Trophic Ecology and Habitat Use of Atlantic Tarpon (Megalops atlanticus)

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Trophic Ecology and Habitat Use of Atlantic Tarpon (*Megalops atlanticus*)

by

Benjamin N. Kurth

A thesis submitted in partial fulfillment of the requirements for the degree of
Master of Science
College of Marine Science
University of South Florida

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Keywords: Stable isotope analysis, genetic tagging, ontogenetic shift, site fidelity, basal resource use, growth

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# TABLE OF CONTENTS

List of Tables .................................................................................................................. iii

List of Figures .................................................................................................................... iv

Abstract ............................................................................................................................. v

Chapter One: General Introduction .............................................................................. 1
  Literature Cited ................................................................................................................. 3

Chapter Two: Backcountry habitat dependence, ontogenetic habitat shifts, and foraging system fidelity of Atlantic Tarpon (Megalops atlanticus) ........................................... 5
  Abstract ............................................................................................................................... 5
  Introduction .......................................................................................................................... 5
  Methods ............................................................................................................................. 7
    Chronological Isotope Recorder ..................................................................................... 7
    Specimen Collector ......................................................................................................... 9
    Sample Preparation ....................................................................................................... 10
    Stable Isotope Analysis ................................................................................................. 10
    Age Estimation ................................................................................................................ 11
    Data Analysis .................................................................................................................. 11
  Results ............................................................................................................................... 12
  Discussion .......................................................................................................................... 13
  Literature Cited ................................................................................................................ 18
  Tables and Figures .......................................................................................................... 23

Chapter Three: Ontogenetic habitat shifts and biology of juvenile Atlantic Tarpon (Megalops atlanticus) in Florida ................................................................. 24
  Abstract ............................................................................................................................... 24
  Introduction .......................................................................................................................... 25
  Methods ............................................................................................................................. 27
    Genetic Tagging ................................................................................................................ 27
    Study Background ........................................................................................................... 27
    Laboratory Analysis ....................................................................................................... 28
    Recapture and Survival Rates ......................................................................................... 28
    Habitat Use ...................................................................................................................... 29
    Abundance ....................................................................................................................... 29
    Expected Ranges of Movement ....................................................................................... 30
    Growth .............................................................................................................................. 30
  Results ............................................................................................................................... 31
  Capture Totals ................................................................................................................... 31
  Recapture Rates ............................................................................................................... 31
Mark-Recapture Analysis ................................................................. 31
Habitat Use .................................................................................. 31
Seasonal and Regional Abundance ............................................... 31
Expected Ranges of Movement ..................................................... 32
Growth ......................................................................................... 32
Discussion ................................................................................... 32
Literature Cited ............................................................................. 39
Tables and Figures ......................................................................... 43

Chapter Four: General Conclusions .................................................. 59

Bibliography .................................................................................. 61

Appendix A: Individual $\delta^{13}$C and $\delta^{15}$N stable isotope profiles of 16 Atlantic Tarpon .......... 67
LIST OF TABLES

Table 2.1. Adult Atlantic Tarpon capture data ................................................................. 23
Table 3.1. Characterization of 9 microsatellite loci for 65 specimens of *Megalops atlanticus* ................................................................................................................. 43
Table 3.2. Sampling totals categorized by year and type of analysis ............................... 44
Table 3.3. Yearly recapture rates (Within-Year, Cumulative, Inter-Annual) .................... 45
Table 3.4. Program Mark estimates of $\Phi$ and $p$ for three different models:  
The $\Phi(s)p(s)$ model fit the data best and was the most parsimonious of the three models................................................................. 46
Table 3.5. Dunn’s Test results for comparison of TL by habitat type .............................. 47
Table 3.6. Specimen counts and average size ± SE for each habitat type ....................... 48
Table 3.7. Von Bertalanffy Growth parameters from recapture data and comparison to otolith-derived parameters ................................................................. 49
LIST OF FIGURES

Figure 3.1. Within-Year Recapture Rates ................................................................. 50
Figure 3.2. Inter-Annual Recapture Rates ................................................................. 51
Figure 3.3. Cumulative Recapture Rates ................................................................. 52
Figure 3.4. Mean TL (± SE) of juvenile Atlantic Tarpon increased with increasing habitat size ................................................................. 53
Figure 3.5. Number of Atlantic Tarpon sampled in each region .......................... 54
Figure 3.6. Number of Atlantic Tarpon sampled in each county .................. 55
Figure 3.7. Distance between capture locations slightly increased as time between captures increased. $r^2=0.07$, $p=0.002$ ................................. 56
Figure 3.8. Von Bertalanffy growth curves from six different estimation methods ........ 57
Figure 3.9. Coastal Systems with high juvenile Atlantic Tarpon abundance and ideal habitat complexity ................................................................. 58
Figure A1. Individual $\delta^{13}$C and $\delta^{15}$N stable isotope profiles .......................... 67
Fish can have complex life histories and use multiple habitats and resources throughout their life span. Consequently, their life histories are often poorly understood. The Atlantic Tarpon, *Megalops atlanticus*, is a large, typically migratory, elopomorph fish that is both ecologically and economically important. Atlantic Tarpon are under threat due to regional exploitation, loss of natal and juvenile habitat, poor water management, and offshore impacts. In addition, little is known about its lifelong habitat and resource use. In Chapter One, I used stable isotope analysis of eye lens δ\(^{13}\)C and δ\(^{15}\)N values to explore patterns in trophic history and habitat use of 16 Atlantic Tarpon from West-Central Florida and Louisiana. The stable isotope chronologies showed 100% use of backcountry habitats during the early life history and an ontogenetic habitat shift to coastal waters at approximately 10 years of age and 140 cm total length. During the coastal phase Atlantic Tarpon displayed among-individual variability and within-individual consistency in basal resource use. In Chapter Two, mark-recapture data from a multi-year genetic tagging program were used to investigate survival and growth rates, ontogenetic habitat use, and migration of juvenile Atlantic Tarpon in Florida. The study found that juvenile Atlantic Tarpon take approximately 10 years to reach the length associated with maturity, and appear to have a high survival rate (~80%), possibly due to effective use of habitats with reduced competition and predation. Atlantic Tarpon underwent several ontogenetic habitat shifts throughout the juvenile phase. In addition, juvenile Atlantic Tarpon did not migrate long distances but instead showed fidelity to systems wherein only short movements were needed to shift habitat types. This work serves to fill critical gaps in our knowledge of Atlantic Tarpon life history and may aid in better management and conservation of the species.
CHAPTER ONE

GENERAL INTRODUCTION

Many fish have complex life histories with varied use of habitats and trophic resources at different life stages (Whitfield 1990, Able and Fahay 1998). Consequently, the life histories and essential habitats of fishes are often poorly understood (Able 2005). Each of these habitats can be critical to the persistence of the species and the loss of any habitat, or migration pathways between habitats, may have negative effects (Rosenberg et al. 2000). Atlantic Tarpon (Megalops atlanticus) is an economically and ecologically important fish found in coastal and inshore waters of the subtropical and tropical Atlantic Ocean (Wade 1962, Crabtree et al. 1992, Ault et al. 2008, Seyoum et al. 2008, Hammerschlag et al. 2012). Unfortunately, we lack a complete understanding of the Atlantic Tarpon life history, with most research focused on larval development and adult population demographics. In order to better understand the Atlantic Tarpon life history I used two types of natural tags to investigate their lifelong trophic ecology and habitat use. I used eye lens stable isotope analysis to describe Atlantic Tarpon habitat use, ontogenetic shifts, and trophic ecology throughout the life span. Additionally, I used a multi-year genetic tagging database to describe habitat use and movement in juvenile Atlantic Tarpon, as well as to produce estimates of demographic parameters such as survival and growth rates. Both of these studies help to better describe Atlantic Tarpon ecology and life history across their entire lifespan.

In Chapter Two, Backcountry habitat dependence, ontogenetic habitat shifts, and foraging system fidelity of Atlantic Tarpon (Megalops atlanticus), I used stable isotope analysis
of Atlantic Tarpon eye lenses to produce 16 Atlantic Tarpon isotopic chronologies. Eye lenses are a chronological recorder of stable isotopes (Wallace et al. 2014) and δ¹³C and δ¹⁵N values can be used to estimate basal resource use and trophic position, respectively (DeNiro and Epstein 1978, Minagawa and Wada 1984, Peterson and Fry 1987). Research on Atlantic Tarpon ecology has generally been limited to snapshot observations and we lack a complete understanding of their full life history. Therefore, it is imperative that we increase our understanding of Atlantic Tarpon habitat and resource use across its entire life history for more effective management. The goal of this research was to analyze the isotope chronologies to answer the following questions: 1) What habitats and basal resources do juvenile and sub-adult Atlantic Tarpon use?, 2) When do Atlantic Tarpon undergo an ontogenetic migration to coastal waters?, and 3) What basal resources were used by adult Atlantic Tarpon?.

In Chapter Three, *Ontogenetic habitat shifts and biology of juvenile Atlantic Tarpon (Megalops atlanticus) in Florida*, I used a multi-year genetic tagging database to investigate the biology and ecology of juvenile Atlantic Tarpon (<1219.2 mm). The Tarpon Genetic Recapture Study was an eight-year study that used recreational anglers as citizen scientists to collect over 22,000 DNA specimens. Success at the juvenile stage has been shown to be critical to the health of adult Atlantic Tarpon populations (Winemiller and Dailey 2002, Holt et al. 2005), however, the juvenile stage is the most poorly understood aspect of the Atlantic Tarpon life history. Individual capture data and recapture events were used to answer questions about juvenile habitat use and movement, as well as to describe demographic aspects such as growth and survival rates. This chapter is currently in preparation to be submitted for publication.

Atlantic Tarpon life history and ecology are poorly understood despite the species’ ecological and economic importance. The results of this study highlighted the importance of backcountry habitats to the juvenile life stage. In addition, the research improved our
understanding of the ontogenetic shift to the adult population, and identified interesting patterns in trophic ecology during the adult stage. Last, the work provides a better understanding of juvenile biology and potential “ideal” juvenile habitats. Overall, this research helps to build upon prior research and fills critical gaps in our knowledge of Atlantic Tarpon life history and ecology.

LITERATURE CITED


CHAPTER TWO
BACKCOUNTRY HABITAT DEPENDENCE, ONTOGENETIC HABITAT SHIFTS, AND FORAGING SYSTEM FIDELITY OF ATLANTIC TARPON (MEGALOPS ATLANTICUS)

ABSTRACT
Fish can have complex life histories and use multiple habitats and resources. Consequently, their life histories are often poorly understood. Atlantic Tarpon (Megalops atlanticus), is an ecologically and economically important sport fish, yet little is known about its lifelong habitat and resource use. This study used stable isotope analysis of eye lens $\delta^{13}C$ and $\delta^{15}N$ values to explore patterns in trophic history and habitat use of 16 Atlantic Tarpon from West-Central Florida and Louisiana. The stable isotope chronologies showed 100% use of backcountry habitats during the early life history and an ontogenetic shift to coastal waters at approximately 10 years of age and 140 cm total length. During the coastal phase Atlantic Tarpon displayed among-individual variability and within-individual consistency in basal resource use. This study highlights the importance of backcountry habitats to the early life stages of Atlantic Tarpon, as well as the possibility that adults show fidelity to coastal systems for feeding and growth. This study represents the first use of the eye lens as a chronological recorder of $\delta^{13}C$ and $\delta^{15}N$ values to reveal lifelong patterns of trophic history and habitat use in a fish species.

INTRODUCTION
Many fish have complex life histories which results in varied habitat and resource use at different stages throughout their lifespans (Whitfield 1990, Able and Fahay 1998). Consequently, the life histories and essential habitats are often poorly understood (Able 2005).
Each of these habitats can be critical to the persistence of the species and the loss of any habitat, or migration pathways between habitats, may have negative effects (Rosenberg et al. 2000). For example, salmonids can be negatively affected by dams and altered water flows that impede migration among habitats resulting in decreased survival and fitness (Pringle et al. 2000, Levin and Tolimieri 2001). Identifying the habitats and resources species use is the first step to understanding the role each plays in the biology of the species.

Atlantic Tarpon, *Megalops atlanticus*, is a large, typically migratory, elopomorph fish found in coastal and inshore waters of the tropical and subtropical Atlantic Ocean (Wade 1962). Atlantic Tarpon are a prized sportfish and the recreational fishery generates billions of dollars and thousands of jobs annually in the United States (Crabtree et al. 1992, Ault et al. 2008, Seyoum et al. 2008). A highly mobile mesopredator, Atlantic Tarpon use different habitats and resources throughout their life cycle, forage on a wide variety of prey, and are themselves prey to several shark species (Ault et al. 2008, Hammerschlag et al. 2012). Despite the ecological and economic importance of the species, we lack a complete understanding of their full life history. Most of the prior research has focused on development of their leptoccephali larvae (Wade 1962, Crabtree et al. 1992, Shenker et al. 2002) as well as demographic aspects of adults such as age, growth, and reproduction, (Crabtree et al. 1992, Crabtree et al. 1995, Crabtree et al. 1997, Andrews et al. 2001). Recently, tagging and microchemical studies have begun to address questions concerning adult migration and habitat use (Brown and Severin 2007, Luo et al. 2008, Woodcock et al. 2013, Rohtla and Vetemaa 2016). In contrast, little is known about their juvenile (post-larval) and sub-adult stages (total lengths <1220mm). Currently listed as vulnerable by the IUCN (Adams et al. 2012), due in part to regional exploitation, loss of natal habitat, poor water management, and offshore disturbances such as oil spills (Ault et al. 2008), it is imperative that we increase our understanding of Atlantic Tarpon ecology across its entire life history for more effective management.
Research on Atlantic Tarpon habitat use has generally been limited to snapshot observations. Following their pelagic leptocephalus larval stage, Atlantic Tarpon typically recruit to upper estuarine habitats such as brackish lagoons, mangroves, and tidal creeks where predation is thought to be low and food resources are high (Crabtree et al. 1995, Seymour et al. 2008). At the sub-adult stage Atlantic Tarpon appear to become more dependent upon deeper water habitats such as rivers, sloughs, and canals that provide access for emigration into coastal waters (Ault et al. 2008), however no definitive link between these habitats and the adult stage has been shown. The juvenile/sub-adult stage is thought to last approximately seven to ten years at which point Atlantic Tarpon become sexually mature and undergo an ontogenetic migration to coastal waters, possibly due to increasing food requirements and to join the adult spawning population (Cyr 1991, Crabtree et al. 1992, Crabtree et al. 1997). However, the movement patterns and trophic ecology of this shift are still poorly understood.

The research presented here sought to examine the entire trophic history of the Atlantic Tarpon using the newly described methods of eye lens stable isotope analysis (Wallace et al. 2014). This work builds upon previous snapshot observations of habitat use for this species at separate life stages. Specifically, I analyzed individual stable isotope profiles to answer the following questions: 1) What habitats and basal resources do juvenile and sub-adult Atlantic Tarpon use?, 2) When do Atlantic Tarpon undergo an ontogenetic migration to coastal waters?, and 3) What basal resources were used by adult Atlantic Tarpon?.

METHODS

*Chronological Isotope Recorder:* Identifying critical habitats and tracking movements among them by migrating species has remained a major research challenge (Elsdon and Gillanders 2003). Traditional external tags (e.g., dart tags, satellite tags) are fraught with logistical constraints such as tag loss, cost, inability to tag small juveniles, and low return rates (Robson
Natural tags such as Trace Element Analysis and Stable Isotope Analysis (SIA) provide alternative means for investigating species movement. Natural tags are advantageous because they are incorporated at an early life stage, can provide continuous life history information (rather than punctuated observations), and cannot be lost (Elsdon et al. 2008). SIA of the eye lens is a novel natural tagging technique that has the potential to increase spatial and temporal resolution of movement and habitat use while minimizing the problems associated with traditional tags (Wallace et al. 2014).

Internally recorded stable isotopes, specifically δ¹³C and δ¹⁵N, can be used to recreate lifelong trends in animal diets, basal resource use, and movements (Post 2002, Wallace et al. 2014). Commonly used to infer basal resource use, δ¹³C values are primarily conserved between trophic levels, with enrichment of ~1‰ per trophic step (DeNiro and Epstein 1978, Peterson and Fry 1987). In contrast, δ¹⁵N increases approximately 3‰ per trophic step and can be used to infer trophic position (Minagawa and Wada 1984, Peterson and Fry 1987). Analyzing tissues that retain δ¹³C and δ¹⁵N over time can allow us to generate trophic histories across an entire lifespan.

Fish eye lenses have been recently shown to be an internal recorder of stable isotopes in fishes and is one of the only known sources of simultaneous δ¹³C and δ¹⁵N temporal records in bony fishes (Wallace et al. 2014, Tzadik 2016). As a fish grows, the eye lens proportionally increases in size (Nicol and Somiya 1989, Horwitz 2003) as new concentric layers are laid down on the outside of the eye lens. The cells in the completed layers undergo attenuated apoptosis in which all organelles are removed, rendering protein synthesis impossible. Therefore, each successive layer represents a distinct, conservative record of dietary stable isotopes at the time of apoptosis (Nicol and Somiya 1989). These layers can be used to make inferences about trophic level, basal resource use, and to explore shifts in isotopic values over time.
In the coastal and estuarine environments there are several assumptions we can use to interpret δ\textsuperscript{13}C values. First, there is typically a 5‰ offset between benthic microalgae (BMA) and phytoplankton (PP) (France 1995). Second, δ\textsuperscript{13}C values between −21 and −18‰ indicate dependence on a PP-based food webs. This type of food web usually dominates in turbid systems where light does not reach the benthic layer sufficiently to support BMA-based food webs (France 1995, Hollander and Peebles 2004). Third, δ\textsuperscript{13}C values greater than −15‰ indicate a dependence on a BMA-based food web, usually occurring in shallow, clear waters where enough light reaches the bottom to support photosynthesis (France 1995, Hollander and Peebles 2004). Fourth, δ\textsuperscript{13}C values between −18 and −15‰ would indicate a diet incorporating both PP and BMA-based food webs. Fifth, carbon values lighter than −21‰ indicate that the basal resource is in a terrestrially influenced, stagnant, backwater habitat (Peterson and Fry 1987, Keough et al. 1998). These extremely light values are associated with the detrital decomposition of macrophytes that enrich the surrounding water with significant amounts of δ\textsuperscript{13}C-depleted dissolved inorganic carbon (DIC) in low-turbulence environments (Keough et al. 1998). However, it should be noted that these threshold values can overlap among basal resources and vary in space and time due to shifting isotopic baselines and ecosystem processes. By applying these assumptions to individual stable isotope profiles, lifelong trophic and habitat use histories can be recreated.

**Specimen Collection:** Adult Atlantic Tarpon were collected opportunistically from fishing mortalities from West-Central Florida (FL, n=13), and Louisiana (LA, n=3) (Table 2.1.). Recreational fishing mortalities often result from exhaustion during the fight or shark attacks. Specimens were collected during the recreational season (April through September) of 2014 and 2015. This time period reflects the months when large numbers of Atlantic Tarpon inhabit the coastal waters of each of the sampling regions. Individuals were kept in a large cooler on ice
from time of collection to dissection. Biological sampling included eyes and eye lenses, sagittal otoliths, and muscle tissue.

Sample Preparation: Left eye lenses of each specimen were delaminated according to Wallace et al. (2014). Whole eyes were removed by severing the sclera at its junction with the optic nerve and by severing the rectus (orbital) muscles near their junction with the sclera. Eyes were individually wrapped in aluminum foil, placed in plastic bags, and frozen upon return to the laboratory. Eyes were thawed before dissection. After thawing, a scalpel was used to create a flap in the cornea, which was then folded back to allow removal of the lens. Exterior tissue and vitreous material were manually removed by rinsing with deionized water. The rinsed lens, which contains the lens nucleus, cortex, and lens epithelium together as one cohesive unit, was then placed in a glass petri dish where successive layers of cortical laminae were separated using two pairs of fine-tip forceps under a dissecting stereomicroscope, until reaching the dehydrated core of the eye lens. The dehydrated cores were approximately 5-6 mm in diameter and contained multiple lens layers. The core is extremely hard and does not delaminate easily like the cortical layers. This was remedied by slicing the core along the equatorial plane and through the nucleus using an Isomet low-speed saw and 0.75 mm spacer. The resulting disk had easily identifiable layers that were divided and removed under a dissecting stereomicroscope until reaching the nucleus of the eye lens (~1 mm in diameter). After each delamination, an ocular micrometer was used to measure the diameter at the equator to the nearest 0.1 mm. Samples were stored in one-dram glass vials after being homogenized with a mortar and pestle.

Stable Isotope Analysis: Eye lens samples were analyzed for carbon and nitrogen (C, N, C:N) and bulk stable isotope ratios ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$). First, 400-1000 µg of each lens layer was collected and weighed on a Mettler-Toledo precision micro-balance, wrapped in tin capsules, and loaded into a Costech Technologies Zero-Blank Autosampler. Samples were combusted at 1050°C in a Carlo-Erba NA2500 Series-II Elemental Analyzer coupled in continuous-flow mode to a Finnigan
Delta Plus XL isotope ratio mass spectrometer. C:N measurements were calibrated and isotopic measurements were normalized to the AT-Air and VPDB scales, respectively, using NIST 8573 and NIST 8574 L-glutamic acid Standard Reference Materials. Measurements were expressed in per mil (‰) using δ notation, where δ = [(Rsample/Rstandard) - 1] × 1000, and R is the isotopic ratio of interest (e.g. 13C:12C). Analytical precision was estimated by replicate measurements of a working standard (NIST 1577b, Bovine Liver) (E. Goddard, personal communication).

Age Estimation: Sagittal otoliths were independently aged by the Age and Growth Lab at Florida’s Fish and Wildlife Research Institute (FWRI). Atlantic Tarpon otoliths have been radiometrically validated as indicators of age (Andrews et al. 2001). Individual annuli were annotated and the radial distance from the core along the succal groove for each annulus was measured. A third order polynomial function was generated for each specimen’s age*(annulus radial distance from core). All polynomial functions had R^2 values greater than or equal to 0.97. The polynomial function was then used to estimate the age and total length (TL) that each laminae represented, assuming the otolith and eye lens grow at similar rates that correspond to body growth. Since the outermost layer of the eye lens is hydrated and is disproportionately thick compared to the other laminae it was excluded from the generation of the polynomial function and estimation of eye lens age. Likewise, the polynomial function was generated only to the outer annulus of the otolith and did not include the marginal increment, assuming the marginal increment and hydrated outer layer of the eye lens represent approximately the same period of time and growth.

Data Analysis: Isotope profiles were generated for δ13C and δ15N values against age and TL for each specimen (Appendix A), and analyzed based on accepted SIA interpretations detailed above. The profiles were separated into three distinct time periods based on the δ13C values which were referred to as, 1) the backcountry phase, characterized by very light δ13C values less than −21‰, 2) a transitional period, or ontogenetic shift, represented by an elevation of
δ^{13}C values, to 3) the coastal phase, in waters with δ^{13}C values greater than −21‰. Coastal phase Atlantic Tarpon were categorized based on dominant basal resource use; BMA-based, PP-based, or mixed basal resource use. I quantified the variation in δ^{13}C and δ^{15}N values during the coastal phase by calculating the coefficient of variation of δ^{13}C and δ^{15}N for each specimen and then calculating the mean of all individuals. Mean age of ontogenetic shift, as well as mean δ^{13}C and δ^{15}N values of the backcountry and coastal phases, the final outside layer of the eye lens (most recent), and muscle tissue were calculated. These mean values were compared between states (FL and LA) using parametric and non-parametric tests based on the normality of the data set (T-Test, Wilcoxon, ANOVA, and Kruskal-Wallis), and were followed by post-hoc tests (Tukey, Dunn’s) when necessary.

RESULTS

All Atlantic Tarpon profiles strongly suggested recruitment to and use of backcountry habitats during the early life history. The mean ± standard error (SE) δ^{13}C value during this phase was −24.83 (± 0.19) ‰, well within the range characterizing backcountry habitats. On average, Atlantic Tarpon used backcountry habitats for 9.8 (± 0.91) years, corresponding with 1390.56 (± 76.76) mm TL, before migrating into coastal waters, as indicated by δ^{13}C values greater than −21‰. Two individuals had an isotopic shift to values just greater than −21‰ at a mean age of 1.78 (± 0.01) years, before displaying another shift to coastal waters at approximately the same age as the other specimens. After the ontogenetic shift, δ^{13}C values were indicative of coastal habitat use, averaging −16.03 (± 0.17) ‰. Atlantic Tarpon from Florida had significantly lower coastal phase δ^{15}N values averaging 11.48 (± 0.15) ‰, while Louisiana averaged 15.19 (± 0.19) ‰ (Wilcoxon: W=48, p<0.001). Once in the coastal phase, Atlantic Tarpon appeared to use a variety of different prey species and basal resources.

During the coastal phase, seven of the 16 (44%) δ^{13}C profiles were indicative of primarily feeding in a BMA-based food web and six (38%) had isotope values indicative of reliance on a
mixture of BMA and PP-based webs. One profile indicated use of a PP-based food web, one had not been mature long enough to develop a complete post-shift profile, and another displayed a mixed-use diet during the beginning of the coastal phase before gradually shifting to a completely PP-based diet. Atlantic Tarpon isotope values were consistent throughout the coastal phase indicating reliance on the same food web and basal resources. Individual coefficients of variation during the coastal phase ranged from −0.03 to −0.14 with a mean of −0.10 ± 0.009 for δ¹³C and 0.01 to 0.14 with a mean of 0.06 ± 0.009 for δ¹⁵N.

DISCUSSION

The research presented here provides the trophic history of the Atlantic Tarpon at the highest temporal resolution to date, which was accomplished with the newly described use of eye lens SIA. It is also the first to describe the entire trophic and habitat use history of adult Atlantic Tarpon in the eastern Gulf of Mexico. This work builds upon previous snapshot observations of habitat use for this species at separate life stages. The results support previous suggestions concerning the importance of backcountry habitat and timing of ontogenetic habitat shifts, while revealing new insights into feeding ecology and trophodynamics relating to seasonal migrations.

The stable isotope profiles suggested that backcountry habitat was essential to the life history of Atlantic Tarpon. Atlantic Tarpon have a vascularized swim bladder which allows them to inhabit low-oxygen backwaters where negative interspecific interactions may be reduced due to the metabolic and aerobic constraints on their predators and competitors (Shlaifer and Breder 1940, Geiger et al. 2000, Seymour et al. 2008). Every adult Atlantic Tarpon sampled in this study used the backcountry habitat during their early life histories. This study supports previous speculation on the importance of backcountry habitats to this species in the eastern Gulf of Mexico (Harrington 1958, Wade 1962, Rickards 1968, Zerbi et al. 2001, Jud et al. 2011, Adams and Cooke 2015).
Atlantic Tarpon use of backcountry habitat was also supported by recent otolith microchemistry work. Brown and Severin (2007) found 33% of Atlantic Tarpon sampled in the western Gulf of Mexico had recruited to fresh or brackish habitats and 67% recruited to marine waters. Rohtla and Vetemaa (2016) found 92% of Atlantic Tarpon sampled in French Guiana had recruited to fresh or brackish water habitats, and 8% had recruited to marine or hypersaline waters. Thus, unlike our study that found 100% use of backcountry habitats neither of these previous efforts using otolith microchemistry found complete recruitment to, or dependence on, this habitat during the early life history. Regional differences in Atlantic Tarpon life history have been suggested (Crabtree et al. 1997, Brown and Severin 2007), possibly explaining this variability across the species’ range.

After the backcountry phase the isotope profiles displayed a distinct shift in δ¹³C values, indicative of an ontogenetic migration to coastal waters (i.e., δ¹³C >= −21‰). The conclusion of the shift occurred, on average, at approximately 10 years of age and 140 cm in total length, corresponding closely with Crabtree et al. (1997) which showed that Atlantic Tarpon in Florida reached sexual maturity at approximately 10.5 years and 125 cm fork length. Thus, the ontogenetic shift from backcountry to coastal waters may occur as individuals approached or reached maturation. Other researchers have also surmised that Atlantic Tarpon, at the end of the juvenile and sub-adult stage, begin to move to estuarine and coastal waters due to increasing resource requirements and to join the spawning population (Wade 1962, Rickards 1968, Cyr 1991, Crabtree et al. 1992, Crabtree et al. 1995, Zerbi et al. 2001, Stein III et al. 2012, Adams and Cooke 2015). In addition, Woodcock and Walther (2014) observed similar shifts of stable isotope values in subsamples of Atlantic Tarpon scales (i.e., core, middle, edge) which corresponded with increased foraging on higher trophic level prey (δ¹⁵N) and movements from inshore to marine and coastal habitats (δ¹³C). Although Woodcock and Walther (2014) interpreted δ¹³C as a proxy for salinity and not directly to basal resource use as was done in the current study, the conclusions drawn support similar ontogenetic habitat shifts.
The transitional period of the ontogenetic shift had increasingly elevated \( \delta^{13}C \) values until reaching those indicative of coastal habitat. These intermediate values may reflect a mixture of backcountry and coastal food webs, with fish moving back and forth between the two, or use of estuarine habitats with intermediate isotope values. This study was unable to distinguish between these two possibilities because each eye lens layer conserves the average stable isotope history over the corresponding period of growth and therefore it was not possible to interpret finer resolution feeding or movement patterns within each lens layer. Two individuals appeared to undergo the ontogenetic shift out of backcountry habitats far earlier than the majority of fish studied. It is possible and perhaps most likely, that the shift reflected a movement to estuarine waters or an ecotone between backcountry and estuarine waters that had a greater estuarine signal due to decreased stagnation. The individuals then underwent another ontogenetic shift to coastal waters at approximately the same age and size as the other specimens. Also, the \(-21\%\) threshold between backcountry and coastal waters is not a definitive one. In reality, the threshold between backcountry and coastal waters likely varies in space and time due to shifting isotopic baselines and ecosystem processes. Atlantic Tarpon display facultative habitat use (Brown and Severin 2007, Shen et al. 2009, Rohtla and Vetemaa 2016) and it is possible that while pre-shift Atlantic Tarpon tended to be most associated with backcountry habitat, certain conditions may make the ecotone or estuarine habitats more suitable during this life stage.

Among individuals, I observed variation in the types of basal resources used during the coastal phase (i.e., BMA, mixed BMA-PP, PP), while within-individual basal resource use remained consistent. The specimens were sampled from the same coastal systems, at the same time of year, and neither age nor size was a factor in the type of food web each used. As generalist predators, the variation in foraging behavior was not expected, since individual diets should assimilate a variety of prey as their availability and biomass varies in space and time. However it is possible that variability in prey biomass, combined with individual specialization
(Bryan and Larkin 1972, Bolnick et al. 2003, Toscano et al. 2016), resulted in the observed foraging patterns. While the mechanism behind the variability in forage selection remains unclear, the within-individual consistency in basal resource use was clear.

Despite well described δ\textsubscript{13}C and δ\textsubscript{15}N isoscapes in the eastern Gulf of Mexico (Radabaugh et al. 2013), and the fact that Atlantic Tarpon are known to migrate across these isoscapes (Ault et al. 2008, Luo et al. 2008), I observed extremely steady values of both δ\textsubscript{13}C and δ\textsubscript{15}N during the coastal phase. The within-individual consistency indicated that Atlantic Tarpon were feeding at similar trophic levels and using basal resources with similar baseline values throughout the entire coastal phase. Importantly, eye lenses only grow and deposit layers during periods of somatic growth (Nicol and Somiya 1989, Horwitz 2003). In fishes, most energy is used for somatic growth during the juvenile phase (Sogard 1992, Stallings et al. 2010), and can be diverted to gonadal growth during spawning periods and increased basal metabolism during migration in adults (Perga and Gerdeaux 2005). Therefore the consistency observed in the isotope profiles were only representative of periods of somatic growth. The first possible explanation for the consistency in basal resource use is that Atlantic Tarpon do not migrate. However, we can confidently exclude this explanation since multiple tagging studies have shown that Atlantic Tarpon undergo long distance migrations (FWC Unpublished Data, Ault et al. 2008, Luo et al. 2008, Hammerschlag et al. 2012). Another possibility is that Atlantic Tarpon alter their feeding habits as they cross isoscape gradients in a way that causes their isotope values to remain constant, however this hypothesis is unrealistic and should not be considered. The most parsimonious explanation is that Atlantic Tarpon return to the same coastal system each year to feed and grow. While Atlantic Tarpon feed during the migratory and spawning periods, the energy from feeding is likely diverted away from growth and therefore would not be reflected in the eye lens. It has been suggested that Atlantic Tarpon feed from late summer through the early fall to recover from migration and spawning in the spring and summer (Crabtree et al. 1997, Ault et al. 2008). Based on the lack of variability in the isotope profiles, the
current study suggests that Atlantic Tarpon returned to the same coastal system after spawning to recover and fed in the same food webs. This conclusion is supported by tagging data that show adult Atlantic Tarpon returned to the same coastal systems year after year (FWC Unpublished Data). In addition, despite no difference in δ\textsuperscript{13}C values, we observed significant elevations (~3‰) of δ\textsuperscript{15}N values in Atlantic Tarpon from Louisiana [likely an isoscape effect, not a trophic one (Radabaugh et al. 2013, Radabaugh and Peebles 2014)], as well as consistency of values during the coastal phase. The results suggest that these fish may have shown fidelity to the Louisiana delta for foraging and growth. Atlantic Tarpon from both Florida and Louisiana reflected this pattern of repeatedly returning to the same system and basal resources to feed.

The recreational fishery for Atlantic Tarpon generates billions of dollars and thousands of jobs annually in the United States (Crabtree et al. 1992, Ault et al. 2008, Seyoum et al. 2008). It is critical that we better understand the complete life history and essential habitat use of Atlantic Tarpon. This study has revealed the importance of backcountry habitats to the Atlantic Tarpon life history. Every fish sampled used backcountry habitats for a significant portion of their life span, highlighting its importance to the early life history of this species. Indeed, consider that from the 1920s through 1940s, Port Aransas, Texas was known as the Tarpon Capital of the World (Holt et al. 2005, Ault 2008) but by the 1950s, Atlantic Tarpon in the region were nearly extirpated. The downfall of the Texas fishery has never been fully understood, however, it has been proposed that recruitment failure, due to the loss of juvenile habitat and altered freshwater flows, was a likely contributor (Holt et al. 2005). In addition, Winemiller and Dailey (2002) modeled populations of Atlantic Tarpon and found that a small, 1% increase in juvenile survival resulted in a tenfold increase in adult cohort abundance. Prior to my research, there had been a lack of conclusive evidence to link backcountry habitats as a major source of juveniles to the adult population. Backcountry habitats can be extremely susceptible to development, alteration, and destruction, especially in Florida (Bortone 2005). The findings of this work elucidate the importance of juvenile habitat and warrant further research on how Atlantic Tarpon use
backwater habitats and their potential roles as nurseries (sensu Beck et al. 2001, Dahlgren et al. 2006).

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## TABLES AND FIGURES

Table 2.1. Adult Atlantic Tarpon capture data. Specimen T08 was excluded from analysis due to not being able to procure otoliths.

<table>
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<th>Total Length (mm)</th>
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CHAPTER THREE

ONTOCRGENETIC HABITAT SHIFTS AND BIOLOGY OF JUVENILE ATLANTIC TARPON

(MEGALOPS ATLANTICUS) IN FLORIDA

ABSTRACT

The Atlantic Tarpon, *Megalops atlanticus*, is a large, typically migratory, elopomorph fish that is both ecologically and economically important. Atlantic Tarpon are under threat due to regional exploitation, loss of natal and juvenile habitat, poor water management, and offshore impacts. In addition, little is known about the juvenile biology and ecology of the species. In this study, mark-recapture data from a multi-year genetic tagging program were used to investigate survival and growth rates, ontogenetic habitat use, and migration of juvenile Atlantic Tarpon in Florida. I found that juvenile Atlantic Tarpon took approximately ten years to reach the length associated with maturity, and appeared to have a high survival rate (~80%) possibly due to use of habitats with reduced competition and predation. Juvenile Atlantic Tarpon underwent several ontogenetic habitat shifts throughout the juvenile phase. In addition, juvenile Atlantic Tarpon did not migrate long distances but instead displayed fidelity to systems wherein only short movements occurred between habitat types. The catch data were used to identify four systems (Indian River Lagoon, Charlotte Harbor, the Everglades, and the Florida Keys), that harbored large numbers of juvenile Atlantic Tarpon and contained the complexity of habitats necessary for ontogenetic development.
INTRODUCTION

Many fish have complex life histories with varied use of habitats and trophic resources at different life stages (Whitfield 1990, Able and Fahay 1998). Consequently, the life histories and essential habitats are often poorly understood (Able 2005). Each of these habitats can be critical to the persistence of the species and the loss of any habitat, or migration pathways between habitats, could have negative effects on population persistence (Rosenberg et al. 2000). For example, salmonids can be negatively affected by dams and altered water flows that impede migration among habitats resulting in decreased survival and fitness (Pringle et al. 2000, Levin and Tolimieri 2001). Identifying the habitats and resources species use is the first step to understanding the role each plays in the biology of the species.

The Atlantic Tarpon, *Megalops atlanticus*, is a large, typically migratory, elopomorph fish that frequents coastal and inshore waters of the tropical and subtropical Atlantic Ocean (Wade 1962). The Atlantic Tarpon is a prized sportfish and its recreational fishery generates millions of dollars and thousands of jobs annually in the United States (Crabtree et al. 1992, Ault 2008, Seyoum et al. 2008). A highly mobile mesopredator, Atlantic Tarpon forage on a wide variety of prey, and are themselves preyed upon by several shark species. In addition, Atlantic Tarpon use several different habitats and other resources throughout their life cycle (Ault et al. 2008, Hammerschlag et al. 2012). Despite the ecological and economic importance of Atlantic Tarpon, we lack a complete understanding of their full life history. Most research has focused on age and growth, reproduction, and leptocephali development (Crabtree et al. 1992, Crabtree et al. 1995, Crabtree et al. 1997, Andrews et al. 2001). Although there is a lack of information on Atlantic Tarpon biology and ecology, it is clear that the species is under threat due to regional exploitation, loss of natal habitat, poor water management, and offshore impacts (Ault et al. 2008). Currently listed as vulnerable by the International Union for Conservation of Nature (Adams et al. 2012), it is imperative that we increase our understanding of Atlantic Tarpon ecology to more effectively manage the species.
Most Atlantic Tarpon research has focused on adult and larval stages, with comparatively few studies on the juvenile life stage (≤ 1219.2 mm) (Crabtree et al. 1997). The juvenile stage is estimated to last approximately seven to ten years, at which point Atlantic Tarpon become sexually mature and join the adult population in coastal waters (Crabtree et al. 1992). Juvenile Atlantic Tarpon typically recruit to coastal habitats after the pelagic leptocephalus larval stage where they are dependent upon upper estuarine habitats such as brackish lagoons, mangroves, and tidal creeks where predation is thought to be low and food supplies high (Crabtree et al. 1995). At the smallest sizes juveniles feed on insects, copepods, and other small crustaceans before moving on to a fish-based diet at larger sizes (Harrington 1958, Rickards 1968, Jud et al. 2011). Larger juvenile Atlantic Tarpon (sub-adults) appear to become more dependent upon deeper water habitats such as sloughs and canals that provide access for emigration into coastal waters (Ault et al. 2008). Unfortunately, characteristics of optimal juvenile habitat, as well as the habitats and regions that supply the adult population, have yet to be identified. This stage is critical to the continued success of the adult population, and modeling has shown that survival of juveniles is the most important factor influencing adult Atlantic Tarpon populations (Winemiller and Dailey 2002). A better understanding of habitat and resource use, as well as other components of juvenile Atlantic Tarpon biology, may help inform management and protection for the species.

The research presented here used catch data and individual recapture histories from a multi-year genetic tagging study to expand upon our limited knowledge of juvenile Atlantic Tarpon biology and ecology in Florida. This was accomplished by describing 1) survival rates and recapture probabilities, 2) ontogenetic habitat use, 3) seasonal and regional patterns of abundance, 4) expected ranges of movement, and 5) juvenile growth parameters. These quantifiable data products were then used to identify coastal systems that have the potential to
act as ideal juvenile habitats. The results of this research may provide managers the information needed to better protect the species and conserve the habitats they use.

METHODS

Genetic Tagging: One of the main challenges of studying migration and resource use is identifying critical habitats and tracking movements among them (Elsdon and Gillanders 2003). Traditional applied tags (e.g., dart tags, satellite tags) are fraught with logistical limitations such as tag loss, cost, inability to tag small juveniles, and low return rates (Robson and Regier 1966, McFarlane et al. 1990). The use of natural tags such as genetic tagging, can be advantageous because they can be incorporated at an early life stage, are relatively inexpensive, and cannot be lost (Elsdon et al. 2008). Genetic tagging is a commonly employed, non-invasive method used to test whether two or more genetic samples belong to the same individual (Miller et al. 2015). Instead of attaching a tag to an individual fish or marking that fish, the researcher simply uses a DNA sample as a natural tag. The resulting DNA “fingerprint” consists of a pattern made up of short DNA fragments (microsatellites) unique to an individual from birth. Although commonly used for terrestrial species, genetic tagging programs have yet to be extensively employed to study fish, but have the capability to answer questions about migration, habitat use, recapture rates, survival rates, and growth (Seyoum et al. 2008).

Study Background: The Tarpon Genetic Recapture Study (TGRS) was an angler-based tagging program started in 2005. Recreational anglers participating in the program “scrubbed” Atlantic Tarpon skin cells from the outer jaw using a small piece of rough cloth, that was then placed in a vial of 10% EtOH solution. Anglers also recorded capture information such as date, time, location, total length (TL), weight, and other relevant information. Once received at Florida Wildlife Research Institute (FWRI), the 10% EtOH in the vials was replaced with 100% EtOH for long term storage and all data were added to the TGRS database. Over 24,000 specimens were
received over the course of the study (2005-2014), and almost 23,000 of the specimens were sampled in Florida. For this study, only hook-and-line caught specimens ≤ 1219.2 mm from Florida were considered for analysis. A more detailed overview of the study was provided in Guindon et al. (2015).

*Laboratory Analysis:* To isolate genomic DNA from tissues, the PUREGENE DNA Purification Kit (Gentra Systems, Inc., Minneapolis, MN) was used in accordance with the manufacturer's directions. The purity of all DNA extractions were quantified prior to polymerase chain reaction (PCR) using a NanoDrop 800 spectrophotometer; DNA concentrations were adjusted as needed. The following nine microsatellite DNA markers, isolated and characterized as described in Seyoum et al. (2008) were used: [Matl 01, 04, 05, 08, 10, 11, 13, 17, and 22 (Table 3.1.)]. Using a reaction profile of 94°C for 2 minutes, 32x(94°C for 30 s, 58°C for 30 s, 72°C for 30 s) and 72°C for 7 minutes, microsatellite loci were assayed in 25-μL PCR reactions seeded with 50-100 ng of genomic DNA. Fragments were sized using GeneScan-500 ROX size standard and visualized on an ABI 3130XL genetic analyzer (Applied Biosystems, Inc.). Raw genotype data were evaluated and processed with GeneMapper software v4.0 (Applied Biosystems, Inc.), examined for matching genotypes using the software MicroChecker (Van Oosterhout et al. 2004), and probabilities of identity were computed in Excel using the θ-corrected single-locus probabilities described in Evett & Weir (1998).

*Recapture and Survival Rates:* Within-year, inter-annual, cumulative by year, and overall recapture rates were calculated using specimens with complete genotypes. Capture histories were constructed for each specimen on a seasonal basis; Spring/Summer (March, April, May, June), Summer/Fall (July, August, September, October), and Winter (November, December, January, February), for each year of the study, 2005-2014. Each specimen was then assigned a “1” in seasons it was captured and a “0” when it was not captured. A Cormack-Jolly-Seber open population model (CJS) was used in Program Mark to analyze the capture histories. The CJS uses the individual capture histories to calculate two parameters: 1) Apparent survival
probability ($\Phi = 1 - \text{emigration - mortality}$), and 2) Recapture probability ($p$). Three models with increasing complexity were developed and run: 1) constant $\Phi$ and $p$ ($\Phi(.)p(.)$), 2) seasonally varying $\Phi$ and constant $p$ ($\Phi(s)p(.)$), and 3) seasonally varying $\Phi$ and $p$ ($\Phi(s)p(s)$). The three models were then compared using both the Akaike Information Criterion (AIC) and deviance of each model.

Capture-recapture models based on genetic tagging are subject to two directionally distinct forms of bias, which arise from false-positive and false-negative classifications, respectively. False-positive classifications can lead to the underestimation of apparent survival, false-negatives to overestimation. For this study, it was assumed that genetic assignment methods were sufficiently robust such that no false-positive classifications were expected and that false-negative classifications due to mistyping and other lab errors were negligible. These assumptions will be quantitatively explored in future work.

**Habitat Use:** Each juvenile Atlantic Tarpon capture event was classified into one of five habitat types based on the provided catch location data: 1) Ditch (small ditches or creeks $\leq$ ~10 meters width), 2) Creek (creeks, canals, or small ponds $\leq$ ~50 meters width), 3) River (coastal rivers, large canals, or lagoons), 4) Bay (embayments, bays, sounds, or Intracoastal), 5) Open water (beaches, Gulf of Mexico, or Atlantic Ocean). Capture events were also classified into seasons (Spring/Summer, Summer/Fall, and Winter), and regions [Panhandle (PH), Northwest (NW), West-Central (WC), Southwest (SW), Everglades (EG), Keys, South (S), Southeast (SE), East-Central (EC), and Northeast (NE)]. Non-parametric Kruskal-Wallis tests were used to compare TL among habitat types, seasons, and regions. When necessary, post-hoc Dunn’s tests were used to examine differences among independent variables.

**Abundance:** Due to the sampling method, quantifying effort in each of the regions or season was not possible. Therefore, typical abundance metrics such as Catch-Per-Unit-Effort (CPUE) were not feasible. Because of this, total number of fish sampled among regions and seasons were compared under the assumption that effort was similar among regions and seasons.
However, it was apparent that effort was not equal in the East-Central region where one angler submitted approximately 1,750 specimens. These specimens were removed from the dataset for analysis of patterns of abundance.

*Expected Ranges of Movement:* For each recapture event, Google Earth and reported catch data were used to determine the shortest straight line distance over water between locations. Linear regression was used to analyze whether a relationship existed between recapture distance and change in length ($\Delta TL$) or time between recaptures ($\Delta T$). Mean ± SE distance and $\Delta T$ between recaptures were calculated, as well as the percent recaptures caught in the same location (same name of reported location or latitude/longitude), within one kilometer (km), and within five km. In addition, this analysis was repeated after removing recaptures in which one or both reported capture locations were vague and could have encompassed very large areas.

*Growth:* Von Bertalanffy parameters ($L_{\infty}$, $K$) were estimated using variations of Fabens (1965). The Fabens method uses length at first capture and $\Delta T$ to estimate growth which makes it optimal for mark-recapture data. However, the original Fabens method is limited in that it does not take into account individual variability in growth. Haddon (2010) provided four variations of the Fabens method that can be used to account for individual variability in growth: 1) a Weighted Least Squares (WLS) method, 2) Negative Log-Likelihood (NLL) with constant variance ($\sigma$), 3) NLL with linearly decreasing variance (Varsig 1), and 4) NLL with exponentially decreasing variance (Varsig 2) (Francis 1988). The models were optimized using the Solver function in Microsoft Excel with the GRG non-linear solving method. Using back-calculated otolith length-at-age data from Chapter Two, $L_{\infty}$ and $K$ were calculated and used to generate a control curve for the juvenile stage. The five curves generated with variations of the Fabens’ method were then compared to the control using least-squares.
RESULTS

Capture Totals: A total of 7,093 juvenile Atlantic Tarpon DNA scrubs were collected and submitted to FWRI. Of these, 6,164 yielded sufficient data for habitat analysis, 6,584 for regional analysis, and 6,512 for seasonal analysis; 5,162 complete genotypes were used for recapture analysis (Table 3.2.).

Recapture Rates: Over the 10-year study, there were 173 juvenile recapture events, yielding a 3.35% overall recapture rate. Within-year recapture rates varied between 0.39 and 2.47% (Figure 3.1.), cumulative recapture rates were low and increased with time until reaching the 3.35% overall recapture rate (Figure 3.2.), and inter-annual recapture rates were highly variable between 0.34 and 2.38% (Figure 3.3.) (Table 3.3.).

Mark-Recapture Analysis: Overall, juvenile Tarpon had an 80% survival rate and a 1% recapture probability. The $\Phi(s)p(s)$ model (Deviance = 216.09, AIC = 1534.55) was the best of the three models, followed by the $\Phi(s)p(.)$ model (Deviance = 256.24, AIC = 1570.69) and the $\Phi(.)p(.)$ model (Deviance = 290.43, AIC = 1600.88) (Table 3.4.).

Habitat Use: There was a statistically significant difference in TL of juvenile Atlantic Tarpon among habitats (Kruskal-Wallis: $X^2 = 4130.8$, DF = 4, p < 2.2e-16). There were also statistically significant differences between all habitat comparisons except Bay versus Open Water (Dunn’s Test) (Table 3.5.). Mean TL of Atlantic Tarpon increased with increasing sizes of water bodies (Table 3.6. and Figure 3.4.).

Seasonal and Regional Abundance: The majority of Atlantic Tarpon (n = 3,229; 49.6%) were caught during the Summer/Fall season, followed by Spring/Summer (n = 2,150; 33.0%), and then winter (n = 1,133; 17.4%). There was a statistically significant difference in average TL of fish among all three seasons (Kruskal-Wallis: $X^2 = 410.82$, df = 2, p < 0.001). Atlantic Tarpon captured in Spring/Summer were larger on average (727.95 mm ± 7.67) than those captured in Summer/Fall (547.75 mm ± 5.46) and winter (515.58 mm ± 9.15) (Dunn’s: p < 0.001).
numbers of juvenile Atlantic Tarpon sampled in each region are displayed in Figures 3.5 and 3.6.

*Expected Range of Movement:* Mean ΔT was 269.07 (± 27.86) days. Mean distance between captures was 5.34 (± 1.81) km. This distance was upwardly skewed by four outliers (62.8, 95.0, 135.1, and 160.9 km). No significant relationship was observed between ΔTL and distance traveled (Pearson’s R² = 0.005, p = 0.45). There was only a slight increase in distance traveled as ΔT increased (Pearson’s R² = 0.070, p = 0.002) (Figure 3.7.). In addition, 44.3% of fish were recaptured in the same reported location as the initial capture, 59.5% within one km, and 87.8% within five km. When specimens with general or inexact capture locations were removed from the dataset these values increased to 48.7%, 65.5%, and 93.3%, respectively, and the mean distance between capture locations dropped to 4.99 (± 1.98) km.

*Growth:* Estimated von Bertalanffy parameters for the five methods can be found in Table 3.7. and Figure 3.8. The method that produced a fit most similar to the otolith-derived control curve was Francis (1988) linear decreasing variance with ΔTL from Fabens (Varsig 1). When compared with the other maximum likelihood approaches the Akaike Information Criterion (AIC) showed that the improvement in the negative log likelihood was worth the addition of two extra parameters.

**DISCUSSION**

The research presented here was accomplished using genetic tagging, via microsatellite DNA, to examine and reveal insights into juvenile Atlantic Tarpon biology that had not previously been documented. This work builds upon limited previous research of juvenile Atlantic Tarpon biology and ecology. Recapture events were used to produce estimates of survival rates and recapture probabilities, while expanding our knowledge of juvenile growth rates, and expected ranges of movement. In addition, data from each individual capture event were used to explore patterns of habitat use and ontogenetic habitat shifts during the juvenile stage.
The overall recapture rate, 3.35%, was low, but possibly indicative of a large population in which the probability of recapturing the same individual was low. The increases in inter-annual and cumulative recapture rates in 2012 were likely the result of biased sampling methods. During this year, one angler accounted for almost 1000 of the 1855 annual captures. Likewise, the drop in recapture rates in 2013 was most likely a result of asking anglers to shift their sampling efforts to adult Atlantic Tarpon $\geq 1219.2$ mm, which resulted in a ~50% reduction in the number of juveniles sampled.

In order to estimate apparent survival and recapture probability, two models with constant $p$ were developed and compared. The parameter $p$ was kept constant based on the assumption that sampling methods were the same each season, and thus there was similar probability of capturing any fish present. In Program MARK the model with the lowest deviance is assumed to be the one that best fits the data, and the lowest AIC indicates the most parsimonious model, which is closest to the “full truth” (Cooch and White 2006). Here, the $\Phi(s)p(.)$ model was considered the best. However, the results indicated that the assumption of constant $p$ was probably incorrect. First, the 100% survival from Winter-Spring and Spring-Fall was likely overestimated. Although juvenile Atlantic Tarpon experience reduced predation in the low-oxygen habitats they inhabit (Shlaifer and Breder 1940, Geiger et al. 2000, Seymour et al. 2008), they still undergo predation from wading birds (Beebe 1927, Rickards 1968) and alligators (Wade 1962), as well as mortality related to resource competition (Rickards 1968). Second, the dramatic decrease in apparent survival to 43% between Fall and Winter was likely overestimated. During the winter, when water temperatures approach 10°C, Atlantic Tarpon experience reduced metabolism, are less active, and feed less (Zale and Merrifield 1989), all of which can reduce catchability. Therefore, it is not surprising that there were distinct differences in the number of Atlantic Tarpon sampled among seasons, with an approximately 50% decrease in specimens collected in the Winter. These observations suggest the original models likely incorrectly attributed the reduced catchability during the winter to reduced survival. Because a
constant probability of recapture was unlikely, the $\Phi(s)p(s)$ model was developed to better analyze the dataset. The results were improved in terms of AIC and deviance, as well as providing a more biologically realistic model. Recapture probabilities were nearly the same in spring and summer but reduced in winter, likely due to temperature-related behavioral changes, as described above. Accordingly, apparent survival also varied between seasons, and seems to take into account reduced survival of newly settled juveniles between fall and winter as well as reduced survival between winter and spring, likely a result of thermal mortality.

Prior to this research, survival rates have not been calculated for juvenile Atlantic Tarpon. However, when modelling populations of Atlantic Tarpon, Winemiller and Dailey (2002) used survival rates between 0.40 to 0.69 for the juvenile life stage, which was substantially lower than the ~80% annual survival rate estimated in the current study. Winemiller and Dailey’s survival rates were derived from McGurk’s dry weight – natural mortality rate regression for fishes (McGurk 1986). One possibility for the disparity between the two estimates is that the Atlantic Tarpon life history strategy of using low-oxygen habitats does afford them increased survival rates when compared to species with more traditional life histories because of reduced predation and resource competition.

The results of my study showed that juvenile Atlantic Tarpon used several different habitats over the course of their ontogeny. Individuals will seek habitats that minimize the ratio of mortality risk to growth rate (Werner and Gilliam 1984, Snover 2008). Species in which the ontogeny spans an extended period of time and a large range of body sizes will then change habitats and diets as they grow, as particular habitats may be limited in the size range of individuals they are able to support (Werner and Gilliam 1984, Werner and Hall 1988). Juvenile Atlantic Tarpon have a life history strategy that emphasizes these considerations to maximize their success at reaching maturity. Atlantic Tarpon have a vascularized swim bladder which allows them to inhabit low-oxygen backwaters where negative interspecific interactions may be reduced due to the metabolic and aerobic constraints on their predators and competitors.
Previous observations show that small juveniles inhabit salt marshes, shallow lined estuaries, and stagnant pools of varying salinity where predation is thought to be low and food supply high (Wade 1962, Crabtree 1995, Shenker et al. 2002, Layman 2007). These juveniles readily feed on copepods, insects, and fishes, and gradually move to a completely piscivorous diet, with prey size increasing in proportion to body size (Hildebrand 1934, Harrington 1958, Rickards 1968). Late juvenile stage Atlantic Tarpon then use coastal sloughs and canals that facilitate emigration into coastal waters and the adult population (Kushlan and Lodge 1974). The findings of my research support these observations and strengthens our understanding of Atlantic Tarpon ontogenetic habitat use and shifts during the juvenile stage. Juvenile Atlantic Tarpon appeared to undergo at least four habitat shifts during their ontogeny that entailed movements to larger bodies of water with increases in size, likely due to increased resource requirements and reduced predation risk at larger sizes. By the end of the juvenile stage, Atlantic Tarpon used habitats such as the coastal bays and open waters which allowed for access to abundant resources and likely facilitated emigration from the juvenile to adult population.

The tag-recapture data also indicated that most juvenile Atlantic Tarpon displayed site fidelity to the same backcountry and estuarine areas, and in many cases to the same location. The average recapture distance of ~5 km seems to indicate site fidelity in juvenile Atlantic Tarpon based on interpretations of movement patterns of similar sized shark species (Garla et al. 2006). In addition, this average recapture distance appears to have been inflated by the movements of several late stage juveniles that may have been on the way to or already had joined the migratory adult population. Instead, it seems that most juvenile Atlantic Tarpon remained in a relatively small area throughout the juvenile stage. This conclusion is supported by the observation that 49% of juveniles were recaptured in the same reported location, 66% within 1 km, and 93% within 5 km. In addition, the relationships between recapture distance and ΔT or ΔTL were minor or nonexistent. These findings suggest that juvenile Atlantic Tarpon did
not generally migrate long distances and remained in the same area throughout this life stage. The site fidelity and habitat shifts that were observed suggest that the ideal juvenile habitat was one that contained all of the habitat classifications described above in close proximity to one another. This habitat use strategy would possibly result in reduced loss of growth from migratory energy expenditures and reduced susceptibility to predation associated with long migrations. Close proximity of habitats used by Atlantic Tarpon throughout the juvenile stage is a characteristic shared by the coastal systems identified in this study as potentially optimal juvenile habitat, as well as the systems that have been historically considered ideal juvenile Atlantic Tarpon habitat.

The larger average size of Atlantic Tarpon sampled in the Spring/Summer season was likely an artifact of the type of fishing effort and data reporting. This time period is known as the “Tarpon Season,” when anglers target migrating groups of adult fish. Since almost all Atlantic Tarpon are released, reported lengths are usually estimated and 1219.2 mm (4 feet) is commonly used to describe smaller adult Atlantic Tarpon. The inclusion of these Atlantic Tarpon into the dataset likely skewed the mean length of the Spring/Summer season. In addition, the influx of young-of-the-year Atlantic Tarpon into the fishery in the late fall and winter likely resulted in the lower average size sampled during the Winter season.

Unfortunately, due to the nature of the sampling in this project it was not possible to quantify effort. Therefore, comparisons between regions could not be made using normal indices of abundance such as CPUE. However, assuming effort was equal among all regions, four regions stood out in terms of number of specimens sampled (East Central, Everglades, Keys, and Southwest). All four regions are in the southern portion of Florida where water temperatures rarely reach the 10°C mortality threshold (Zale and Merrifield 1989) that inhibits juveniles from surviving in northern regions. The low number of specimens sampled in the northern regions strongly suggest that they do not have considerable populations of juvenile Atlantic Tarpon, likely due to seasonal thermal mortality. The Indian River Lagoon in the East
Central, Charlotte Harbor/Pine Island Sound in the Southwest, river systems of the Everglades, and the entirety of the Keys region (Figure 3.9.) have the complexity of habitats in close proximity to one another that is optimal for ontogenetic development. It is interesting that large numbers of juveniles were not sampled in the SE and S, even though these regions provide the thermal protection necessary for juvenile survival. One possibility is that there was a lack of effort in sampling in this area. Another possibility is that there was a lack suitable habitat in these regions and environmental alteration and degradation of existing habitats has resulted in a lack of juvenile Atlantic Tarpon in these regions.

The growth models I produced had lower TL∞ and higher K than the growth models produced by Crabtree et al. (1995). This is likely due to only using juvenile recapture events in the current study. The samples in Crabtree et al. (1995) were biased toward large adults and small juveniles and did not include many intermediate-sized sub-adults (TL = 900-1200mm). By only using juvenile recapture events, the current study observed Atlantic Tarpon at their period of fastest growth when almost all available energy is used for growth (Sogard 1992, Stallings et al. 2010). Upon reaching maturation, growth slows as resources are devoted away from growth towards migration and reproduction (Perga and Gerdeaux 2005). The difference in the size distribution of specimens between the two studies is likely the reason for the differences in growth parameters. Therefore, the growth functions presented in this paper should only be applied to juvenile Atlantic Tarpon. Crabtree et al. (1995) should be used for adult Atlantic Tarpon growth models. The Fabens method (1965) is specifically designed for tag-recapture based data, and this study used the four alternatives that Haddon (2010) recommended to account for individual variability in growth. One of the downfalls of the Fabens method is that it does not use or calculate a T₀ parameter for use in the von Bertalanffy growth curve, however the addition of the T₀ from Crabtree et al. (1995) did not improve the fit of the curve. When compared to the control curve derived from adult Atlantic Tarpon otoliths, the fit of the best tagging-derived curve (Varsig 1) was similar but did not exhibit as fast of a growth rate, K. There
are several explanations that may account for this, the first being that the otoliths used in this study grew at a different rate during a different time period and set of environmental conditions than the genetic tagging specimens. The second, is that Atlantic Tarpon otoliths are notoriously hard to read (Crabtree et al. 1995), and accidentally excluding one or more early annuli could result in an apparent faster growth curve than the actual growth rate. The curves generated with the tag-recapture data showed that Atlantic Tarpon reached the length associated with maturity at approximately 10 years of age, similar to the age at maturity described by Crabtree (1997) and Ault (2008). In the first chapter of this thesis, the examination of Atlantic Tarpon eye lens stable isotopes showed that 10 years is also the approximate age at which Atlantic Tarpon completed an ontogenetic shift from the backcountry to coastal waters to join the adult population.

The recreational fishery for Atlantic Tarpon generates billions of dollars and thousands of jobs annually in the United States (Crabtree et al. 1992, Ault et al. 2008, Seyoum et al. 2008). Although our understanding of juvenile ecology is limited, it has been shown that this stage is critical to the health of adult populations. The decline of the recreational fishery in Texas in the 1950s has been attributed to recruitment failure, due to the loss of juvenile habitat and altered freshwater flows (Holt et al. 2005). In addition, Winemiller and Dailey (2002) modeled populations of Atlantic Tarpon and found that a small, 1% increase in juvenile survival resulted in a tenfold increase in adult cohort abundance. The habitats juvenile Atlantic Tarpon rely on can be extremely susceptible to development, alteration, and destruction, especially in Florida (Bortone 2005). It is imperative to protect as well as restore critical juvenile habitats to maintain and increase adult Atlantic Tarpon populations. The findings of this work elucidate the complexity of habitat use and ontogenetic migration in juvenile Atlantic Tarpon, and warrant further research to identify coastal systems that supply the adult population and their potential roles as nurseries (sensu Beck et al. 2001, Dahlgren et al. 2006).
LITERATURE CITED


Table 3.1. Characterization of 9 microsatellite loci for 65 specimens of *Megalops atlanticus*

<table>
<thead>
<tr>
<th>Locus</th>
<th>Primer Sequence (5' - 3')</th>
<th>Repeat Motif</th>
<th>Allele Size Range</th>
<th>Observed Heterozygosity</th>
<th>Expected Heterozygosity</th>
<th>Genebank Accession number</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Matl01</strong></td>
<td>F: AGCTAGGTACCGAAGAGGACA-NED R: CACCTGTTTCTCTGCA TGATT</td>
<td>(CT)$<em>7$ ... (CA)$</em>{12}$</td>
<td>158-164</td>
<td>0.57</td>
<td>0.54</td>
<td>DQ076485</td>
</tr>
<tr>
<td><strong>Matl04</strong></td>
<td>F: TCCACTACGAATAGTCCGTA-FAM R: CATACCTGGAAAGCGCAAAAACAAATTCATGTATT</td>
<td>(GT)$_9$</td>
<td>143-153</td>
<td>0.56</td>
<td>0.59</td>
<td>DQ076488</td>
</tr>
<tr>
<td><strong>Matl05</strong></td>
<td>F: GGGCCAATAACAAAGAGAGTGAT-NED R: CGACAATTTCCATGTTTGCAATT</td>
<td>(TR)$_{24}$TT(TR)$_7$</td>
<td>160-178</td>
<td>0.56</td>
<td>0.58</td>
<td>DQ076489</td>
</tr>
<tr>
<td><strong>Matl08</strong></td>
<td>F: CACACTGTGTCCCAATCTCT-NED R: AAAACGCACATTGATGTGAATT</td>
<td>(CA)$_{17}$ ... (CA)$_5$</td>
<td>184-204</td>
<td>0.70</td>
<td>0.71</td>
<td>DQ076492</td>
</tr>
<tr>
<td><strong>Matl10</strong></td>
<td>F: TTGGAAATGTATGGATTGATCATTGG-FAM R: CAGATTCGCTGAAAAACAATTA</td>
<td>(AC)$_{20}$</td>
<td>179-189</td>
<td>0.60</td>
<td>0.65</td>
<td>DQ076494</td>
</tr>
<tr>
<td><strong>Matl11</strong></td>
<td>F: GGTTTTTTGCTCAATGGTCCT-FAM R: TTGCTATTGCTTGCTGCTGT</td>
<td>(AC)$_{15}$(GC)$_4$</td>
<td>180-194</td>
<td>0.70</td>
<td>0.65</td>
<td>DQ076495</td>
</tr>
<tr>
<td><strong>Matl13</strong></td>
<td>F: AAACCTCAAAAGCCACACTT-FAM R: GAAACCAACCAAGTGACACCAC</td>
<td>(CR)$_{11}$</td>
<td>246-262</td>
<td>0.64</td>
<td>0.59</td>
<td>DQ076497</td>
</tr>
<tr>
<td><strong>Matl17</strong></td>
<td>F: GGGCCTGATGTGAAGAGAAGAAGA CAGACCATGATGTCGTCGTC</td>
<td>GT(12)</td>
<td>214-224</td>
<td>0.118</td>
<td>0.057</td>
<td>AY144364</td>
</tr>
<tr>
<td><strong>Matl22</strong></td>
<td>F: CCTCCAGGACTGTGGTGG AAGGGATGGTGAACAATACCATGATGATG</td>
<td>TCTA(16)</td>
<td>178-210</td>
<td>0.687</td>
<td>0.806</td>
<td>AY144368</td>
</tr>
</tbody>
</table>
Table 3.2. Sampling totals categorized by year and type of analysis

<table>
<thead>
<tr>
<th>Year</th>
<th>Total</th>
<th>Habitat</th>
<th>Regional</th>
<th>Recapture</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2006</td>
<td>79</td>
<td>73</td>
<td>77</td>
<td>81</td>
</tr>
<tr>
<td>2007</td>
<td>220</td>
<td>219</td>
<td>219</td>
<td>190</td>
</tr>
<tr>
<td>2008</td>
<td>309</td>
<td>305</td>
<td>307</td>
<td>254</td>
</tr>
<tr>
<td>2009</td>
<td>716</td>
<td>676</td>
<td>689</td>
<td>570</td>
</tr>
<tr>
<td>2010</td>
<td>654</td>
<td>583</td>
<td>588</td>
<td>370</td>
</tr>
<tr>
<td>2011</td>
<td>1523</td>
<td>1342</td>
<td>1407</td>
<td>1061</td>
</tr>
<tr>
<td>2012</td>
<td>1855</td>
<td>1462</td>
<td>1757</td>
<td>1459</td>
</tr>
<tr>
<td>2013</td>
<td>1209</td>
<td>1056</td>
<td>1103</td>
<td>825</td>
</tr>
<tr>
<td>2014</td>
<td>400</td>
<td>328</td>
<td>331</td>
<td>255</td>
</tr>
<tr>
<td>2015</td>
<td>25</td>
<td>24</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>NA</td>
<td>100</td>
<td>92</td>
<td>7</td>
<td>91</td>
</tr>
<tr>
<td>Total</td>
<td>7093</td>
<td>6163</td>
<td>6512</td>
<td>5162</td>
</tr>
</tbody>
</table>
Table 3.3. Yearly recapture rates (Within-Year, Cumulative, Inter-Annual)

<table>
<thead>
<tr>
<th>Year</th>
<th>Within-Year</th>
<th>Cumulative</th>
<th>Inter-Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>2.47%</td>
<td>2.38%</td>
<td>2.38%</td>
</tr>
<tr>
<td>2007</td>
<td>0.53%</td>
<td>1.09%</td>
<td>0.36%</td>
</tr>
<tr>
<td>2008</td>
<td>0.39%</td>
<td>0.95%</td>
<td>0.38%</td>
</tr>
<tr>
<td>2009</td>
<td>1.40%</td>
<td>1.73%</td>
<td>1.28%</td>
</tr>
<tr>
<td>2010</td>
<td>1.89%</td>
<td>1.98%</td>
<td>0.68%</td>
</tr>
<tr>
<td>2011</td>
<td>1.60%</td>
<td>2.10%</td>
<td>0.95%</td>
</tr>
<tr>
<td>2012</td>
<td>1.85%</td>
<td>3.06%</td>
<td>1.73%</td>
</tr>
<tr>
<td>2013</td>
<td>1.21%</td>
<td>3.24%</td>
<td>0.71%</td>
</tr>
<tr>
<td>2014</td>
<td>0.78%</td>
<td>3.35%</td>
<td>0.34%</td>
</tr>
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</table>
Table 3.4. Program Mark estimates of $\Phi$ and $p$ for three different models: The $\Phi(s)p(s)$ model fit the data best and was the most parsimonious of the three models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Time Period</th>
<th>Apparent Survival</th>
<th>Standard error</th>
<th>Recapture Probability</th>
<th>Standard error</th>
<th>AIC</th>
<th>Deviance</th>
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</thead>
<tbody>
<tr>
<td>$\Phi(.)p(.)$</td>
<td></td>
<td>0.79</td>
<td>0.03</td>
<td>0.01</td>
<td>0.001</td>
<td>1600.88</td>
<td>290.43</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>0.01</td>
<td>0.001</td>
<td>1570.69</td>
<td>256.24</td>
<td></td>
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<tr>
<td>$\Phi(s)p(.)$</td>
<td>Winter-Spring</td>
<td>1</td>
<td>2.1E-08</td>
<td>0.01</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring-Fall</td>
<td>1</td>
<td>5.4E-08</td>
<td>0.01</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fall-Winter</td>
<td>0.43</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Phi(s)p(s)$</td>
<td>Winter-Spring</td>
<td>0.76</td>
<td>0.18</td>
<td>0.01</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spring-Fall</td>
<td>1</td>
<td>2.3E-07</td>
<td>0.01</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fall-Winter</td>
<td>0.63</td>
<td>0.15</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
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</table>
Table 3.5. Dunn’s Test results for comparison of TL by habitat type. Mean TL in each habitat type were significantly different except for Bay versus Open Water.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Z (mm)</th>
<th>P-unadjusted</th>
<th>P-adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ditch-Creek</td>
<td>-281.97</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Ditch-River</td>
<td>-751.81</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Creek-River</td>
<td>-731.24</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Ditch-Bay</td>
<td>-1061</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Creek-Bay</td>
<td>-1158.14</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>River-Bay</td>
<td>-392.58</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Ditch-Open Water</td>
<td>-1044.32</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Creek-Open Water</td>
<td>-1100.40</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>River-Open Water</td>
<td>-406.37</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Bay-Open Water</td>
<td>-38.61</td>
<td>0.128</td>
<td>0.128</td>
</tr>
</tbody>
</table>
Table 3.6. Specimen counts and average size ± SE for each habitat type

<table>
<thead>
<tr>
<th>Habitat Type</th>
<th>n</th>
<th>Average TL (mm)</th>
<th>±SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ditch</td>
<td>561</td>
<td>263.6</td>
<td>4.66</td>
</tr>
<tr>
<td>Creek</td>
<td>2846</td>
<td>406.2</td>
<td>3.67</td>
</tr>
<tr>
<td>River</td>
<td>1082</td>
<td>729.7</td>
<td>6.23</td>
</tr>
<tr>
<td>Bay</td>
<td>938</td>
<td>1008.3</td>
<td>6.10</td>
</tr>
<tr>
<td>Open Water</td>
<td>736</td>
<td>1042.0</td>
<td>6.55</td>
</tr>
</tbody>
</table>
Table 3.7. Von Bertalanffy Growth parameters from recapture data and comparison to otolith-derived parameters. The linearly decreasing variance method (Varsig1) of estimating von Bertalanffy parameters produced the curve most similar to the control curve.

<table>
<thead>
<tr>
<th>Otoliths (control)</th>
<th>Least Squares</th>
<th>Weighted Least Squares</th>
<th>Negative Log Likelihood</th>
<th>Linearly decreasing Variance (Varsig1)</th>
<th>Exponentially decreasing Variance (Varsig2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$TL_\infty$</td>
<td>1317.36</td>
<td>1381.081</td>
<td>2213.725</td>
<td>1381.061</td>
<td>1407.47</td>
</tr>
<tr>
<td>$K$</td>
<td>0.267</td>
<td>0.184</td>
<td>0.1397</td>
<td>0.184</td>
<td>0.181</td>
</tr>
<tr>
<td>Sigma</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>83.35</td>
<td>NA</td>
</tr>
<tr>
<td>Nu</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>77.44</td>
<td>54.23</td>
</tr>
<tr>
<td>Tau</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>0.02</td>
<td>83.35</td>
</tr>
<tr>
<td>SS</td>
<td>NA</td>
<td>527396</td>
<td>3751178</td>
<td>527393</td>
<td>461378</td>
</tr>
</tbody>
</table>
Figure 3.1. Within-Year Recapture Rates
Figure 3.2. Inter-Annual Recapture Rates

![Bar chart showing inter-annual recapture rates from 2005 to 2013. The y-axis represents recapture rate percentage, and the x-axis represents years. The chart indicates a general trend of increased recapture rates from 2005 to 2011, followed by a decline in 2013.]
Figure 3.3. Cumulative Recapture Rates
Figure 3.4. Mean TL (± SE) of juvenile Atlantic Tarpon increased with increasing habitat size. Significant differences in size existed between all habitat comparisons except Bay versus Open Water.
Figure 3.5. Number of Atlantic Tarpon sampled in each region. The East Central region is inflated due to disproportionate sampling as well as a large amount of juvenile habitat and large populations of juvenile Atlantic Tarpon. One angler accounted for ~1750 specimens in the EC region. Even when these are removed the EC had the highest number of specimens submitted.
Figure 3.6. Number of Atlantic Tarpon sampled in each county. Brevard County is inflated due to disproportionate sampling as well as a large amount of juvenile habitat and large populations of juvenile Atlantic Tarpon. There was a paucity of specimens submitted from Northern counties likely due to thermal tolerances of the species.
Figure 3.7. Distance between capture locations slightly increased as time between captures increased. $R^2 = 0.07$, $p = 0.002$
Figure 3.8. Von Bertalanffy Growth Curves from six different estimation methods. The linearly decreasing variance method (Var1) produced the estimation most similar to the control (Oto) curve, but with a smaller K value. SS and NLL are obscured by Var2 due to extremely similar parameter estimations.
Figure 3.9. Coastal Systems with high juvenile Atlantic Tarpon abundance and ideal habitat complexity. A) Indian River Lagoon B) Charlotte Harbor C) Everglades D) Florida Keys
CHAPTER FOUR
GENERAL CONCLUSIONS

The research presented here helps to better understand aspects of the life history and ecology of Atlantic Tarpon that had previously been understudied or undescribed. The importance of the backcountry habitat to the life history was revealed, as well as unanticipated patterns of adult trophic dynamics. In addition, this research described key dynamics of the understudied juvenile stage. This research helps to better understand Atlantic Tarpon ecology across the entire life history and will hopefully aid in better management of the species in the future.

In Chapter Two, I used eye lens stable isotope chronologies to describe lifelong habitat use and trophic dynamics of the Atlantic Tarpon. The isotope profiles showed that Atlantic Tarpon sampled in Florida rely on the backcountry for a significant portion of the early life history. Atlantic Tarpon then underwent an ontogenetic shift to coastal habitats at approximately 10 years of age. After joining the adult population in coastal waters Atlantic Tarpon appeared to show individual specialization in the type of forage that they rely upon (PP, BMA, and Mixed). In addition, the within-individual consistency of adult stage stable isotope values during the coastal phase suggested that Atlantic Tarpon show fidelity to foraging grounds used for somatic growth.

In Chapter Three, I used a multi-year genetic tagging database to better understand juvenile habitat use and ontogenetic migrations, as well as to characterize demographic aspects of this life stage. I found that juvenile Tarpon use habitats of increasing size as they grow but also show fidelity to the same coastal systems throughout the juvenile life stage. In addition, juvenile Atlantic Tarpon appear to be thermally limited to the southern regions of Florida. I also
found that the habitats that juvenile use afford them a higher survival rate, ~80%, than would be expected for other similar sized fish species. Last, I identified four coastal systems that appear to have the ideal combination of habitats for juvenile Atlantic Tarpon and may warrant further investigation as nursery habitat in the future.

In these two studies I used natural tags to fill gaps in our knowledge of the Atlantic Tarpon life history and ecology. The first study produced the highest temporal resolution profile of habitat use and trophic dynamics of the Atlantic Tarpon life history, while the second chapter used genetic tagging to better understand the poorly studied juvenile life stage. Both studies combine to fill gaps in our knowledge about this ecologically and economically important species while highlighting the importance of the backcountry as juvenile habitat. Success during the juvenile stage has been shown to be critical to adult populations and this research reinforces the importance of backcountry habitats to the Atlantic Tarpon life history. Future research can use these findings to better understand the juvenile stage and identify critical and nursery habitats for protection and conservation.
BIBLIOGRAPHY


Archipelago, Brazil: the potential of marine protected areas for conservation of a nursery ground. Marine Biology 149(2):189-199


APPENDIX A

INDIVIDUAL $\delta^{13}\text{C}$ AND $\delta^{15}\text{N}$ STABLE ISOTOPE PROFILES OF 16 ATLANTIC TARPON

The $\delta^{13}\text{C}$ profiles were separated into four regions with each indicating different basal resource use; I. Backcountry-based, II. Phytoplankton-based, III. Mixed-use, IV. Benthic Microalgae-based. Individuals were categorized by basal-resource use during the coastal phase.

a. BMA-Based
b. Mixed-use
c. PP-based

d. No coastal phase
Figure A1. Individual $\delta^{13}$C and $\delta^{15}$N stable isotope profiles. The $\delta^{13}$C profiles were separated into four regions with each indicating different basal resource use; I. Backcountry-based, II. Phytoplankton-based, III. Mixed-use, IV. Benthic Microalgae-based. Individuals were categorized by basal-resource use during the coastal phase.