperature typically drives habitat selection and could affect vertical behavior (Matthews et al. 1985; Suski and Ridgway 2009) for striped bass in temperatures above 21 °C (Thompson et al. 2011). Although striped bass were expected to have a greater depth for relief during the summer months, decreased dissolved oxygen (possibly due to increased nutrient input) could have
pushed striped bass into shallower waters (Tubber and Able 2000). Depths occurring in Zone 4, Plymouth Harbor, were greater, as this zone has a greater mean depth. Activity in other zones seemed to coincide with shallower habitats, sand bars, rocky shores and grass beds and could be driving depth shifts across zones. Diel vertical movements differed for other environmental factors including photoperiod (day and night) and tidal stage (Figure 2.8). As there is a 3m tidal change in PKD Bay, it was expected that the striped bass also show a greater depth during a high tide when there was a greater volume of water in the bay.

Currently, there is a void in ecological behavior and activity levels for striped bass that summer in New England estuaries. Due to their popularity among anglers, the fishery has grown extensively to be one of the most targeted species along the northeastern coast of the U.S., warranting the need for educated management decisions to maintain a healthy fishery and ecosystem. Further documentation of these free-ranging marine species in space and time is important to understanding the fundamentals of their natural history, ecological interactions, and habitat to aid in effective management and conservation efforts.
References


Figure 2.1: Study area in the Plymouth, Kingston, Duxbury (PKD) Bay along the east coast of Massachusetts including the 34 receiver locations (receivers with temperature loggers are underlined). Separate zones (n=4) were created to analyze striped bass movements and are shown in gray text divided by black lines.
Table 2.1: Summary of telemetry data from 35 striped bass tagged with acoustic tri-axial accelerometers in PKD Bay.

<table>
<thead>
<tr>
<th>Tagging Group</th>
<th>Tag ID</th>
<th>Date tagged</th>
<th>TL (cm)</th>
<th>Number of Acceleration hits</th>
<th>Number of Pressure hits</th>
<th>Number of days in array</th>
<th>Number of days detected</th>
<th>Total no. of receiver detected on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>2702/2703</td>
<td>7/5/2011</td>
<td>58.2</td>
<td>466</td>
<td>476</td>
<td>73</td>
<td>25</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>2704/2705</td>
<td>7/5/2011</td>
<td>42.4</td>
<td>1575</td>
<td>1540</td>
<td>115</td>
<td>75</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>2706/2707</td>
<td>7/5/2011</td>
<td>46.3</td>
<td>382</td>
<td>365</td>
<td>106</td>
<td>24</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>2708/2709</td>
<td>7/5/2011</td>
<td>40.3</td>
<td>3067</td>
<td>3036</td>
<td>116</td>
<td>75</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>2710/2711</td>
<td>7/5/2011</td>
<td>71.5</td>
<td>62</td>
<td>78</td>
<td>75</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2712/2713</td>
<td>7/5/2011</td>
<td>38.5</td>
<td>1236</td>
<td>1232</td>
<td>116</td>
<td>56</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>2692/2693</td>
<td>7/6/2011</td>
<td>80.5</td>
<td>302</td>
<td>320</td>
<td>15</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2694/2695</td>
<td>7/6/2011</td>
<td>56</td>
<td>470</td>
<td>473</td>
<td>99</td>
<td>28</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>2696/2697</td>
<td>7/6/2011</td>
<td>59.7</td>
<td>977</td>
<td>1002</td>
<td>90</td>
<td>46</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>2698/2699</td>
<td>7/6/2011</td>
<td>64.8</td>
<td>1271</td>
<td>1245</td>
<td>115</td>
<td>43</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>2700/2701</td>
<td>7/6/2011</td>
<td>72.3</td>
<td>202</td>
<td>211</td>
<td>115</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Group 2</td>
<td>5820/5821</td>
<td>8/12/2011</td>
<td>50.1</td>
<td>3742</td>
<td>3809</td>
<td>62</td>
<td>51</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>5822/5823</td>
<td>8/12/2011</td>
<td>74.9</td>
<td>16</td>
<td>14</td>
<td>18</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>5824/5825</td>
<td>8/12/2011</td>
<td>48.2</td>
<td>551</td>
<td>563</td>
<td>68</td>
<td>31</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>5826/5827</td>
<td>8/12/2011</td>
<td>43.7</td>
<td>2190</td>
<td>2207</td>
<td>77</td>
<td>52</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>5808/5809</td>
<td>8/17/2011</td>
<td>48.2</td>
<td>275</td>
<td>265</td>
<td>20</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>5810/5811</td>
<td>8/17/2011</td>
<td>80.5</td>
<td>167</td>
<td>184</td>
<td>33</td>
<td>14</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>5812/5813</td>
<td>8/17/2011</td>
<td>51.7</td>
<td>2958</td>
<td>2954</td>
<td>72</td>
<td>46</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>5814/5815</td>
<td>8/17/2011</td>
<td>41</td>
<td>3247</td>
<td>3217</td>
<td>72</td>
<td>49</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>5816/5817</td>
<td>8/17/2011</td>
<td>60.5</td>
<td>1140</td>
<td>1177</td>
<td>60</td>
<td>28</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>5804/5805</td>
<td>8/18/2011</td>
<td>40.1</td>
<td>2486</td>
<td>2455</td>
<td>73</td>
<td>40</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>5806/5807</td>
<td>8/18/2011</td>
<td>61.4</td>
<td>555</td>
<td>540</td>
<td>47</td>
<td>31</td>
<td>14</td>
</tr>
<tr>
<td>Group 3</td>
<td>5818/5819</td>
<td>9/10/2011</td>
<td>63.9</td>
<td>3</td>
<td>2</td>
<td>20</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>6368/6369</td>
<td>9/10/2011</td>
<td>45.3</td>
<td>158</td>
<td>151</td>
<td>48</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>6370/6371</td>
<td>9/10/2011</td>
<td>74.4</td>
<td>63</td>
<td>73</td>
<td>15</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>6374/6375</td>
<td>9/10/2011</td>
<td>77</td>
<td>53</td>
<td>56</td>
<td>9</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>6378/6379</td>
<td>9/10/2011</td>
<td>51</td>
<td>38</td>
<td>37</td>
<td>32</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>6380/6381</td>
<td>9/10/2011</td>
<td>56.9</td>
<td>1813</td>
<td>1888</td>
<td>48</td>
<td>28</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>6372/6373</td>
<td>9/11/2011</td>
<td>49</td>
<td>455</td>
<td>518</td>
<td>44</td>
<td>19</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>6360/6361</td>
<td>9/14/2011</td>
<td>44.7</td>
<td>2413</td>
<td>2398</td>
<td>43</td>
<td>41</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6364/6365</td>
<td>9/14/2011</td>
<td>53</td>
<td>134</td>
<td>123</td>
<td>22</td>
<td>7</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>6366/6367</td>
<td>9/14/2011</td>
<td>49.4</td>
<td>316</td>
<td>312</td>
<td>42</td>
<td>13</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>6358/6359</td>
<td>9/15/2011</td>
<td>65.9</td>
<td>397</td>
<td>394</td>
<td>30</td>
<td>27</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>6362/6363</td>
<td>9/15/2011</td>
<td>40.7</td>
<td>1639</td>
<td>1654</td>
<td>45</td>
<td>35</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>6376/6377</td>
<td>10/12/2011</td>
<td>49.3</td>
<td>431</td>
<td>470</td>
<td>16</td>
<td>12</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.2: Proportion of detections of tagged striped bass for each month (July, August, September, and October) across zones (1-4) within PKD Bay.
Table 2.2: Summary of total and weekly activity space estimates, including the results of GLM (looking at relationship between size and 50% and 90% total activity space) and GAMM (generalized additive mixed models) models (TL, average wk temp, time (wk of monitoring period on 50 and 95% weekly activity space). The table shows sample size, range, and mean ± SD of all activity space estimates for 2011. Significant relationships (p<0.001) are in bold.

<table>
<thead>
<tr>
<th>Tagging Group</th>
<th>n</th>
<th>Activity Space (km²)</th>
<th>TL (cm)</th>
<th>Temp</th>
<th>Week</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAS%95</td>
<td>32</td>
<td>4.66 – 32.94</td>
<td>t= -0.488</td>
<td>p=0.629</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(16.51 ± 7.7)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAS%50</td>
<td>32</td>
<td>0.13 – 7.72</td>
<td>t= 1.502</td>
<td>p=0.143</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(2.75 ± 1.58)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WAS%95</td>
<td>214</td>
<td>0.13 – 26.36</td>
<td>t=2.89</td>
<td>p=0.004*</td>
<td>F=58.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(7.78 ± 5.02)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WAS%50</td>
<td>214</td>
<td>0.055 – 6.68</td>
<td>t=4.422</td>
<td>p &lt; 0.001</td>
<td>F=33.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(1.70 ± 1.12)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Zuur et al. (2009) recommends using p<0.001 to choose significant relationships.

TL-total length (cm)

TAS- Total activity space estimate

WAS- mean weekly activity space estimate
Figure 2.3: Estimates of striped bass 95% activity space within PKD Bay across months of study period (July, August, September, and October) and total activity space.
Figure 2.4: Mean weekly activity spaces (95% and 50%) for 2011 (17 weeks) ± 1 standard deviation. Dark gray circles represent 95% activity space and light gray squares represent 50% activity space.
Table 2.3: Summary of mean weekly depth and acceleration, including results from GAMM (looking at relationship between size, mean weekly temperature, week). Table shows sample size, range, and mean ± sd of all mean weekly depth and acceleration for 2011. Significant relationships (p<0.001) are in bold.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>n</th>
<th>Sensor Value (depth=m, acc= m/s^2)</th>
<th>TL</th>
<th>Temp</th>
<th>Week</th>
</tr>
</thead>
<tbody>
<tr>
<td>DWK</td>
<td>214</td>
<td>0.43 – 4.04 (1.37 ± 0.57)</td>
<td>F= 0.18</td>
<td>p= 0.67</td>
<td>F=68.69 p&lt; 0.001</td>
</tr>
<tr>
<td>AWK</td>
<td>214</td>
<td>0.43 – 3.65 (1.37 ± 0.63)</td>
<td>F= 8.256 p= 0.005*</td>
<td>F=28.32 p&lt; 0.001</td>
<td>F=28.47 p&lt; 0.001</td>
</tr>
</tbody>
</table>

*Zuur et al. (2009) recommends using p<0.001 to choose significant relationships.

TL-total length (cm)

DWK- mean weekly depth (m)

AWK- mean weekly acceleration (m/s^2)
Table 2.4: Summary of mean hourly depth and acceleration (acc), including results from GAMM (investigating relationship between size, tide stage, zone, temp, photoperiod). Table shows range and mean ± sd of mean hourly depth and acceleration for 2011. Significant relationships (p<0.001) are in bold.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Sensor Value (depth=m, acc=m/s²)</th>
<th>Size (TL)</th>
<th>Stage</th>
<th>Temp</th>
<th>Zone</th>
<th>Day/Night</th>
<th>Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>0 – 14.95 (1.96 ± 1.43)</td>
<td>F= 0.47</td>
<td>p= 0.49</td>
<td>F= 1145.3</td>
<td>p&lt; 0.001</td>
<td>F= 58.11</td>
<td>p&lt; 0.001</td>
</tr>
<tr>
<td>Acc</td>
<td>0.068 – 4.9 (0.8 ± 0.51)</td>
<td>F= 4.8</td>
<td>p= 0.02*</td>
<td>F= 12.27</td>
<td>p&lt; 0.04*</td>
<td>F= 28.39</td>
<td>p&lt; 0.001</td>
</tr>
</tbody>
</table>

*Zuur et al. (2009) recommends using p<0.001 to choose significant relationships.

TL-total length (cm)
Figure 2.5: Frequency histogram of wild striped bass acceleration (m s$^{-2}$). Lab calibration values of accelerometers are included for relative comparison with acceleration values collected from wild fish.
Figure 2.6: Seasonal patterns of mean weekly depth (Top), acceleration (middle), and temperature (bottom).
Figure 2.7: Diel patterns in average depth (top), acceleration (middle), and temperature (bottom) binned by hour of day (0 – 23 hrs) pooled for the entire season.
Figure 2.8: Mean depth (top) and mean acceleration (bottom) for day (6AM-6PM) and night are displayed for each tidal stage, ebb, flood, high, and low.
CHAPTER 3

PHYSICAL INJURY, PHYSIOLOGICAL STRESS, AND POST-RELEASE ACTIVITY PATTERNS ON STRIPED BASS A MASSACHUSETTS ESTUARY FOLLOWING CATCH-AND-RELEASE RECREATIONAL ANGLING

Abstract

Striped bass are highly targeted by recreational anglers along the Atlantic coastline and are an important source of revenue for the sport fishing industry. With both voluntary and mandatory catch-and-release being practiced by recreational anglers, it is important to understand the physical and physiological consequences associated with an angling event in order to apply this knowledge to best-handling practices. The purpose of this study was to 1) quantify physical injury and physiological stress of striped bass in a New England coastal estuary following capture via rod and reel, and 2) measure post-release activity patterns on a subsample of fish using tri-axial accelerometer transmitters after release. A total of 102 striped bass were angled and blood sampled between July and November 2011. A subsample of 35 striped bass captured in three separate months (July n=11, August n=11, September n=13) were implanted with tri-axial acoustic accelerometers to assess relative behavior and survival post-release. Results from principle component analyses produced five factors describing 72.7% of the variance for blood physiology parameters, total length, and water temperature. Subsequently, only eigenvalues from PC1, with high loading for blood lactate, plasma sodium and chloride, and total length, were significantly correlated with fight time. Eight individual fish were detected within 12 hours of release and exhibited their greatest mean daily activity space estimate within that time (1.5 km$^2$ ± 0.6, 50%; 5.6 km$^2$ ± 2.2, 95%). Depth ranged from 0-6.15 m (1.89±1.3 m) and acceleration ranged from 0.095-3.51 (0.95±0.33). In summary, no observed immediate or
long-term mortality suggests that fish were able to recover from the physical and physiological impacts of angling.

**Introduction**

Recreational angling is a popular past-time activity in the United States and a greatly valued resource for the economy (Cooke et al. 2002). Striped bass (*Morone saxatilis*) are highly targeted by resident and visiting recreational anglers along the Atlantic coastline and are an important source of revenue for the sport fishing industry (Karas 1993). In 2006, more than 75% of recreational anglers fishing in saltwater along the coast of Massachusetts (approximately 225,000 individuals) were specifically targeting striped bass, spending in excess $350 million (U.S. Fish and Wildlife Service 2008).

In coastal marine systems, increases in fishing effort, and possibly increased efficiency of present-day anglers, have contributed to high exploitation (Post et al. 2002, Coleman et al. 2004, Arlinghaus and Cooke 2008, Cooke and Schramm 2007). In the past, populations of striped bass along the Atlantic coast have seen periods of decline (U.S. Fish and Wildlife Service 1983) suggesting impacts related to harvest and other related activities. Any overexploitation can ultimately affect biodiversity and through trophic interactions, the entire ecosystem (Cooke and Cowx 2004, Cooke and Schramm 2007).

To reduce mortality associated with commercial and recreational fishing, management tools, such as bag limits and size restrictions, have been established, thus, resulting in mandatory catch-and-release (Karas 1993, ASMFC 2011). There is also a growing trend among recreational anglers targeting striped bass to practice catch-and-release voluntarily as a conservation measure (Cooke and Cowx 2004; Arlinghaus et al. 2007). In theory, catch-and-release angling should reduce the negative impacts imposed by a fishing event on individual fish, yet there is increasing evidence that this is not always the case (Cooke et al. 2004). Angling
events include several techniques that can cause varying degrees of physical damage, physiological stress, and post-release effects (Arlinghaus et al. 2007). These factors could influence the sustainability of striped bass and, ultimately, should be considered when incorporating catch-and-release methods into fisheries management plans (Mather et al. 2009).

There is growing body of literature documenting the sub-lethal consequences of catch-and-release including physiology and angling injury (Cooke et al. 2002, Bartholomew and Bohnsack 2005, Cooke and Suski 2005). There is also an abundance of literature documenting short-term mortality associated with catch-and-release practices (Muoneke and Childress 1994, Arlinghaus et al. 2007). In some instances, individual fish do not survive after release (Millard et al. 2003; Graves et al. 2009). Fish that do survive an angling event are impacted by physical and physiological (both anthropogenic and environmental) stressors that could ultimately disrupt normal behavior post-release (i.e. feeding behavior; O’Toole et al. 2010; Murchie et al. 2011). Other possible outcomes include increased susceptibility to diseases, vulnerability to predation, reduced reproductive success, and reduced fitness (Muoneke and Childress 1994; Tomasso and Isely 1996; Arlinghaus et al. 2007; Skomal and Mandelman 2012).

Interestingly, despite the popularity of striped bass as a recreationally targeted species, very little has been done to examine how striped bass in coastal waters respond to the potential stresses associated with angling events. Existing studies have focused on striped bass in freshwater systems (both stocked in reservoirs and occurring naturally in coastal rivers) that are devoid of certain potential stressors, such as large predators (Cech et al. 1996, Tomasso et al. 1996). Other angling-based studies on striped bass are limited in scope, focusing on issues such as mortality related to handling and physical damage caused by hooking (Diodati and Richards 1996; Millard et al. 2003; Meka 2004, Tomasso et al. 1996, Nelson 1998). There is evidence that environmental stress and stress-induced mortality is potentially greater for striped bass in
freshwater ecosystems (Cech et al. 1996; Tomasso et al. 1996), however, the presence of large predators and other environmental factors not usually found in freshwater ecosystems may add to post-release stress, potentially increasing behavioral impairment and mortality (Cooke et al. 2004, Danylchuk et al. 2007). With a void in related research, it is important to understand how angling can influence physiology, survival, and post-release behavior of individual coastal striped bass to ensure that the benefits of catch-and-release, when used as a conservation and management tool, are not overestimated.

The goal of this study was to quantify physical injury, physiological stress, and post-release activity patterns of striped bass following catch-and-release in a Massachusetts coastal tidal bay. First, I examined physical consequences and physiological stress response of coastal striped bass exposed to catch-and-release angling and those characteristics of the angling event that influenced such measurements. Secondly, I used acoustic transmitters with pressure and tri-axial accelerometer sensors on a subset of angled striped bass to measure post-release movement and activity levels.

**Materials and Methods**

**Study Site**

The study area included the Plymouth, Kingston, and Duxbury (PKD) Bay (42° 42’41.59" N, 70° 47’41.89” W), approximately 50 km south of Boston, Massachusetts. This coastal embayment serves as a popular fishing destination for recreational anglers targeting striped bass. PKD Bay (8,240 ha) is dominated by geographical features including two barrier beaches that together form a 1.6 km wide inlet connecting the embayment to the much larger Cape Cod Bay. PKD Bay contains one small residential island, Clarks Island, in the northern portion of the bay. There are also several inflows, including Jones River in Kingston and Eel River in Plymouth.
PKD Bay is relatively shallow, averaging 2-3 meters and ranging from a several centimeters to 20 meters in boating channels. Characteristics of PKD Bay include large channels surrounded by sand and mud flats, salt marshes, and tidal creeks that are partially or completely exposed at low tide (Kneebone 2012).

**Capture**

To evaluate the impacts of catch-and-release fishing on individual striped bass, fish were sampled while working with volunteer recreational anglers from small boats in the PKD bay (during bass tournaments as well as opportunistic fishing trips with experienced and beginner anglers). Anglers employed conventional striped bass capture methods, including spinning and fly fishing gear. A variety of artificial lures, including soft plugs and fly lures, were used at the anglers’ discretion, ranging in size from 5-15 cm with 1-3 barbed hook points. The use of natural bait has previously been suggested to lead to deeper hooking (Meka et al. 2004), therefore cut or live bait (mainly mackerel) was also used when available. All striped bass were angled in less than 5 m of water.

For each fish, date and time of hook up, observers to the event, specific location, and point of capture (e.g., boat) was measured. The duration of each fishing event and handling time was noted to the nearest second (fight time, hook removal, time involved to collect a blood sample, and total duration of handling/time out of water before release were noted). Variables related to the angler include total years of fishing/ years fishing for striped bass, level of experience, and fishing gear type used (gear type, rod size, line type and strength, leader type and strength, hook size and style, lure or bait type). I measured observed environmental conditions including weather, sea state, wind conditions, water temperature, water depth, and air temperature.
**Physical Trauma**

All angled striped bass were examined for physical injuries after being landed. Relative hooking depth was measured from the tip of the snout to the point of hook entry and corrected for the total length for comparison among fish sizes as outlined by Cooke et al. (2001). Hooking location was categorized as critical (gills, gullet, eyes) or non-critical (jaw, hinge, roof of mouth, foul hooked in body) using the criteria of Meka (2004) and Arlinghaus et al. (2008). Angling related injury was quantified as minor (minimal or no tissue damage and less than two cumulative injuries in non-critical areas) or severe (critical hook location and three or more critical injuries including tissue damage, foul hooking, and line wrap). Presence of bleeding (either present or absent) at the hook site and ease of hooking (>30 s = easy, <30 s = hard) was also recorded (O’Toole et al. 2010).

**Physiological Profiling**

For each individual fish landed, approximately 1.5 mL of blood was drawn from the caudal vessel using a 21-gauge needle into a 3 mL vacutainer containing lithium heparin (BD vacutainer blood collection tube). Time allowed for blood drawing was recorded, with any sample taking more than 45 s being noted for potential added stress (Shultz et al. 2011). Blood samples were held in an ice water slurry prior to blood analyses. Following the blood sampling, fish were measured for total length, fork length, and girth (to the nearest mm). Lactate and glucose levels were measured from whole blood samples with handheld glucose (ACCU-CHEK glucose meter, Roche diagnostics Corp., Indianapolis, IN) and lactate (Lactate Pro LT-1710 portable lactate analyzer, Akray Inc., Kyoto, Japan) meters. Appropriate standards and calibrations were used with handheld meters prior to analysis as per manufacturer guidelines. The Lactate Pro has previously been validated for fieldwork physiology (Pyne et al. 2000, Mizock 2002) including fish (Venn Beecham et al. 2006). Packed cell volume (PCV) was measured following centrifugation in
a hematocrit spinner as the proportion of packed red blood cells to the total volume of the sample. These field diagnostic tools have been previously verified for use on fish by comparing data obtained in the field to laboratory derived data (Venn Beecham et al. 2006; Cooke et al. 2008).

The remaining whole blood sample was centrifuged (Clay Adams Compact II Centrifuge) at 10,000× gravity for 5 minutes. The plasma samples were separated by pipette after spinning and transferred to two 0.5 mL standard micro test tubes and immediately stored in a liquid nitrogen dry shipper (at a minimum of -80° C) until laboratory analyses can be conducted. In the laboratory, plasma cortisol was quantified using a fully validated direct enzyme immunoassay (EIA; see Carey and McCormick 1998). To assess the levels of plasma Ca\(^{2+}\), K\(^+\), Na\(^+\), and Cl\(^-\), samples were run using Nova Biomedical StatProfile pHOX blood gas analyzer (Nova Biomedical Corporation, Waltham, MA).

**Reflex Assessment**

Measuring the presence of reflex actions in fishes can provide an integrative measure of fish condition and predict survival (Davis 2010, Cooke et al. 2011). In this study, striped bass underwent reflex and mortality predictors (RAMP) assessment indicated by the presence or absence of the following reflexes: operculum, mouth, dorsal fin, gag, body flex while the fish was held in the water just prior to release. To measure the operculum reflex, opercular movement was observed. Mouth reflexes were tested by pulling open the lower jaw to see if the mouth closes again. Similarly, the dorsal fin reflex was recorded as present if the individual raised its dorsal fin after it is laid flat against the body. The gag reflex required the back of an individual’s tongue to be pushed down to observe a contraction of the esophagus; no muscle contraction was recorded as an absent reflex. The body flex was measured by holding the individual and gently flexing the caudal peduncle to one side, if there was resistance or a tail
thrust the reflex was recorded as present. Using these data, a reflex impairment index value was calculated for each individual to serve as an indicator of relative condition (Cooke et al. 2011).

**Receiver deployment and acoustic monitoring**

An array of 34 fixed acoustic receivers (VR2W, Vemco Division, AMIRIX Systems Inc., Halifax, Nova Scotia) was deployed from the first week of May 2011 through October 2011 (FIGURE 2.1). Receivers were deployed to maximize coverage in the bay while creating nodes that corresponded with transitions between habitat types (e.g., shallow flat to deep channel). The configuration of the study site has only one small inlet; therefore, a curtain of receivers was deployed across the mouth to capture immigration and emigration from the bay. Acoustic detection limits were tested using a subset of receivers deployed in various depths and substrates (e.g. tidal flats and channels). The detection radius of receivers ranged from \(\sim 100\) m in water depths \(<3\) m to \(\sim 350\) m in water depths \(>5\) m (see Chapter 2 for more details).

To examine potential effects of temperature on post-release behavior of striped bass within PKD Bay, several temperature loggers (model HOBO Pendant, Onset Computer Corporation, Onset, MA) were deployed at pre-determined receiver locations (n=13) throughout the estuary to record temperature readings (°C) every 30 minutes with an accuracy of ±0.7 °C (range -20 to 70 °C).

**Tagging**

Tri-axial acoustic accelerometer transmitters (V9AP-1L, 9 mm diameter, 46 mm long, 6.3 g in air, 50 m depth range, min and max delay times 60 and 180 s, accelerometer parameters 5 samples/sec with a 25 sec sample time, 160 day battery life, Vemco Inc., Halifax, NS) were implanted in 35 striped bass (3 separate periods during 2011: early-June, mid-July, and mid-September). Once landed, each fish was removed from the water, hook removed, and a non-
lethal blood sample was collected. The fish was anesthetized in a MS-222 bath (approximately 100 ppm) and transferred to a V-shaped surgery table lined with pre-wetted neoprene with continuous fresh seawater running over the gills. Transmitters were implanted in the body cavity through a small (2-3 cm) abdominal incision on the ventral side of the fish and closed with 2-3 interrupted sutures (Ethicon 3-0 PDS II, Johnson and Johnson, New Jersey). When within the range of an acoustic receiver (roughly 400-600m, Model VR2W, Vemco Inc., Halifax, NS), these tags provide presence and absence data with a time stamp and alternating pressure and acceleration readings with a nominal delay between 60 and 180 seconds. Immediately following surgery, striped bass were measured (total length, fork length, and girth to the nearest cm) and held in a floating mesh holding pen (1.2 m x 1.2 m x 1.2 m, 1.5 cm mesh, Memphis Net & Twine Co., Memphis TN) alongside of boat until visually recovered (active swimming). Recovery time was limited to a minimum of ten minutes and a maximum of 20 minutes to reduce potential confinement stress. Careful time measurements were recorded throughout the tagging event including: fight time, time related to hook removal, time to complete blood sample, anesthesia time, surgery time, measurement time, recovery time, and time release from recovery pen.

The accelerometer transmitters were calibrated for the raw readings of acceleration in a 5,700 L outdoor holding tank at the Jones River Landing Environmental Heritage Center in Kingston, MA. Six striped bass were angled in the PKD Bay near the Jones River and then transported (< 30 min) in aerated onboard coolers (110-L x -48-W x 46-H) to the holding tank. After a 24-hour acclimation period, individual fish were implanted with accelerometer transmitters in the same fashion listed above and given an hour to recover in the tank. A manual hydrophone (VR100 receiver, Vemco Division, AMIRIX Systems Inc., Halifax, Nova Scotia) was used to record raw acceleration readings given by the implanted accelerometer. These readings were visually compared with striped bass behavior categorized as resting on the
bottom, swimming in water column, and fast-paced swimming (by chasing fish in tank twice for 2 min). Individual fish were euthanized by cerebral percussion and allowed to rest on the bottom of the tank to observe readings associated with a dead fish (see Chapter 2 for results).

Data analysis

**Physical Injury**

Hooking related injury was assessed using contingency table analysis to determine relationships between categorical variables such as hook placement or hook type with bleeding, severity of injury (critical vs. non-critical), ease of hook removal, and length corrected hooking depth (Zar 1996, O’Toole et al. 2010). Length corrected depth was $\log_{10}$ transformed to meet the assumption of normality and homogeneity of variance.

**Physiology**

Regression analysis was used to determine whether there was a relationship between body size and angling variables including fight time, time to bleed, and total handling time (Zar 1994). Baselines (fish that were “minimally stressed”) were identified as fish angled for less than one minute (Landsman 2013), and relative percent changes from baselines were compared using a t-test to determine between stress state and “minimally stressed” individuals (Skomal 2007). Although fight time and hook removal is a measurement that is reflective of an angling event, the additional time to bleed and/or surgery time was not. Therefore, for all analyses that quantified the relationship between the nature of the angling event and physiological impacts, I used fight time, bleed time and total angling time (fight time plus hook removal handling time) as independent variables.

Physiological variables were subjected to a multivariate principle component analysis (PCA) with varimax rotation (Kaiser 1960; Tabachnick and Fidell 1989) to relate physiological characteristics to the angling event. Included in the PCA were physiological parameters (blood
glucose and lactate, PCV, and plasma cortisol, chloride, potassium, calcium, and sodium). Total length and water temperature were also included since these could covary with the physiological response. Only principle factors with eigenvalues greater than 1 were used to determine the relationship between physiological factors and the angling event. Factors with eigenvectors greater than 0.4 or less than -0.4 were used to characterize each principle component (Kaiser 1960). Simple linear regression was used to compare the rotated principle components against fight time and start bleed time. For categorical factors (i.e. hook placement, reflex index) rotated principle components were compared using one-way ANOVA.

Reflex impairment index values were compared to the total duration of the angling event (angling time plus handling time) using logistic regression, as the reflex indices were measured just prior to release (Zar 1996). RAMP indexes were not measured for fish that underwent surgery.

**Activity and Movement**

Striped bass post-release survival was determined if an individual was detected on multiple receivers (moving freely) within PKD Bay for at least 48hrs within the transmitter’s battery life or was detected leaving the bay at any point post-release. Mortality was assumed if an individual was continually detected on a single receiver for multiple days or suddenly not detected without showing evidence that the fish left PKB Bay (Hightower et al. 2001, Kneebone et al. 2012).

Because most recovery happens within 48 hours of an angling event (Muoneke and Childress 1994), tagged striped bass were only included in subsequent post-release analyses if they were detected within the first two days of the angling event. In order to capture to full scope of the potential recovery-period, post-release movement and activity analyses was restricted to the first full 14 days after the release of a fish.
Data exploration showed a high level of correlation between water temperature and sampling period. An analysis of variance (ANOVA) was used to compare the size of striped bass among sampling periods for tagged individuals. To establish whether total length or water temperature differed between sampling groups in July, August, and September, analysis of variance was used (ANOVA). Pending no significance for total length among the sampling periods, data were pooled accordingly.

To understand the short-term behavior of striped bass after an angling event, the center of activity (COA) for each tagged striped bass was calculated every 30 minutes (see Simpfendorfer et al. 2002). COA positions were then utilized to calculate the activity space of tagged striped bass within PKD Bay and how that changes over time. A latticed-based estimator (Barry and McIntyre 2011) was used to generate 2-dimensional activity space estimates for all tagged fish. A common approach to defining a home range is to find the smallest area that contains a given proportion of the density (Barry and McIntyre 2011), and activity space estimates were chosen at 50% and 95% of the density for each individual (Kneebone 2012). Activity spaces (50% and 95%) were calculated daily for 14 days post-release for all tagged fish to assess any changes. A fixed value for the optimal smoothing parameter (k) was used (see Chapter 2 for further details). All lattice-based estimates of activity space were obtained using the latticeDensity package in R (Barry 2011).

In order to understand activity changes for striped bass after an angling event, mean depth and mean acceleration readings were calculated for each day post-release (for a total of 14 days) for each individual. Movement and mean daily activity data (activity space, depth, and acceleration) was evaluated using two-way repeated measures ANOVA (since daily activity space estimates consisted of repeated measures for an individual, thus violating the assumption of independence (Girden 1992)).
If most recovery happens within 48 hours of tagging (Muoneke and Childress 1994), a fish’s activity during the first 2 days should be the most likely to show a relationship to post-release activity and movement. Therefore, regression analysis was also used to determine whether there is a relationship between angling event variables (fight time and handling time) and mean activity space estimates (50% and 95%), mean acceleration, and mean depth of tagged fish for those first two days post release.

All statistical analyses were conducted using statistical software program R v. 3.0 (R Development Core Team 2011). A probability level of α=0.05 was the significance threshold used in all statistical analyses, and means are reported as ± 1 standard deviation where appropriate.

**Results**

**Angling and Tagging**

Over the course of the sampling period, a total of 102 striped bass were captured ranging in size from 19.5 to 88 cm TL (57 ± 13.3 cm). Anglers ranged in experience from beginner (n=1), average (n=4), to expert (n=9). Blood sampling occurred over periods where surface water temperatures ranged from 9.4 to 22.8 °C. Fight time of all angled striped bass ranged from 29 - 451 seconds (129.22 ± 78.63 sec) and was positively related to total length ($r^2=0.18$, df=98, $p<0.001$). Time to bleed ($r^2=0.173$, df=98, $p<0.001$) and total handling time ($r^2=1.17$, df=98, $p<0.001$) were also positively related to total length.

Tagged striped bass (n=35) ranged from 38.5 to 80.5 cm TL (55.75 ± 12.54 cm). Total length of the tagged striped bass did not significantly differ between the three sampling groups in July, August, and September (df=2, F=0.155, $p=0.85$). Water temperature did significantly
differ between sampling periods (df=2, F=6.29, p=0.005) being warmest during the August sampling.

**Physical Trauma**

Hook depth ranged from 3 – 102mm (35 ± 28 mm) while length-corrected hooking depth ranged from 0.004 – 0.261 (0.069 ± 0.061) of the body length. Most fish preferred and hit artificial lures (especially soft 4-5 inch plugs) throughout the season (live or cut bait, n=9; artificial plug, n=56; fly, n=37). The majority of hooking locations were identified as non-critical (n=87), with twelve fish showing critical injuries (i.e. hooked in gullet or gills). The inexperienced angler’s fish had difficult hook removal (greater than 30 sec) 80% (>30s, n=8; non-critical, n=6, critical, n=2) of the time, whereas 25% (n=17) of the experts’ catches (fly rod, n=4; spinning, n=10; critical, n=3) were difficult. Blood from a hooking injury was present in 20% of all angled striped bass. Contingency table analysis results did not reveal an association among types of lure (bait, lure, fly) and the severity of injury ($\chi^2=1.09$, df=2, p=0.58), presence of bleeding ($\chi^2=2.16$, df=2, p=0.34), hook placement ($\chi^2=13.9$, df=10, p=0.1776), or ease of hook removal ($\chi^2=2.24$, df=2, p=0.33). One-way ANOVA also failed to reveal differences among the three lure types and the mean length-corrected hooking depth (df=2, F=0.05, p=0.95).

**Physiological Assessment**

PCA on blood physiology parameters produced five factors describing 72.7% of the variance in the physiology variables used in this study (Table 3.1). Principle component 1 (PC1) accounted for 24.1% of the variance and was characterized by high positive factor loadings for blood lactate, chloride, sodium, and total length (Table 3.2). Principle component 2 (PC2) described 15.3% of the variance and was characterized by factor loading for high plasma cortisol and low water temperature. Principle component 3, 4 and 5 (PC3, PC4, and PC5) accounted for 12.6%, 10.6% and 10.1% of the variance respectively. PC3 was characterized by high calcium
and low potassium, where PC4 loaded with both low PCV and water temperature. Finally, PC5 was characterized by low blood glucose and potassium (Table 3.2). Of the principle components generated, only PC1 was significantly related to fight time ($r^2=0.3449$, df=62, p<0.001) and start bleed time ($r^2=0.39$, df=62, p<0.001) with scores increasing with duration.

When compared to baseline values in fish angled under one minute, several physiological factors of ‘stressed’ fish were elevated. More specifically, following a Welch Two Sample t-test, blood lactate (p<0.001) as well as plasma sodium (p=0.0018) and chloride (p=0.006) were the only parameters to display significant differences from the controls.

**Reflex Assessment**

A total of twenty striped bass (32.8%) showed no sign of reflex impairment for any of the five indices used (Table 3.3). Twenty-one striped bass (34.4%) exhibited impairment for one of the five indices (gag: n=5; body: n=16). Of the angled striped bass, 26.2% exhibited two impairments (1 mouth, 12 gag, 3 fin, 16 body) and 6.6% exhibited three impairments (1 operc, 2 mouth, 4 gag, 1 fin, and 4 body). Of the striped bass with three impairments, all of them were categorized as having critical injuries (hooked in gills or gut) and angled using J hooks.

**Post-Release Behavior**

All 35 tagged striped bass were detected within 4 weeks of the event on multiple receivers and considered alive. Four individuals (11.4%) were not detected within the first two weeks of release, however, all fish were detected continuously on multiple receivers within 27 days post-release. The number of fish detected in the first 12 hrs post release was low, only eight fish. Each of the eight fish moved from their tagging location to areas near Eel River or Jones River inflows following release. They also exhibited their greatest mean daily activity space estimate within the 12 hours of release ($1.5 \text{ km}^2 \pm 0.6$).
There were 29 fish (82.8%) detected within the first two days of the angling event and continuously detected for a two-week period, and were, therefore, included in the analyses. Daily estimated activity space over the first 14 days post-release ranged from 0.13 – 13.69 km (95%) and 0.007 – 3.95 km (50%). Activity space estimates were not significantly related to day post-release (Figure 3.2).

Acceleration was significantly related to time post-release in July (df=14, F=2.52, p=0.003), where acceleration increased with day post-release (Figure 3.2). Depth data showed noticeable differences among sampling groups, as a result, fish were separated by sampling month (July, August, and September) to analyze depth data. Depth was found to be significantly related to day post-release in fish tagged in July (July: df=14, F=1.95, p=0.02), with depth becoming greater with time post-release (Figure 3.2). Depth during the August sampling period remained relatively constant between (1-1.8m) over the 14 day post-release monitoring period (Figure 3.2).

In addition, activity space estimates post-release ranged from 0.01-3.95 km\(^2\) (1.14±0.6 km\(^2\); 50%) and 0.13-13.69 km\(^2\) (4.49±2.2 km\(^2\); 95%). Depth ranged from 0-6.15 m (1.89±1.3 m) and acceleration ranged from 0.095-3.51 (0.95±0.33). Following regression analysis of post-release behavior during the first two days (mean activity space, depth, and acceleration) and angling variables (fight time and total handling time), neither fight time nor total handling time produced a significant relationship.

**Discussion**

**Physical Injury**

During an angling event, minor injury to an individual fish is inevitable (Arlinghaus et al. 2007) due to the nature of hooking the fish and reeling them to the side of the boat or up the beach/jetty. In this study, lure type was not significantly related to severity of injury, presence
of bleeding, or hook placement, though most fish seemed to prefer and hit artificial lures (especially soft 4-5 inch plugs) throughout the season. J hooks have been found to potentially be a confounding factor in post-release behavior and survival in already severely stressed individuals (Cooke and Suski 2004). Circle hooks, on the other hand, have been shown to decrease the incidence of a critically injured fish (Cooke and Suski 2004). Prior studies have demonstrated that the extent of a hook related injury and likelihood of damage to vital organs in a fish can be influenced by number and style of hooks and the type of bait used (Millard et al. 2003). Diodati and Richards (1996) suggested that lure type (artificial or bait) can influence the severity of physical injury and probability of mortality in striped bass. Nelson (1998) studied caught-and-released striped bass in the Roanoke River, North Carolina and found that most striped bass caught on artificial lures were generally hooked in the jaw and mouth, whereas fish caught with live bait were more likely to be deep hooked. A greater sample size using a wider diversity of baits and hook types may add additional insights into hooking injury and mortality for striped bass in their summer estuaries.

**Physiological Assessment**

An angling event unavoidably causes some level of physiological disturbance for fish (Arlinghaus et al. 2007, Cooke and Sneddon 2007). In my study, it was indicated by comparison to controls and in PC1 that angling related exercise caused significant physiological disturbances in blood lactate as well as plasma ions sodium and chloride. Previous studies have shown that when fish are angled to exhaustion, lactic acid builds up in the tissues of the fish from increased muscle function and anaerobic activity (Wood 1991; Wang 1994, Skomal and Mandelman 2012). Rising levels of hormones caused by an angling event can also lead to an increase in red blood cells released from the spleen for the uptake of Na\(^+\) and Cl\(^-\) ions to aid in increasing the O\(_2\) delivery throughout the fish’s body during the angling event (Pickering and Pottinger 1998).
Plasma acidification occurs as pH decreases in the blood stream leading to increases in Cl⁻ ions to buffer pH disturbances (Thompson et al. 2002). The adrenaline produced during exercise disturbs the individual’s natural osmoregulation and ionic balance (Moyle and Cech 1996, Arlinghaus et al. 2007). Primary responses may also lead to increases in the permeability and gill-diffusing capacity to aid in oxygen demands, therefore a stress response could include the loss of water and gain of ions across the gills (O’Toole et al. 2010). Tomasso et al. (1996) found blood lactate and plasma sodium to increase proportionally with playing time in striped bass angled in freshwater.

None of the remaining principle components were found to be significantly related to fight time even though PC2 and PC5 showed high factor loadings for characteristics commonly associated with increased stress, such as cortisol and glucose (Barton 2002, Skomal and Mandelman 2012). Though statistical power was low when comparing angling and bleed time for the principle components loading with many non-significant effects, this may be explained by the short period of time from capture to blood sampling that may not have allowed some parameters to peak (Landsman et al. 2011). For instance, plasma cortisol concentrations for juvenile Chinook salmon (*Oncorhynchus tshawytscha*) peaked after one hour from the final stressor (Barton et al. 1986). Cortisol (known as the ‘stress hormone’) is released, as a fish’s primary response to exercise, aiding in the mobilization of energy reserves (Suski et al. 2007, Skomal and Mandelman 2012). However, observed cortisol levels in most fishes tend to peak between 0.5-1 hr (Cech et al. 1996, Barton et al. 2002). Tomasso et al. (1996) did not find cortisol levels to increase with playing time until after 2.5 min in freshwater during the summer, and they did not rise during the fall. Davis and Parker (1990) reported striped bass to have a robust cortisol response that was temperature-sensitive, and results from the current study support this observation.
Although not significant here, biochemical changes include the rapid mobilization of glucose to the blood to meet energetic demands (causing hyperglycemia) (Cooke et al. 2002). Tomasso et al. (1996) looked at glucose levels of angled striped bass in freshwater during the summer (26-32°C) and fall (16-19°C), and found that hyperglycemia was only evident during the summer and not the fall. Davis and Parker (1990) found glucose levels in striped bass to increase only after a delay of up to an hour at temperatures of 10 and 21°C. It has also been noted that striped bass angled in saltwater versus freshwater may show decreased physiological stress from an angling event (Landsman et al. 2011). Higher salinity levels may aid in moderating physiological imbalances associated with stress by helping to improve potential osmoregulatory dysfunction and electrolyte imbalances that result from stress (Harrell 1988).

In any case, angling time was found to be a significant stressor in Atlantic striped bass. Although I did not measure the physiological recovery profile for striped bass in my study, no immediate or long-term mortality was observed, suggesting that fish were able to recover from the physical and physiological impacts of angling.

**Reflex Impairment**

Another metric that has been used to assess the impacts related to catch-and-release angling on sport fish is examining the degree of reflex impairment (Landsman et al. 2011; Raby et al. 2012). Reflexes are tested as a rapid, overall measure of stress and condition (Davis and Ottmar 2006). My study observed no mortality for angled striped bass and, therefore, no conclusions could be drawn for correlations between mortality and the absence of particular reflexes. Even so, anglers can still use reflex impairment to assess individual fish prior to release. When comparing reflex indices of angled striped bass, it was observed that fish with three impairments were all categorized as having critical injuries (hooked in gills or gut) and angled using J hooks. Prior studies have indicated that J hooks could cause a larger percentage
of critical injuries (Meka 2004) and could ultimately effect the overall condition of the fish and lead to post-release mortality (Cooke and Suski 2004). Anglers could potentially use observations such as reflex impairment to adapt handling procedures to ensure that the fish recovers. These types of observations could be adapted to handling procedures, although further validation of reflex impairment testing may be needed to confirm its applicability in recreational fisheries.

**Mortality**

Components of an angling event can exacerbate stress levels experienced by an individual fish, and possibly influence post-release behavior and lead to mortality (Arlinghaus et al. 2007). Based on the detections recorded on the fixed receiver array, none of the 35 tagged striped bass died as a result of the angling event. These findings of no mortality is less than the 8% mortality rate currently accepted by the Atlantic States Marine Fisheries Commission (ASMFC) for striped bass caught-and-released by recreational anglers in saltwater ecosystems (ASMFC 2011). This mortality rate is based on the results from Diodati and Richards (1996) in which they observed hooking mortality in striped bass hooked and released in a saltwater impoundment in Massachusetts. It is not possible to have a fishery in which no angling mortality exists (Cooke and Suski 2005, Arlinghaus et al. 2007), but future telemetry studies may benefit from longer monitoring periods to generate an accurate mortality estimate.

Hooking mortality is often higher with live baits than artificial baits (Bettoli and Osborn 1998). Although both J-hooks and circle hooks were used with bait and lures to sample striped bass, only two of the tagged striped bass were caught on live or dead bait. Mortality rate might have been higher if more striped bass were sampled with live bait (Bettoli and Osborn 1998, Landsman et al. 2011). Future studies are also encouraged to look into other variables related to the angling event, including fishing location (i.e. boat, shore, bridge) as there may be more
physical injuries and stress with higher risk locations (i.e. being dragged up the shore/jetty; Muoneke and Childress 1994).

The present study is consistent with mortality rates in specialized fisheries that are often less than 5% and sometimes below 0.1% (Policansky 2002, Landsman et al. 2011). Previous studies on coastal striped bass post-release mortality during the winter months found 100% survival using pop-up satellite archival tags on a relatively low sample size (n=8) (Graves et al. 2009). Landsman et al. (2011) also reported no mortality in muskellunge caught-and-released in Ottawa by specialized anglers. It was suggested that future studies include novice anglers who may cause more stress and injury to the fish (Landsman et al. 2011). Most of the anglers who volunteered in the current study considered themselves experts when it came to fishing (with over 5 years of targeting striped bass), however, there were a few intermediate anglers and one beginner. Having a wider range of angler experience may be beneficial for future studies on striped bass catch-and-release to better cover the range of impacts associated with the diversity of capture techniques.

**Post-Release Movement and Activity**

Aspects of whole-animal performance occur as a result of certain stressors and have a variety of potential outcomes depending of duration and magnitude of the stress, including changes in post-release behavior (Barton 2002, Arlinghaus et al. 2007). The eight fish detected on the same day as tagging (within 12 hours of release) had their greatest activity space estimates on that same day. This could potentially coincide with individual striped bass leaving the immediate area (angling could be associated with danger and the flight response). Each of these fish was detected in shallower depths (1-2 m) near Eel River or Jones River within a few hours of release, indicating that these areas might be a refuge with safer habitat. Within the first few hours or days after release, some biotelemetry studies have observed increased
movement activity (Sundstrom and Gruber 2002; Gurshin and Szedlmayer 2004; Thorstad et al. 2004), which could represent hyperactivity related to hyperglycemia (Wood 1991). Decreased movement activity has also been observed, although less frequently (Holland et al. 1993). Reduced activity may simply be a result of fatigue from the angling event, whereas increased behavior could result from an escape response to avoid areas that are unfavorable (Arlinghaus et al. 2007). Minor changes in behavior may be adaptations to increase survivability or can be reflective of how the fish senses and responds to its environment, while significant alterations in normal patterns could lead to decreased probability of survival (Schreck et al. 1997).

Post-release behavior is a response to physiological condition and environmental factors (Shepard et al. 2008). Even if an exhausted striped bass survives sublethal hooking and angling stress, once released it may be less likely to resume normal behavior (Barton 2002, Cooke et al. 2004). It is common in fishes to observe little activity following exercise, where the goal is to minimize metabolic costs of restoring basal metabolism (Wood 1991). Of the 29 fish included in analysis, daily estimated activity space over the first 14 days post-release ranged from 0.13 – 13.69 km (95%) and 0.007 – 3.95 km (50%). Activity space estimates were not significantly related to day post-release (Figure 3.2). Acceleration activity was significantly related to day post-release showing increased acceleration with time displaying ‘normal’ behavior by approximately day 7 (Figure 3.2). This lower initial activity makes sense, as the energy expenditure in fish is largely driven by locomotion (Cooke et al. 2004) and the fish would cease activity to recover as quickly as possible. Similar reduced activity following angling was also found in northern pike (Klefoth et al. 2008) and muskellunge (Landsman et al. 2011).

In most species, changes due to exhaustive exercise induced by catch-and-release events will return to resting control levels within a 2-48 hour period (Wang 1994; Suski et al. 2006), however, problems occur due to the fish having to exchange long-term health for short-
term energy bursts. Analysis of post-release activity during the first two days (mean activity space, depth, and acceleration) and angling variables (fight time and total handling time) indicated that neither fight time nor total handling time produced a significant relationship. It is unclear what affects, if any, the accelerometers and surgical procedure had on striped bass. The use of MS222 as an anesthetic and the surgery itself may be a confounding variable that will hinder a rigorous assessment of the impacts of angling stress on post-release behavior, however because each tagged striped bass was treated the same, the effects of the angling event should still be remnant. In addition, a study by Anderson et al. (1997) comparing clove oil and MS222, neither anesthetic caused a change in the swimming performance of the experimental rainbow trout. Further investigation with a broader range of fight times are recommended for future studies to encompass the variety in physiological stress and related behavior.

Elevated water temperatures can potentially exacerbate the effects of angling stress (Thompson et al. 2002) and a number of studies have documented that stress levels in striped bass caught-and-released are temperature dependent (Harrell 1988, Hysmith et al. 1994, Tomasso et al. 1996, Millard et al. 2003). As water temperature rises above the optimal range, angler-induced stress increases (which also increases possibility for post-release behavioral changes). Higher temperatures, therefore, can potentially lead to longer recovery post-release. Visual observations of depth data showed noticeable differences among sampling groups, as a result, fish were separated by sampling month (July, August, and September) to analyze depth data. Depth was found to be significantly related to day post-release in fish tagged in July and September with depth becoming greater with time post-release (Figure 3.3). Fish that were tagged in August, showed similar patterns in activity space and acceleration, however depth remained relatively shallow throughout the 14 day observation, potentially due to higher temperatures during this period. Another possibility could have been the arrival of Hurricane
Irene on August 28th, which did coincide with the last 3-5 days of post-release activity for striped bass in sample Group August. Similar behavior was noted in fish sampled in July during the days leading up to the storm. McCargo et al. (2008) noted decrease movement in fish assemblages during a hurricane in North Carolina.

The present study demonstrated that the angled striped bass tagged with accelerometers exhibited similar post-release behavior and were relatively robust to catch-and-release practices, but more fine-scale behavioral analyses could increase the understanding of the recovery dynamics in striped bass. Results from this research have the potential to aid in improving the ability to effectively manage fish stocks and increase the sustainability of the valued striped bass fishery for Massachusetts and throughout the United States Atlantic coastline. Due to the popularity of recreational angling targeting striped bass, it will be important to gain a better understanding of the behavioral and movement changes associated with catch-and-release, as well as linking these changes to the physiological effects that can also occur with exercise. This information will aid in improving catch-and-release techniques and management.
References


Figure 3.1: Study area in the Plymouth, Kingston, Duxbury (PKD) Bay along the east coast of Massachusetts including the 34 receiver locations (receivers with temperature loggers are underlined).
Table 3.1: Summary of physiological characteristics measured in 102 striped bass in PKD Bay. Table shows mean, ± 1 SD, minimum value, and maximum value for each characteristic measured.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose (mg/dL)</td>
<td>75.6</td>
<td>10.5</td>
<td>57</td>
<td>101</td>
</tr>
<tr>
<td>Lactate (mmol/L)</td>
<td>3.6</td>
<td>1.4</td>
<td>1.4</td>
<td>7.8</td>
</tr>
<tr>
<td>Cortisol (ng/mL)</td>
<td>8.2</td>
<td>3.2</td>
<td>0</td>
<td>49.9</td>
</tr>
<tr>
<td>Chloride (mmol/L)</td>
<td>144</td>
<td>3</td>
<td>136</td>
<td>151</td>
</tr>
<tr>
<td>Calcium (mmol/L)</td>
<td>1.42</td>
<td>0.11</td>
<td>0.98</td>
<td>1.93</td>
</tr>
<tr>
<td>Sodium (mmol/L)</td>
<td>171</td>
<td>4.4</td>
<td>161.6</td>
<td>184.9</td>
</tr>
<tr>
<td>Potassium (mmol/L)</td>
<td>4.4</td>
<td>0.6</td>
<td>1.9</td>
<td>6.5</td>
</tr>
<tr>
<td>PCV (fraction)</td>
<td>0.36</td>
<td>0.06</td>
<td>0.25</td>
<td>0.61</td>
</tr>
</tbody>
</table>
Table 3.2: Summary of results from principle components analysis. Table shows principle components with eigenvectors greater than 1 (PC1-PC5) and the variance explained. Eigenvalues >0.4 or <-0.4 are shown in bold.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
<th>PC5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvalue</td>
<td>2.41</td>
<td>1.53</td>
<td>1.26</td>
<td>1.06</td>
<td>1.01</td>
</tr>
<tr>
<td>Glucose</td>
<td>-0.125</td>
<td>0.332</td>
<td>0.329</td>
<td>-0.168</td>
<td>-0.444</td>
</tr>
<tr>
<td>Lactate</td>
<td>0.446</td>
<td>0.278</td>
<td>-0.141</td>
<td>-0.006</td>
<td>0.079</td>
</tr>
<tr>
<td>Cortisol</td>
<td>0.139</td>
<td>0.431</td>
<td>-0.307</td>
<td>0.162</td>
<td>0.38</td>
</tr>
<tr>
<td>Chloride</td>
<td>0.405</td>
<td>-0.252</td>
<td>-0.124</td>
<td>0.379</td>
<td>-0.145</td>
</tr>
<tr>
<td>Calcium</td>
<td>0.295</td>
<td>0.167</td>
<td>0.596</td>
<td>0.151</td>
<td>-0.219</td>
</tr>
<tr>
<td>Sodium</td>
<td>0.509</td>
<td>0.073</td>
<td>0.158</td>
<td>-0.059</td>
<td>-0.169</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.015</td>
<td>0.043</td>
<td>-0.546</td>
<td>0.287</td>
<td>-0.669</td>
</tr>
<tr>
<td>PCV</td>
<td>0.246</td>
<td>0.305</td>
<td>-0.273</td>
<td>-0.691</td>
<td>-0.064</td>
</tr>
<tr>
<td>Total Length</td>
<td>0.429</td>
<td>-0.324</td>
<td>0.058</td>
<td>0.0178</td>
<td>0.26</td>
</tr>
<tr>
<td>Water</td>
<td>0.11</td>
<td>-0.574</td>
<td>-0.079</td>
<td>-0.464</td>
<td>-0.185</td>
</tr>
<tr>
<td>% Variance Explained</td>
<td>24.1</td>
<td>15.3</td>
<td>12.6</td>
<td>10.6</td>
<td>10.1</td>
</tr>
</tbody>
</table>
Table 3.3: Summary table of reflex impairments. Table shows number of fish with impairments for each reflex test (operculum, mouth, gag, dorsal, and body flex).

<table>
<thead>
<tr>
<th>RAMP</th>
<th>Operc</th>
<th>Mouth</th>
<th>Gag</th>
<th>Dorsal</th>
<th>Body Flex</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (n=20)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.2 (n=22)</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>0.4 (n=15)</td>
<td>0</td>
<td>1</td>
<td>12</td>
<td>3</td>
<td>16</td>
</tr>
<tr>
<td>0.6 (n=4)</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 3.4: Summary of post-release activity data for all tagged striped bass (n=35). Activity space, depth, and acceleration (mean ± sd) were all limited to two days post-release. An asterisk denotes fish that were not detected within the first two days post-release and were not used in behavior analyses.

<table>
<thead>
<tr>
<th>Tagging Group</th>
<th>Tag ID</th>
<th>Date tagged</th>
<th>Final Tracking Date</th>
<th>TL (cm)</th>
<th>95% Activity Space</th>
<th>50% Activity Space</th>
<th>Depth (m)</th>
<th>Acceleration (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>2692/2693</td>
<td>7/6/2011</td>
<td>7/20/2011</td>
<td>80.5</td>
<td>3.32</td>
<td>1.07</td>
<td>0.87</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>2694/2695</td>
<td>7/6/2011</td>
<td>10/12/2011</td>
<td>56</td>
<td>5.81</td>
<td>0.81</td>
<td>1.18</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>2696/2697</td>
<td>7/6/2011</td>
<td>10/3/2011</td>
<td>59.7</td>
<td>4.83</td>
<td>1.37</td>
<td>2.08</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>2698/2699</td>
<td>7/6/2011</td>
<td>10/28/2011</td>
<td>64.8</td>
<td>11.72</td>
<td>3.26</td>
<td>2.63</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>2700/2701</td>
<td>7/6/2011</td>
<td>10/28/2011</td>
<td>72.3</td>
<td>5.63</td>
<td>1.44</td>
<td>2.25</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>2702/2703</td>
<td>7/5/2011</td>
<td>9/15/2011</td>
<td>58.2</td>
<td>6.23</td>
<td>1.64</td>
<td>3.53</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>2704/2705</td>
<td>7/5/2011</td>
<td>10/27/2011</td>
<td>42.4</td>
<td>2.19</td>
<td>0.52</td>
<td>1.38</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>2706/2707</td>
<td>7/5/2011</td>
<td>10/18/2011</td>
<td>46.3</td>
<td>3.67</td>
<td>0.64</td>
<td>1.90</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>2708/2709</td>
<td>7/5/2011</td>
<td>10/28/2011</td>
<td>40.3</td>
<td>2.15</td>
<td>0.22</td>
<td>1.62</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>2710/2711</td>
<td>7/5/2011</td>
<td>9/18/2011</td>
<td>71.5</td>
<td>5.26</td>
<td>1.36</td>
<td>3.53</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>2712/2713</td>
<td>7/5/2011</td>
<td>10/28/2011</td>
<td>38.5</td>
<td>2.78</td>
<td>0.67</td>
<td>1.44</td>
<td>0.53</td>
</tr>
<tr>
<td>Group 2</td>
<td>5804/5805</td>
<td>8/18/2011</td>
<td>10/29/2011</td>
<td>40.1</td>
<td>1.65</td>
<td>0.42</td>
<td>1.64</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>5806/5807</td>
<td>8/18/2011</td>
<td>10/3/2011</td>
<td>61.4</td>
<td>3.42</td>
<td>0.93</td>
<td>1.35</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>5808/5809</td>
<td>8/17/2011</td>
<td>9/5/2011</td>
<td>48.2</td>
<td>3.00</td>
<td>0.79</td>
<td>1.42</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>5812/5813</td>
<td>8/17/2011</td>
<td>10/27/2011</td>
<td>51.7</td>
<td>1.65</td>
<td>0.42</td>
<td>0.84</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>5814/5815</td>
<td>8/17/2011</td>
<td>10/27/2011</td>
<td>41</td>
<td>1.65</td>
<td>0.42</td>
<td>1.75</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>5816/5817</td>
<td>8/17/2011</td>
<td>10/15/2011</td>
<td>60.5</td>
<td>3.00</td>
<td>0.79</td>
<td>2.51</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>5820/5821</td>
<td>8/12/2011</td>
<td>10/12/2011</td>
<td>50.1</td>
<td>1.65</td>
<td>0.42</td>
<td>1.20</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>5822/5823*</td>
<td>8/12/2011</td>
<td>8/29/2011</td>
<td>74.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5824/5825</td>
<td>8/12/2011</td>
<td>10/18/2011</td>
<td>48.2</td>
<td>1.65</td>
<td>0.42</td>
<td>1.23</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>5826/5827</td>
<td>8/12/2011</td>
<td>10/27/2011</td>
<td>43.7</td>
<td>1.65</td>
<td>0.42</td>
<td>1.07</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>6358/6359</td>
<td>9/15/2011</td>
<td>10/14/2011</td>
<td>65.9</td>
<td>6.90</td>
<td>1.61</td>
<td>1.12</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>6360/6361</td>
<td>9/14/2011</td>
<td>10/26/2011</td>
<td>44.7</td>
<td>4.63</td>
<td>1.07</td>
<td>4.05</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>6362/6363</td>
<td>9/15/2011</td>
<td>10/29/2011</td>
<td>40.7</td>
<td>5.81</td>
<td>2.23</td>
<td>1.44</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>6364/6365</td>
<td>9/14/2011</td>
<td>10/5/2011</td>
<td>53</td>
<td>4.83</td>
<td>1.94</td>
<td>1.81</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>6366/6367*</td>
<td>9/14/2011</td>
<td>10/25/2011</td>
<td>49.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6368/6369*</td>
<td>9/10/2011</td>
<td>10/27/2011</td>
<td>45.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Code</td>
<td>Date</td>
<td>Date</td>
<td>Value1</td>
<td>Value2</td>
<td>Value3</td>
<td>Value4</td>
<td>Value5</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>------------</td>
<td>------------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>6370/6371</td>
<td>9/10/2011</td>
<td>9/24/2011</td>
<td>74.4</td>
<td>3.32</td>
<td>1.07</td>
<td>1.19</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>6374/6375</td>
<td>9/10/2011</td>
<td>9/19/2011</td>
<td>77</td>
<td>4.63</td>
<td>1.07</td>
<td>1.12</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>6376/6377</td>
<td>10/12/2011</td>
<td>10/27/2011</td>
<td>49.3</td>
<td>3.06</td>
<td>0.18</td>
<td>4.05</td>
<td>0.66</td>
<td></td>
</tr>
<tr>
<td>6378/6379</td>
<td>9/10/2011</td>
<td>10/11/2011</td>
<td>51</td>
<td>5.63</td>
<td>2.41</td>
<td>1.44</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>6380/6381</td>
<td>9/10/2011</td>
<td>10/27/2011</td>
<td>56.9</td>
<td>6.23</td>
<td>1.18</td>
<td>1.81</td>
<td>0.77</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.2: Changes in movement and activity post-release for the first 14 days. Mean 95% activity space (top), 50% activity space (middle), and acceleration (bottom) of striped bass (n=33).
Figure 3.3: Changes in mean depth of striped bass (n=33) for the first 14 days post-release (G1=July, G2=August, G3=September).
CHAPTER 4

GENERAL DISCUSSION

The goal of this research was to conduct an investigation into the spatial ecology and effects of catch-and-release angling on the physiology and behavior of coastal striped bass. Prior to my research, there was a void in the understanding of the fine-scale behavior and activity levels of striped when occupying New England estuaries during the summer months. Similarly, to date, there was no study that addressed the physiological consequences of angling-induced exercise for striped bass in New England coastal waters. In Chapter 2, I addressed questions regarding fine-scale behavioral patterns of striped bass using multi-sensor acoustic transmitters. Chapter 3 summarized the physical injury, physiological consequences, post-release behavior, and survival associated with catch-and-release of striped bass in a northern estuary. Collectively, my thesis research addressed both fundamental issues related to the behavioral ecology of striped bass and explored the consequences of catch-and-release angling.

Findings and Implications

Due to their popularity among anglers (Graves et al. 2009), there has been a great deal of research regarding striped bass migration and distribution using external tagging methods (Clark 1968, Kohlenstein 1981; Boreman and Lewis 1987; Dorazio et al. 1994; Waldman and Fabrizio 1994). However, still not much is known about striped bass movement patterns or ecological behavior within New England coastal estuaries. This study is one of the first to use accelerometer transmitters to quantify activity levels in striped bass, a tool that might prove useful for also understanding the link to physiological stress and impacts related to catch-and-release angling of coastal striped bass. My telemetry study identified striped bass short-term
movement patterns in a non-natal estuary. Overall, the majority of tagged striped bass took up residency within the study estuary (PKD Bay) from July through October, and used a mosaic of habitat types before emigrating from the bay for potential migration. Following emigration, most of the striped bass were detected on other acoustic telemetry arrays in Connecticut and New Jersey. While in PKD Bay, striped bass spent much of their time engaged in low locomotory activity (slow swimming or swimming in place), with occasional high activity and burst swimming, often within the upper 3 m of the water column. Striped bass were also observed having variation in seasonal movement patterns, with decreased activity space throughout the month of August and increases in activity space prior to emigration from the estuary. The identification of fine-scale movement and activity patterns for economically important sport fish, such as striped bass, may contribute to future marine and coastal management to protect essential fish habitat and movement corridors. A more complete understanding of striped bass in space and time is important to understanding the fundamentals of their natural history, ecological interactions, and habitat to contribute to the effective management and conservation efforts of the species and the ecosystem they live in.

Striped bass are highly targeted by resident and visiting recreational anglers along the Atlantic coastline and are an important source of revenue for the sport fishing industry (Karas 1993). Very little has been done to examine how individual striped bass respond to angling events in New England coastal waters; information that could lead to the development of best practices and sound management. Physical injuries, physiological consequences, and post-release behavior are presented in Chapter 3. Lure type was not found to influence injury, bleeding, hook removal, or hooking depth, however higher RAMP indices (three reflex impairments) corresponded to critical hooking locations. Blood lactate, plasma sodium and chloride, and total length were found to be significantly related to fight time up to 8 minutes
and handling duration up to 10.5 minutes. No mortality was observed in this study. The effects of angling were not found to influence post-release behavior. Fish detected within the first 12 hours post release (n=8) exhibited their greatest mean daily activity space estimate within that time frame and were each detected in shallower depths (1-2 m) near Eel River or Jones River within a few hours of release, indicating that these areas might be a possible refuge. To reduce the potential of physiological effects from angling, it is recommended that anglers land fish quickly and keep handling time to a minimum. Environmental conditions and anthropogenically induced stressors can produce a wide range of responses due to inherent physiological and morphological characteristics among species (Cooke and Suski 2005), therefore, it is important to have species-specific angling guidelines and best-practices.

**Future Research Directions**

Despite the information gained from this work, further research is needed to better understand the behavioral ecology of striped bass within PKD Bay. In Chapter 2, I briefly touched on emigration data and showed that the majority of striped bass left the bay for southern migration. More in-depth analyses between fine-scale movements and activity patterns in estuaries and coastal migrations could provide important knowledge regarding environmental cues and possible anthropogenic environmental consequences affecting marine populations. With more researchers networking and sharing information through telemetry networks such as the Atlantic Cooperative Telemetry (ACT) Network, it is possible to use acoustic transmitters to gain additional details about migration. Although pop-up satellite archival tags provide an enormous amount of detail, they are expensive with generally limited sample sizes (Graves et al. 2009). Accelerometer loggers allow data to be stored in the tag rather than relying on a receiver to detect the data being transmitted, however, the tag must be
retrieved from the animal in order to collect the data. Although my array was extensive, I did not always detect tagged striped bass that had not yet exited the bay. Manual tracking may be required to supplement data collected from the fixed array, especially in shallow areas where the detection range can be limited. Detailed information regarding vertical movement and activity patterns could lead to insights into prey availability and bioenergetics, potentially influencing Atlantic coast-wide management and conservation practices.

Ecological factors such as water temperature and tidal stage were shown to potentially drive striped bass distribution within New England estuaries with seasonal movement and vertical distribution, as well as, diel depth selection and activity levels. Although I did not measure aspects related to prey availability or movement in this study, this could have potentially played a role in striped bass distribution within PKD bay. Currently, there is little evidence quantifying foraging activity and prey availability, however it could be a critical link between striped bass movement patterns and their prey. Seasonal changes in depth distribution could be linked to changes in foraging behavior (Meyer and Holland 2005, Whitney et al. 2007, Thompson et al. 2011). Prey could also be an influencing factor effecting diel increased activity and shallower depth distribution (Thompson et al. 2011). To improve the understanding of factors motivating habitat selection, future studies should continue to examine movement and activity patterns of striped bass, coupled with examination of habitat type, substrate type, environmental factors, and prey availability. Laboratory experiments could be designed to focus on how striped bass react to certain environmental stressors in salt water, like water temperature and dissolved oxygen, to confirm any future experiments in natural habitat.

Chapter 3 quantified some of the physiological effects of fight time and handling duration on striped bass during angling events. Although angling time was found to be a
significant stressor, higher salinity levels may aid in moderating physiological imbalances associated with stress by helping to improve potential osmoregulatory dysfunction and electrolyte imbalances that result from stress (Harrell 1988). Therefore, to fully test physiology related to catch-and-release, it may be necessary to use prolonged fight times and air exposure. Prior catch-and-release studies have shown that prolonged fight times and air exposure during handling (including hook removal and photography) in occurrence with seasonal water temperature extremes contribute to greater physiological consequences (Suski et al. 2007).

My study observed no mortality for striped bass angled up to 4.2 minutes, yet, it is not possible to have a fishery in which no angling mortality exists (Cooke and Suski 2005, Arlinghaus et al. 2007). The extent of a hook-related injury and likelihood of damage to vital organs in a fish can be influenced by the number and style of hooks as well as the type of bait used (Millard et al. 2003). Hooking mortality is often higher with live baits than artificial baits (Bettoli and Osborn 1998). Striped bass caught on artificial lures generally are hooked in the jaw and mouth, whereas fish caught with live bait were more likely to be deep hooked (Nelson 1998). A greater sample size of angling events using circle hooks and/or natural bait (instead of an artificial lure) are needed to make further conclusions, and future studies may see a significant relationship. Future studies are also encouraged to look into other variables related to the angling event, including angler experience and fishing location (i.e. boat, shore, bridge) since there may be more physical injuries and stress with higher risk locations (i.e. being dragged up the shore/jetty; Muoneke and Childress 1994).

The present study, generally, demonstrates that individual angled striped bass all exhibit similar post-release behavior and are relatively robust to catch-and-release practices. The use of acoustic telemetry can be coupled with physiological indicators in the blood to evaluate the
individual physiological condition before release and follow the behavior and fate of those same individuals post-release (Cooke et al. 2005; Moyes et al. 2005; Skomal 2007). It is unclear what affects, if any, the accelerometers and surgical procedure had on striped bass, however the use of an anesthetic (i.e. MS222) has been suggested to have possible physiological consequences on fish (Anderson et al. 1997). With the continual growth of technology and tools to assess ecological and post-release behavior, future studies will likely be able to use a transmitter that creates negligible physiological consequences. This will allow more fine-scale behavioral analyses that could benefit the understanding of the recovery dynamics of striped bass. One possible solution is gastric tagging, which does not require surgery or full anesthesia. This is good for short-term studies, but is usually ineffective for longer deployment periods due to poor tag retention (smaller tags should be used to avoid regurgitation; Smith et al. 2009). This can be followed by manual tracking to improve detection data immediately post-release. Another possibility for future research involves laboratory experiments to understand how physiology changes over time after an angling event and how long it takes striped bass to recover in salt water.

Afterword and Summary

The overall objective of my thesis research was to examine the spatial ecology and effects of catch-and-release angling on the physiology and behavior of striped bass in a New England estuary. I have added to past studies completed on ecology, behavior, and catch-and-release of this important migratory sport fish in the following ways:

1. Seasonal distribution of coastal striped bass in New England Estuaries is driven by environmental cues.
Ecological factors such as water temperature were shown to potentially drive striped bass distribution within New England estuaries with seasonal movement and vertical distribution, as well as, diel depth selection and activity levels. Striped bass were not evenly distributed throughout the estuary, and they demonstrated site fidelity to areas with mosaic habitats. Continued research is needed to test if prey availability and distribution could have also influenced striped bass movement.

2. Descriptions of the general activity and depth patterns of striped bass.

Striped bass spend much of their time at low-level locomotory activity with occasional burst of high-level activity, often within 3 m of the surface. Activity space was significant over the course of the season and increased with water temperature. Striped bass remained at shallower depths when temperatures exceeded 21 °C, exhibited diel vertical migration to shallower depths during the daylight hours, and displayed greater depths during high tides.

3. Continued research is needed to quantify behavior of migratory striped bass.

The majority of striped bass left the bay for southern migration (67% detected on other receiver arrays). Further telemetry work is necessary to provide more in-depth analyses between behavioral ecology in estuaries and coastal migrations regarding environmental cues and possible anthropogenic environmental consequences affecting marine populations.

4. Coastal striped bass are relatively resilient to some aspects of catch-and-release angling.

Some physiological stress responses occurs as a result of fight time and handling duration. No mortality was observed post-release. Even so, appropriate handling procedures should always be used and striped bass should be landed quickly to reduce possible consequences.

5. Continued research is needed to quantify and assess post-release behavior of striped bass.

Individual angled striped bass exhibited similar post-release behavior and are relatively robust to catch-and-release practices. Some individual fish showed increased behavior within 12 hours
of release followed by a decrease in activity for several days post-release. Further telemetry work to provide additional detail of striped bass immediately following release is warranted.

References


GENERAL REFERENCES


