

AGE, GROWTH, AND MIGRATION PATTERNS OF DOLPHINFISH  
(*CORYPHAENA HIPPURUS*) IN THE NORTHWESTERN GULF OF MEXICO

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## ABSTRACT

The common Dolphinfish (*Coryphaena hippurus*) is a well-known pelagic food and gamefish with cosmopolitan distribution in tropical and subtropical waters. Dolphinfish are an economically important species as they support artisanal, recreational, and commercial fisheries throughout the world. Dolphinfish occur in U.S. waters in the Pacific off the coast of California, in the Atlantic from North Carolina to the Florida east coast and in the Gulf of Mexico from the Florida west coast to Texas. In the Western North Atlantic, Dolphinfish support an impressive commercial and recreational fishery. The recreational sector has grown more than 20% in the past 20 years creating the fastest growing fisheries sector in the Gulf of Mexico. Highly migratory species present unique management challenges, and scientific information is much needed. Key information gaps for Dolphinfish in the Gulf of Mexico include our lack of knowledge of their life history and migration patterns. Thus, the primary goal of this study was to examine biological parameters of Dolphinfish in the northwestern Gulf of Mexico to generate an understanding of key parameters such as age and growth, and migration. A major component to achieving this goal was participation of citizen scientists through large-scale tagging efforts and collection of fish for analyses. We created a cooperative program by building an interactive webpage and personally soliciting the participation of recreational anglers, local fishermen and fish processors to help provide fish samples, as well as tag and release Dolphinfish. Scientists and citizen scientists tagged 261 Dolphinfish that yielded an expected low rate of return. Sagittal otolith increments were used to estimate daily age, and otolith weights and diameter measurements were used to establish a relationship between otolith formation and somatic growth for Dolphinfish in

the northwestern Gulf of Mexico. The estimated growth rate for Dolphinfish off the coast of Texas was 3.45 mm fork length day<sup>-1</sup>. Length-weight relationships, growth rates, and age and length at 50% maturity were estimated for Gulf of Mexico Dolphinfish. These data show that the rapid growth rate and early maturity of Dolphinfish indicate their ability to withstand a reasonable amount of exploitation. The findings of this study serve as a foundation for fisheries managers, researchers, interest groups, recreational anglers, and the general public to build a management strategy that serves the dual purpose of ensuring both the recreational enjoyment and sustainability of this important fishery.

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## INTRODUCTION

The common Dolphinfish (*Coryphaena hippurus*), also known as dolphin, dorado, or mahi-mahi is a well known pelagic food and game-fish with cosmopolitan distribution in tropical and subtropical waters ( $>20^{\circ}\text{C}$ ) (Beardsley 1967; Oxenford and Hunte 1986). The pompano Dolphinfish, *Coryphaena equiselis*, is similar in appearance but considerably smaller at maturity. Difficult to discern as juveniles both species commonly intermingle and together make up the Dolphinfish fishery (Gibbs and Collette 1959). Dolphinfish are an economically important species internationally as they support artisanal, recreational, and commercial fisheries in many locations including the US, Caribbean, Brazil, Panama, Columbia, Mexico, Japan, Taiwan, and throughout the Mediterranean (Bannister 1976; Costa et al. 2003; Deudero et al. 1999; Ghailen et al. 2010; Holland et al. 1992; Lasso and Zapata 1999; Mahon and Oxenford 1999; Schwenke and Buckel 2008; Wu et al. 2001). Harvesting strategies vary with location but include purse seining, deployment of Fish Attracting Devices (FADs), hook and line gear and surface trolling (Beardsley 1967; Deudero et al. 1999; Gibbs and Collette 1959; Thompson 1999).

Dolphinfish occur in U.S. waters in the Pacific off the coast of California, in the Atlantic from North Carolina to the Florida east coast and in the Gulf of Mexico from the Florida west coast to Texas (Norton 1999; Thompson 1999). In US waters, Dolphinfish support a commercial and recreational fishery in the Western North Atlantic dominated by a recreational sector that has seen an increase in landings and average weight of fish amidst a highly variable Catch Per Unit Effort (CPUE) (Thompson 1999). A 1987-1988

survey of Gulf of Mexico charter boats reported Dolphinfish to be among the species targeted by fishermen(Holland *et al.* 1992). Total Dolphinfish landings for the Gulf of Mexico from 1984-1996 ranged from 608.8 mt in 1984 to 3967.4 mt in 1995 (Thompson 1999). The average annual number of Dolphinfish caught per directed trip for the Gulf of Mexico recreational fishery from 1981-2013 fluctuated in range from as little as 1.04 fish per trip in 1984 to as high as 3.69 in 1997(NOAA 2014). The large annual catch variability suggest that Dolphinfish may be an annual crop making it difficult to evaluate their sustainability in the Gulf of Mexico (Thompson 1999). The marine recreational sector has grown more than 20% in the past 20 years and is the fastest growing fisheries sector in the Gulf of Mexico accounting for 64% of the total marine landings in 2002 (Coleman et al. 2004). If present trends continue, finding more ways to incorporate the fast growing recreational sector into future scientific studies will become increasingly important to ensure a sustainable fishery.

Highly migratory species present unique management challenges that can only be overcome through internationally cooperative regional management (Mahon and Oxenford 1999). Currently there are no federal regulations for Dolphinfish in the US and only three states off the southeastern coast (Florida, Georgia, and North Carolina) have regulations for state waters (Thompson 1999). The current FMP for Dolphinfish only covers the Atlantic and does not directly involve the Gulf of Mexico. (South Atlantic Fishery Management Council (U.S.) *et al.* 2003). The omission of the Gulf of Mexico in the FMP is in part due to the lack of scientific data on Dolphinfish in the Gulf.

Dolphinfish occupy more than 30 % of the ocean's surface and seasonally occupy an additional 15 % (Norton 1999). As the subtropical regions of the world ocean warm,

Dolphinfish movement and reproduction are shifting poleward potentially expanding total Dolphinfish habitat to more than 40% of the world ocean's surface layers if warming trends continue (Norton 1999). Despite basic knowledge of this distribution, research is needed to develop better abundance estimates for Dolphinfish in the Gulf of Mexico. Uncertainty remains about population structure for most marine species due to complex dispersal patterns (Thresher 1999). A technique often used by fisheries managers to better understand movement patterns is passive tagging. These programs can provide important biological information such as movement patterns, stock contribution, growth, and survival (Hilborn et al. 1990). Hallprint PDAT plastic barb dorsal dart tags are recommended by the manufacturer for Dolphinfish and successfully used by other Dolphinfish tagging programs (Hammond 2006). Slight genetic differences, and life history differences between Dolphinfish from Miami and Barbados, combined with the seasonality of catch data in the western central Atlantic suggested the possibility of two Dolphinfish stocks in the western central Atlantic (Oxenford and Hunte 1986). However, the genetic differences and life history traits could have been due to regional climate differences and the prevailing north and south, two-stock hypothesis for Dolphinfish in the western central Atlantic is based on the seasonality of catch data (Oxenford and Hunte 1986). The existence of additional stocks in the Gulf of Mexico, and the central/western Caribbean have not been investigated and are considered likely (Norton 1999; Oxenford and Hunte 1986). Genetic analysis on microsatellite loci in Dolphinfish collected from 13 sites in the Gulf of California detected significant temporal and spatial genetic heterogeneity, but no distinct populations suggesting that Dolphinfish

form a single panmictic population with high genetic variation and gene flow (Tripp-Valdez *et al.* 2010b).

Short-lived and fast growing, members of this cosmopolitan species rarely live past the age of three years and maximum life span is estimated at 4 years for Florida Dolphinfish (Beardsley 1967). Dolphinfish in the Caribbean are estimated to live ~12-18 months in the southern Caribbean and a maximum of 2-3 years in the northern Caribbean (Mahon and Oxenford 1999). Growth rates of Dolphinfish can be as high as 4 mm day<sup>-1</sup> but vary considerably (Oxenford and Hunte 1983) depending on location and season (Oxenford 1999). Based on captive fish, water temperature is thought to affect growth rates of dolphin fish and age-length relations of wild *C. hippurus* should be examined to further describe variations in size at age (Uchiyama *et al.* 1986). By examining the correlation between number of sagittal rings and fish standard lengths, Oxenford and Hunt (1983) suggest that daily rings occur in the otoliths of all sizes of Dolphinfish (174-1100 mm) and that counts of otolith rings provide an accurate method for estimating age of Dolphinfish. Age and growth rates of larval and juvenile Dolphinfish have been validated from fish of known age reared up to 191 days (Uchiyama *et al.* 1986).

Sexual dimorphism is considered a valid method for sex determination in adults and Dolphinfish have been shown to be sexually dimorphic at ~40-50 cm fork length (Beardsley 1967; Massuti and Morales-Nin 1997). According to available age/growth charts male and female Dolphinfish are discernible by the time they are 4-5 months old by examining the slope of their forehead (Beardsley 1967). Males have a blunt or square shaped head while the heads of females and sexually immature dolphin are rounder in appearance. Dolphinfish exhibit sexually dimorphic growth and curves generated for

female Dolphinfish in the western Mediterranean exhibit negative allometric growth while male growth was isometric (Massuti *et al.* 1999). Male Dolphinfish in North Carolina waters were heavier per unit length than female Dolphinfish (Rose and Hassler 1968). Based on the average weights of stomach contents, male Dolphinfish forage at a more active rate than female Dolphinfish in North Carolina and the Mediterranean (Morales-Nin *et al.* 1999; Rose and Hassler 1968). Maturity levels for Dolphinfish from the Florida Current were categorized using 5 stages for females and 2 stages for males (Beardsley 1967). Dolphinfish in the Western Atlantic show a tendency to reach maturity in 5-7 months (Oxenford 1999). Female Dolphinfish in the Western Central Atlantic have a batch fecundity range from 58,000 to 1.5 million eggs and can spawn continuously (Oxenford 1999). The year-round presence of Dolphinfish larvae in the Gulf of Mexico (GOM) suggest that Dolphinfish spawn all year long in the Gulf possibly peaking in the fall and spring (Ditty *et al.* 1994). Dolphinfish are “high performance” with regard to their rates of somatic and gonadal growth, rates of digestion, and rates of recovery from exhaustive exercise (Brill 1996). Dolphinfish are an important part of the pelagic food web and ecosystem structure in the Pacific Ocean and their consumption rate estimates averaged 5.6% of body weight per day (Olson and Galvan-Magana 2002). Stomach contents of Dolphinfish specimens from the Mediterranean included flying fish (Exocoetidae sp.), common mackerel (Scombridae sp.), pilot fish (Carangidae sp.), Dolphinfish (Coryphaenidae sp.) as well as unidentified species of Medusae and Crustacea (Bannister 1976). With a feeding strategy that is more opportunistic rather than selective, stomach contents of Dolphinfish vary greatly with location (Oxenford

1999). Dolphinfish are cannibalistic with the tendency towards cannibalism increasing with size (Rudershausen *et al.* 2010).

*Sargassum*, an essential fish habitat (EFH) in the pelagic realm, is a ubiquitous brown alga present in the surface waters of the GOM that provides food and shelter for early life stages of several pelagic species such as billfishes, tunas, swordfishes and Dolphinfish (Wells and Rooker 2009). Stable isotope ratios of Dolphinfish, as well as several other juveniles pelagic fishes, indicate that *Sargassum* serves as a critical source of organic matter during larval stages and that survival may be linked to the distribution and abundance of *Sargassum* in the GOM (Wells and Rooker 2009). *Sargassum* sp. has been found in stomachs of Dolphinfish suggesting a strong relationship between Dolphinfish and the mobile habitat with which it is so closely linked (Gibbs and Collette 1959). Dolphinfish stomach contents collected over a ten year time span in North Carolina supported other findings in that the consumption *Sargassum* dependent species occurred across the full size range of Dolphinfish (Rudershausen *et al.* 2010). Dolphinfish stomach contents from the Gulf of California indicate an overlap between Dolphinfish diet and season implicating that seasonality has an effect on prey availability (Tripp-Valdez *et al.* 2010a). For these reasons, Dolphinfish are well-known to have a high affinity for this floating algae.

Dolphinfish have been recorded in literature as occurring off the Texas coast. Pew (1957) reported juvenile Dolphinfish in the bay system near Rockport, TX. Baughman (1941) reported a large number of Dolphinfish off the coast of Port Aransas, TX. To date, no previous works have been dedicated solely to estimating biological parameters of Dolphinfish of the northwestern Gulf of Mexico. Given the large gaps in

our knowledge of the migration patterns, life history and general ecology of Dolphinfish in the Gulf of Mexico, and the fact that this data gap hinders management of a stock that migrates across numerous foreign and domestic boundaries, the major goals of this proposed study are to: 1) gather information about the life history and ecology of Dolphinfish in the Gulf of Mexico; and 2) identify the major seasonal migration routes of Dolphinfish along the coast of Texas. Unlocking the life history components and driving factors behind these large scale migrations will further our understanding of Dolphinfish ecology and provide valuable information for fishery managers tasked with the challenge of properly managing this the Dolphinfish fishery in the Gulf of Mexico.

**OBJECTIVES:**

- 1) Determine age and growth rates of Dolphinfish in the northwestern Gulf of Mexico.
- 2) Determine the age at maturity and seasonal reproductive status of Dolphinfish in the Northwestern Gulf of Mexico.
- 3) Identify the major seasonal migration routes of Dolphinfish using passive tagging.

**H<sub>0</sub>:** Dolphinfish will not exhibit a cumulative migration pattern in the Gulf of Mexico.

**H<sub>A</sub>:** Dolphinfish will exhibit a cumulative pattern of migration in the Gulf of Mexico.

## METHODS

### *Study site*

The study site, located in the northwestern Gulf of Mexico, is defined as a 3600 km<sup>2</sup> rectangle where the four corners of this rectangle would be from approximately 27° N, 96° W; 25° N, 96° W; 25° N, 92° W; and 27° N, 92° W (Figure 1). This area was targeted because of well-known high catch rates from Dolphinfish that are common in this area starting in the spring and continuing throughout the summer and fall.

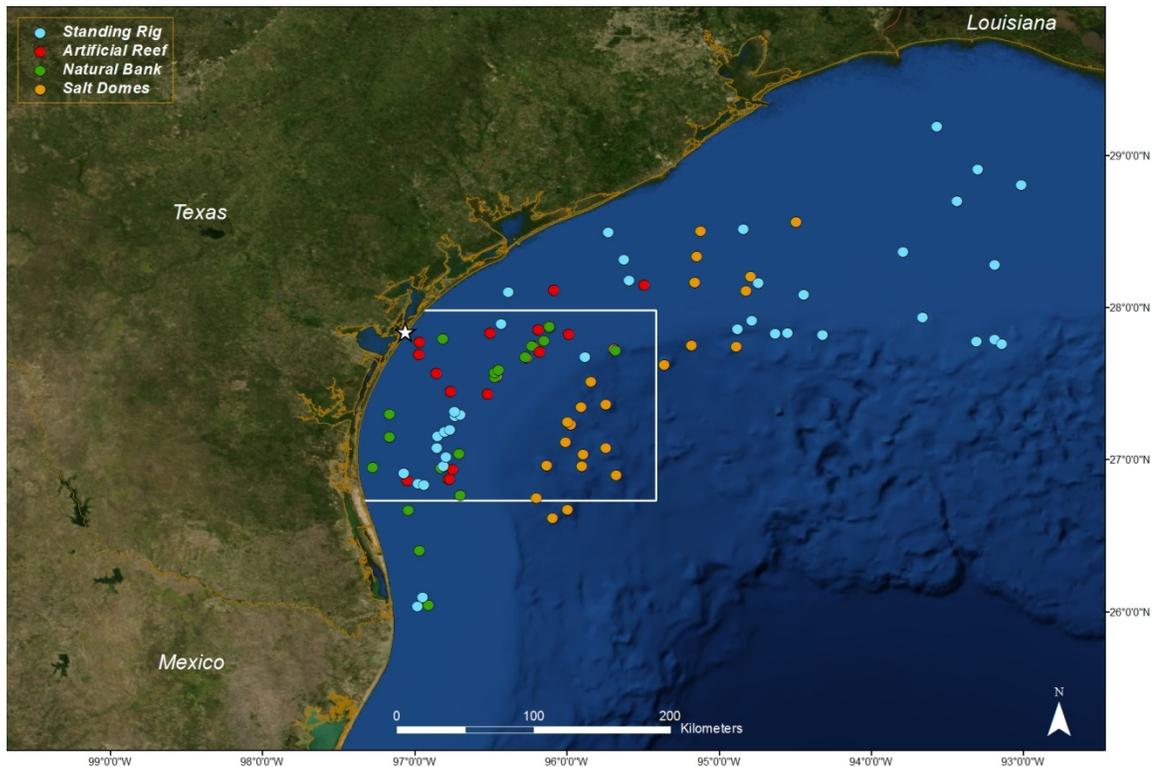


Figure 1. Study site located in the Gulf of Mexico where Dolphinfish were collected from October of 2010 through December of 2011. The star indicates the location of Port Aransas, TX.

### *Collection*

Whole Dolphinfish and carcasses were collected as part of a cooperative program developed for this study that involved recreational anglers, local fishermen, and fish processors from October of 2010 through December of 2011, with the majority collected in the summer of 2011. Individuals were informed about the purpose and intent of the Dolphinfish study and their cooperation was enlisted in the collection of Dolphinfish to increase sample size. Most carcasses used in this study were collected and donated by local fish processors, head boats, charter boats, and private individuals. All Dolphinfish collected were kept on ice and frozen within 1 day of capture for later processing.

### *Initial processing*

Initial processing of individuals began in January of 2011 and continued through December of 2011. Whole Dolphinfish and carcasses were thawed, examined for species identification and weighed to the nearest .01 kg. Total length, fork length and standard length was recorded to the nearest 0.1 cm. Gonads were removed and weighed to nearest .001 kg. Gonads were examined macroscopically for sex determination and reproductive condition of individual gonads was assessed using Beardsley's (1967) method to categorize maturity level of Dolphinfish from the Gulf of Mexico using 5 stages for females (I-immature, II-early maturing, III-late-maturing, IV-ripe, V-spent); and 2 for males (I-immature, II-mature). Intact stomachs were removed and placed in a perforated Ziploc bag and fixed in 10% formalin for at least 24 hours then transferred to 70% EtOH for storage.

### *Otolith extraction*

Like many pelagic fish, Dolphinfish are visual predators and have small otoliths relative to their body size. Dolphinfish otoliths are typically less than 2 mm in total

length. Due to their small size, a repeatable and reliable microscopic otolith extraction method had to be developed. The Dolphinfish cranial cavity is relatively small in comparison to the amount of bone and cartilage in the head. The first step in developing a successful field extraction method was to identify the precise location of the saccules in the Dolphinfish cranium. After cutting away excess bone with a hacksaw, the excess cranium was shaved away with a scalpel and examined under a dissecting microscope until the precise location of the saccules was discovered. After accessing the saccules in the Dolphinfish cranium using a series of cuts with a hacksaw, the saccules containing the otoliths were removed from the cranium section with tweezers under a microscope. The saccules were placed in individually labeled centrifuge tubes in 70% EtOH and taken to the lab for storage and further extraction from the saccules (Secor et al. 1990).

#### *Otolith preparation and morphology*

Once the field extraction process was completed for all specimens, only the left otoliths were removed from their saccules (Secor et al. 1990). Under a dissecting microscope, the centrifuge tubes containing the EtOH solution along with the saccules and otoliths were each poured into an empty petri dish. Otoliths were removed from the saccules and transferred into a labeled centrifuge tube containing a 10% bleach solution for cleaning (Secor et al. 1990). After one hour, the otoliths were transferred via 5 ml dropper into a dish containing DI water and rinsed. The otoliths were then rinsed in 90% EtOH and placed on a labeled microscopic slide to dry. After 24 hours the sagittal otoliths were weighed to the nearest 0.001 milligram. Otoliths were then photographed under 10X magnification, for digital measurements of otolith morphology (Olympus QColor-3 camera and Qcapture program) (**Figure 2**). From these images, the rostrum

diameter, anti-rostrum diameter and a rostrum radial measurement of the sagittal otoliths were recorded to the nearest 0.001 millimeter (Oxenford and Hunte 1983).

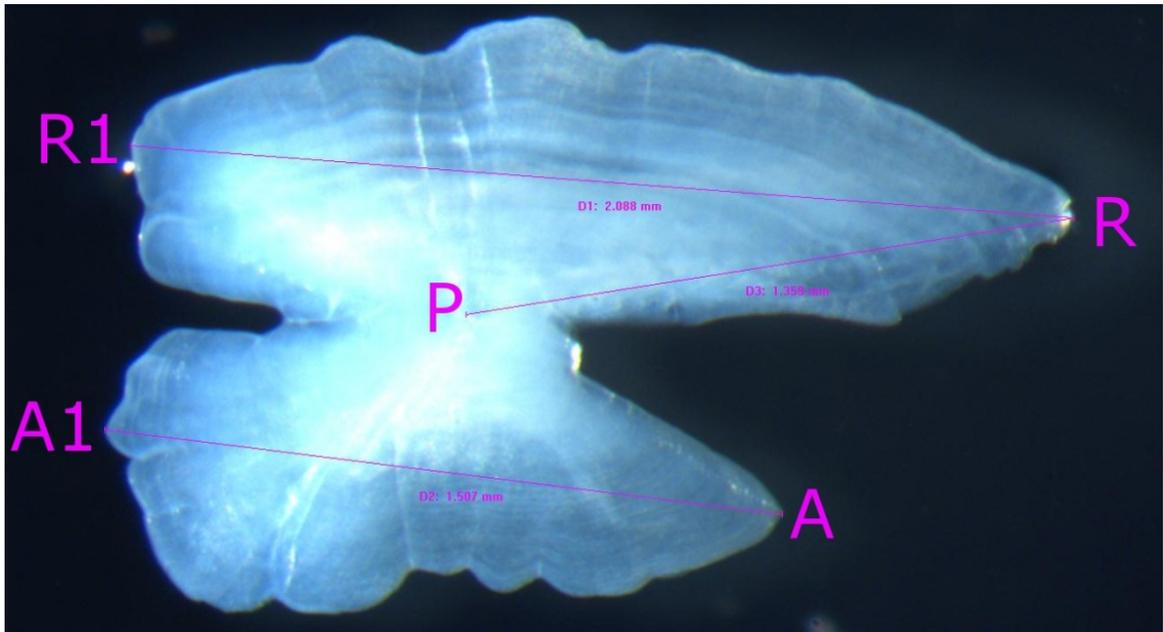


Figure 2. Left saggital otolith and associated measurements of a male Dolphinfish (54.2 cm FL) collected from the northwestern Gulf of Mexico.

### *Otolith age estimation*

Boehlert (1985) was among the first to use multiple regression models to estimate age of fish via measurable otolith parameters. Secor (1989) used pond reared striped bass to attribute differences in individual otolith scaling patterns to varying rates of somatic growth. Based on previous works, counting sagittal otolith increments is considered a viable method for estimation of age in Dolphinfish (Bentivoglio 1989; Massuti et al. 1999; Oxenford and Hunte 1983; Schwenke and Buckel 2008). As shown by regular incremental formation of the otolith, it has been determined that no adjustment is required to the incremental counts of wild fish sagittae to estimate age up to 191 days (Uchiyama et al. 1986). After recording the dry weight, the left sagittal otoliths were covered with a drop of immersion oil for reading and photography (Oxenford and Hunte 1983). An Olympus CX41 compound microscope under 40X magnification, an Olympus QColor-3 camera and the Qcapture program were used to capture images at various focal points. Due to the concave nature of the Dolphinfish sagittal otoliths, the initial photograph was taken with the primordium or center of the otolith in focus. Successive photographs were taken as the fine focus was adjusted to clearly show the sagittal rings outward from the center to the dorsal or ventral edge of the otolith for ease of reading (Schwenke and Buckel 2008). Depending on otolith shape, clarity and the degree of convexity as few as four and as many as fourteen photographs were necessary to digitally capture sagittal rings. As long as the slide containing the otolith is not moved during this process it is possible to overlay the images and perform ring counts using an image program (GIMP 2.6.2). Some otoliths were too large to capture the entire otolith in one image and the otolith had to be shifted on the stage. In this case, identifying features of the otoliths were used to establish a frame of reference for counting. From these images, initial ring counts of all

the otoliths were conducted by the author. Otoliths that were not clear enough to accurately count the rings were excluded. After at least two months, the otoliths were randomized and the ring counts were performed a second time. To minimize bias the data recording the initial ring counts were not reviewed during this period. Otoliths with more than a 10% discrepancy between readings were excluded (Schwenke and Buckel 2008). The average of the two readings with less than 10% discrepancy was taken if the readings were not the same.

#### *Migration patterns and passive tagging*

Recreational anglers were recruited to participate in passive tagging projects as a means to generate migration data on Dolphinfish (Merten et al. 2014b). In recruiting the general public for participation in a scientific study the initial step was to disseminate information about the study in a presentable and attractive format. Equally important was attracting a large number of participants. Capitalizing on the competitive nature of recreational anglers, The Center for Sportfish Science and Conservation at Harte Research Institute hosted a Dolphinfish tagging contest. As incentive, prizes and t-shirts were awarded to boats and participants and to those who successfully measured and tagged the most Dolphinfish. As an addition to the outreach effort, Dr. Stunz, members of the HRI research team and I had an opportunity to promote the program in a television episode of a program called “Majesty Outdoors”. Since participation in this study was open to the public, I wanted to make information about the study, the results and participants as accessible and unambiguous as possible while also providing a platform to launch the tagging contest. I was able to secure the domain: [www.tagpelagic.org](http://www.tagpelagic.org). Using this website as a link on the main Fisheries and Ocean Health page I was able to create a

webpage that would inform potential recruits about my study as well as provide them with information about this study and Dolphinfish in general (Figure 3). As part of the study the recruited recreational anglers were asked to measure, tag and release Dolphinfish they encountered at various locations in the northwest Gulf of Mexico. All participants received promotional packets containing Hallprint PDAT tags, a tagging device, data collection/information cards (Figure 4) and educational material to recreational anglers at various tournaments and sportfishing events (Hammond 2006). Educational material included in the handout packet indicated to anglers optimal dorsal tag location for proper embedment in Dolphinfish dorsal pterygiophores as recommended by the manufacturer (Hall 2010). Educational material also briefed project participants on the best method of measure as well as general information concerning the role of science in the campaign of conservation and the importance of accurately filling out the information card. Participants were asked to provide the following information: species (common or pompano), specimen total length (inches), specimen sex, general location, precise location (latitude and longitude), water temperature, water color, estimated direction of predominant current, presence, quantity and form of sargassum. The decision to request specimen total length in inches was based on the familiarity of the general public with the English system. The majority of the participating anglers and boats fished out of Port Aransas, TX. Tag cards were collected directly, from various locations in Port Aransas business and wharfs, and several participants used the website to report their tagged dolphin information. This information was subsequently sent to me via email in electronic format by the website.

**TAGPELAGIC.ORG**  
THE HARTE RESEARCH INSTITUTE DOLPHINFISH TAGGING INITIATIVE

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ABOUT DOLPHINFISH  
HOW TO TAG  
LATEST DATA  
PICTURES AND VIDEO  
NEWS AND UPDATES  
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**ABOUT DOLPHINFISH**

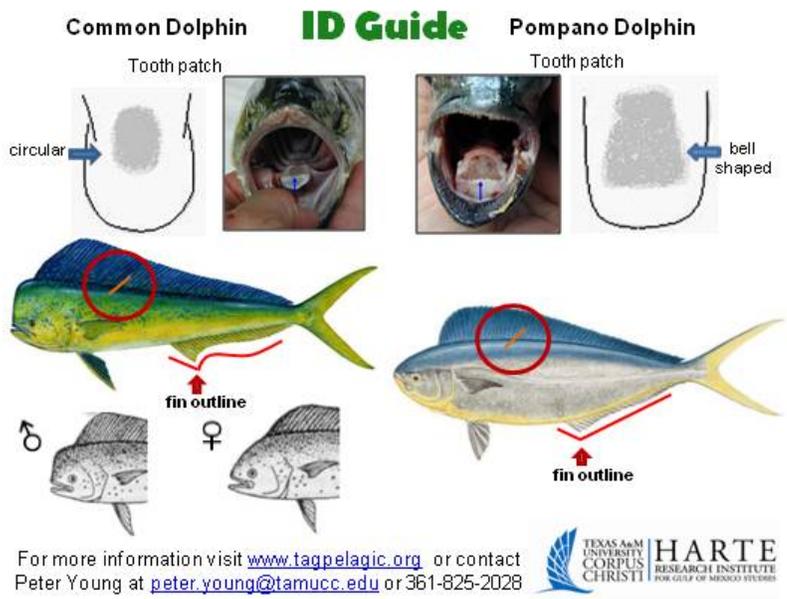
General    Distribution    Stock Structure    Life History    Sexual Dimorphism  
Ecological Role    Sargassum and Stomach Content    Global Economic Roles    Domestic Economic Significance    Management



Photo courtesy of Mo Azul Sportsfishing

General: The common dolphinfish (*Coryphaena hippurus*), dolphin, dorado, mahi-mahi, or lampuki is a well known epipelagic food and game fish with cosmopolitan distribution in tropical and subtropical waters (>20°C) across the globe. Smaller at maturity, the pompano dolphinfish, *Coryphaena equiselis*, is very similar in appearance to the common dolphinfish and the two species are often encountered together and sometimes mistaken for one another. The two species can be distinguished by noting differences in body depth, dorsal and anal rays. Adult pompano dolphinfish seldom exceed 76 cm in total length or ~4 kg in weight while common dolphinfish are typically larger with TLs exceeding 152 cm and weight exceeding 36 kg. [Top](#)

Figure 3. A screenshot of the “About Dolphinfish” page featured on the website: [www.tagpelagic.org](http://www.tagpelagic.org).



Please take the time to fill in as many details as possible or enter information at: [www.tagpelagic.org](http://www.tagpelagic.org)  
 "We would love to see your photos or videos, so don't forget to upload them at the website above"

TAG NUMBER \_\_\_\_\_ DATE \_\_\_\_\_  
 BOAT \_\_\_\_\_ TOT. LENGTH (in.) \_\_\_\_\_

ANGLER'S NAME \_\_\_\_\_ SPECIES  COMMON DOLPHIN  POMPAÑO DOLPHIN  UNKNOWN

PHONE NUMBER \_\_\_\_\_ SEX  MALE  FEMALE  UNKNOWN

EMAIL \_\_\_\_\_

LAT/LONG \_\_\_\_\_ SARGASSUM PRESENT  YES  NO  UNKNOWN

LOCATION \_\_\_\_\_ DENSITY  SOLID  MODERATE  DISPERSED

WATER TEMP (F) \_\_\_\_\_ WATER COLOR \_\_\_\_\_ FORM  LARGE RAFT  SMALL PATCH  GRASS LINE

DIRECTION OF CURRENT \_\_\_\_\_

TEXAS A&M UNIVERSITY CORPUS CHRISTI Thank you for participating in our dolphinfish tagging initiative! HARTE RESEARCH INSTITUTE FOR GULF OF MEXICO STUDIES

Figure 4. Two sided information cards used in the packet to collect information from participants tagging Dolphinfish.

### *Data analysis*

Generalized linear models (GLM) were used to estimate age at 50% maturity and length at 50% maturity for Dolphinfish in the northwestern Gulf of Mexico. Von Bertalanffy growth parameters were estimated for Dolphinfish collected in this study. One slight variation used in many Dolphinfish studies is to use fork length instead of total length for the von Bertalanffy growth equation (Bentivoglio 1989; Oxenford and Hunte 1983; Schwenke and Buckel 2008). Fork length was used as it is a more consistent measurement as the tips of Dolphinfish tails are fragile and tend to become damaged during collection process. The basic form of the von Bertalanffy equation was used:  $L_t = L_\infty * [1 - e^{-K(t-t_0)}]$ , where  $L_t$  = fork length at time (years),  $L_\infty$  = maximum theoretical attainable fork length (cm),  $K$  = growth coefficient ( $\text{year}^{-1}$ ) and  $t_0$  = time (years) when length would theoretically be equal to zero (Von Bertalanffy 1957). The statistical program, "R" of the R-cran project, was used for all calculations, regressions, and models. Sigmaplot 11.0 was also used to generate graphs for inclusion in this document. The programs ArcMap and Google Earth were used to generate maps of tag and recapture locations as well as to measure distances traveled by recaptured fish.

## RESULTS

### *Collection summary*

A total of 357 specimens were collected for inclusion in this study. Through dimorphic observations and macroscopic examination of the gonads 205 specimens were identified as females, 134 were identified as males and the gonads were missing or sex could not be determined on 18 of the smallest specimens (Table 1). The male to female ratio of Dolphinfish collected was 1:1.5. Because Dolphinfish are highly prized as a food source, the majority of the weights obtained were of carcasses. A total of 32 whole fish weights were recorded and 290 carcass weights were observed (Table 1). Fish whose gonads and stomach contents were mutilated during the cleaning process were not weighed and a total of 290 gonad weights were recorded (Table 1). Maturity was assessed for a total of 332 fish using Beardsley's (1967) method for categorizing maturity levels in Dolphinfish (Table 1). Successful sagittal otolith extraction, cleaning, drying and weighing was completed for a total of 225 sagittal otolith weights (Table 1). Additionally 219 left sagittal rostrum diameter, 221 left sagittal antirostrum diameter, and 214 left sagittal rostrum radial measurements were recorded (Table 1). Of the 225 successfully extracted otoliths, a total of 103 or 45% of the sagittal otoliths were readable using our technique (Table 1).

Table 1. A summary of specimens collected and a tally of the observed biological parameters and otolith measurements collected for Dolphinfish in the northwestern Gulf of Mexico.

| <b>Biological Parameter Totals</b>        |     |
|---|-----|
| Total Number of Specimens                 | 357 |
| Total Males                               | 134 |
| Total Female                              | 205 |
| Total Unknown                             | 18  |
| Whole weight measurements                 | 32  |
| Carcass weight measurements               | 290 |
| Gonad weight measurements                 | 290 |
| Gonadal assessments                       | 332 |
| <b>Left Sagittal Otolith measurements</b> |     |
| Left sagittal weight                      | 225 |
| Left rostrum measurements                 | 219 |
| Left antirostrum measurements             | 221 |
| Left radial measurements                  | 214 |
| Daily ring counts                         | 103 |

*Tagging summary*

We recruited 17 boats to participate in the Dolphinfish tagging initiative with a total of 261 Dolphinfish tagged and released from May 27 to October 23 of 2011 (Figure 5). The most Dolphinfish tagged by a citizen scientist boat was 26 total Dolphinfish aboard the “Bandit” in August of 2011. Between the “Pez Vela”, the “Game On”, the “Aly Gator” and the “Mo Azul,” the HRI researchers and I tagged a total 155 Dolphinfish in July and August of 2011. The smallest fish tagged had a total length of 30.48 cm while the largest fish tagged had a total length of 109.2 cm, and the mean  $\pm$  S.E. total length of tagged Dolphinfish was  $63.91 \pm 0.88$ cm.

Of the 261 fish tagged, only two were recaptured in July of 2011. The fish were tagged within 5 km of each other on July 4, 2011 approximately 49 km at 165 degrees (SSE) of the Port Aransas jetties. On July 16, 2011 the two fish were recaptured together at the same location 53 km due East of the Port Aransas jetties. An exact location was not reported by the angler for the recapture of the two fish but rather a distance and bearing in reference to the Port Aransas jetties. According to the angler’s direction and distance, the two fish traveled roughly 62 km NE from their tagged location to their recapture location. The two Dolphinfish traveling 62 km in 12 days is equal to an average travel distance of around  $5 \text{ km day}^{-1}$ .

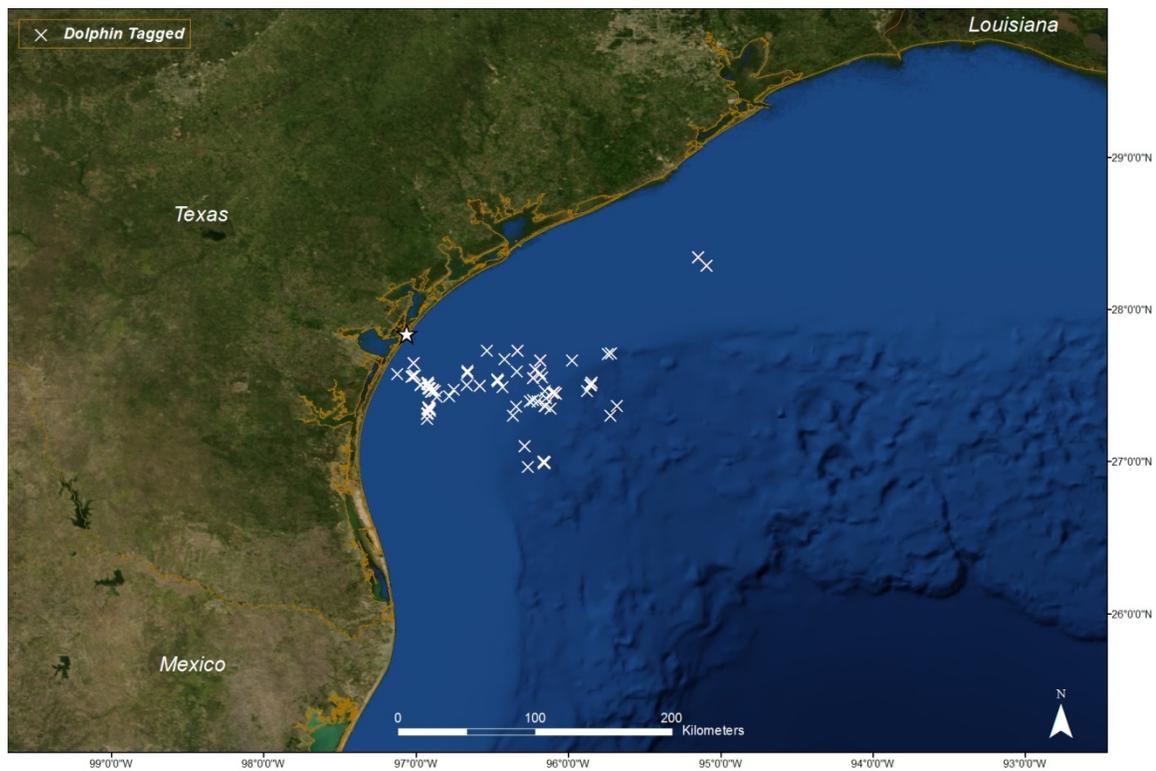


Figure 5. Map of the northwestern Gulf of Mexico showing tag and release locations for 261 Dolphinfish tagged and released from May 27 to October 23 of 2011.

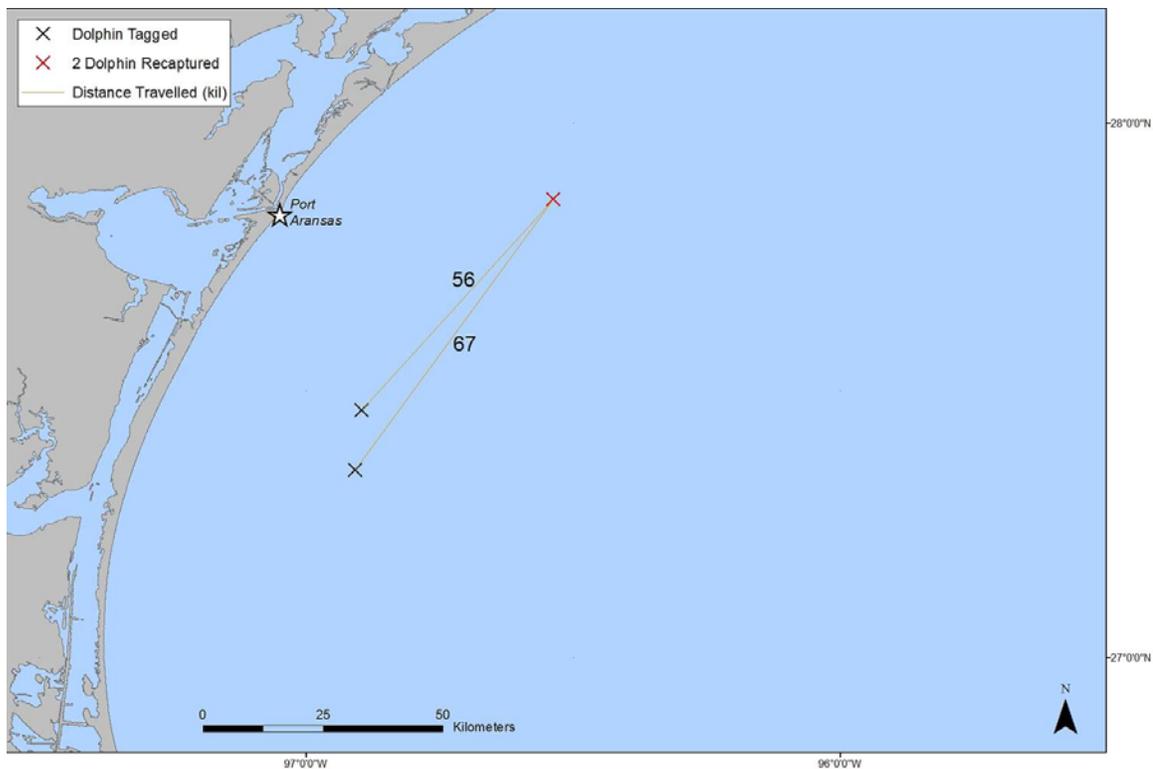


Figure 6. Map of the northwestern Gulf of Mexico showing the locations where the two recaptured Dolphinfish were first tagged on July 4, 2011 in separate locations (~5 kilometers apart). The two fish were recaptured at the same location on July 16, 2011. Fish one moved approximately 56 kilometers in 12 days while fish two moved approximately 67 kilometers in 12 days.

*Somatic parameters*

A total of 357 total lengths, 356 standard lengths and 356 fork lengths were observed of the 357 male, female and Dolphinfish of unknown sex collected from the northwestern Gulf of Mexico. For all specimens the minimum total length observed was 27.60 cm while the maximum total length observed was 148.50 cm with a mean  $\pm$  S.E. total length of  $72.22 \pm 1.29$  cm. For all specimens the minimum fork length observed was 23.30 cm while the maximum fork length observed was 121.00 cm with a mean  $\pm$  S.E. fork length of  $59.63 \pm 1.05$  cm. For all specimens the minimum standard length observed was 21.50 cm while the maximum standard length observed was 112.60 cm with a mean  $\pm$  S.E. standard length of  $56.54 \pm 0.99$  cm. For the combined sex Dolphinfish, both the fork length (cm) to standard length (cm) regression line, and the fork length (cm) to total length (cm) regression line, showed a strong correlation with a positive slope (Table 2 ; Figure 7). Of 32 whole weights recorded, the minimum whole weight observed for the combined sex Dolphinfish was 0.150 kg while the maximum whole weight observed was 17.600 kg with a mean  $\pm$  S.E. whole weight of  $3.521 \pm 0.69$  kg. The fork length (cm) to whole weight (kg) regression line for combined male, female, and unknown sex Dolphinfish showed a strong correlation with a positive slope (Table 2 ; Figure 8). For the combined sex Dolphinfish, a total of 290 carcass weights (CW) were recorded with a minimum carcass weight of 0.072 kg, a maximum carcass weight of 12.240 kg and a mean  $\pm$  S.E. carcass weight of  $1.452 \text{ kg} \pm 0.10$  kg. The fork length (cm) to carcass weight (kg) regression line for the combined male, female, and unknown sex Dolphinfish showed a strong correlation with a positive slope (Table 2; Figure 9).

For female Dolphinfish in the northwestern Gulf of Mexico, a total of 206 total lengths, 205 standard lengths and 205 fork lengths were collected. For female Dolphinfish the minimum total length observed was 42.60 cm while the maximum total length observed was 140.50 cm with a mean  $\pm$  S.E. total length of  $71.12 \pm 1.38$  cm. For female Dolphinfish the minimum fork length observed was 36.10 cm while the maximum fork length observed was 119.50 cm with a mean  $\pm$  S.E. fork length of  $58.98 \pm 1.15$  cm. For female Dolphinfish the minimum standard length observed was 34.10 cm while the maximum standard length observed was 110.50 cm with a mean  $\pm$  S.E. standard length of  $55.99 \pm 1.09$  cm. For female Dolphinfish a total of 174 carcass weights (CW) were recorded with a minimum carcass weight of 0.072 kg, a maximum carcass weight of 7.740 kg and a mean  $\pm$  S.E. carcass weight of  $1.161 \text{ kg} \pm 0.08 \text{ kg}$ . The fork length (cm) to carcass weight (kg) relationship for female Dolphinfish can be described by the equation:  $CW = 0.3527 - 0.0294*FL + 0.0007*FL^2$  (Figure 10).

For male Dolphinfish in the northwestern Gulf of Mexico, a total of 135 total lengths, standard lengths and fork lengths were collected. For male Dolphinfish the minimum total length observed was 27.60 cm while the maximum total length observed was 148.50 cm with a mean  $\pm$  S.E. total length of  $77.24 \pm 2.53$  cm. For male Dolphinfish the minimum fork length observed was 23.30 cm while the maximum fork length observed was 121.00 cm with a mean  $\pm$  S.E. fork length of  $63.29 \pm 2.03$  cm. For male Dolphinfish the minimum standard length observed was 21.50 cm while the maximum standard length observed was 112.60 cm with a mean  $\pm$  S.E. standard length of  $59.93 \pm 1.91$  cm. For male Dolphinfish a total of 117 carcass weights (CW) were recorded with a minimum carcass weight of 0.180 kg, a maximum carcass weight of 12.240 kg and a

mean  $\pm$  S.E. carcass weight of  $1.888 \pm 0.212$  kg. The fork length (cm) to carcass weight (kg) relationship for male Dolphinfish can be described by the equation:  $CW = 2.10 - 0.0959*FL + 0.0013*FL^2$  (Figure 11).

#### *Otolith parameters and somatic growth*

For combined male, female, and unknown sex Dolphinfish of the northwestern Gulf of Mexico, a total of 225 left sagittal otolith weights (SW) were recorded with a minimum sagittal weight of 0.171 mg, a maximum sagittal weight of 2.507 mg, and a mean  $\pm$  S.E. sagittal weight of  $0.574 \pm 0.022$  mg. The fork length (cm) to sagittal weight (mg) regression line for the combined male, female, and Dolphinfish of unknown sex showed a strong correlation with a positive slope (Table 2; Figure 12). For the combined Dolphinfish a total of 219 left sagittal rostrum diameter measurements (RD) were recorded with a minimum sagittal rostrum diameter of 1.503 mm, a maximum sagittal rostrum diameter of 4.006 mm, and a mean  $\pm$  S.E. sagittal rostrum diameter of  $2.061 \pm 0.025$  mm. The fork length (cm) to left sagittal rostrum diameter measurement (mm) regression line for the combined sex Dolphinfish showed a strong correlation with a positive slope (Table 2; Figure 15). For the combined sex Dolphinfish a total of 221 left sagittal antirostrum diameter measurements (AD) were recorded with a minimum sagittal antirostrum diameter of 1.037 mm, a maximum sagittal antirostrum diameter of 2.714 mm and a mean  $\pm$  S.E. sagittal antirostrum diameter of  $1.534 \pm 0.018$  mm. The fork length (cm) to left sagittal antirostrum diameter measurement (mm) regression line for the combined sex Dolphinfish showed a strong correlation with a positive slope (Table 2; Figure 18). For the combined sex Dolphinfish a total of 214 left sagittal rostrum radial measurements (RR) were recorded with a minimum sagittal rostrum radius of 0.908 mm,

a maximum sagittal rostrum radius of 2.343 mm and a mean  $\pm$  S.E sagittal rostrum radius of  $1.299 \pm 0.016$  mm. The fork length (cm) to left sagittal rostrum radial measurement (mm) regression line for the combined sex showed a strong correlation with a positive slope (Table 2; Figure 21). For the combined sex Dolphinfish a total of 103 left sagittal daily rings (DR) were counted with a minimum of 67 daily rings recorded, a maximum of 364 daily rings recorded and a mean  $\pm$  S.E daily ring count of  $139.6 \pm 5.11$ . The fork length (cm) to left sagittal daily rings regression line for the combined sex Dolphinfish showed a strong correlation with a positive slope (Table 2; Figure 24).

For female Dolphinfish of the northwestern Gulf of Mexico, a total of 135 left sagittal otolith weights (SW) were recorded with a minimum sagittal weight of 0.237 mg, a maximum sagittal weight of 1.799 mg and a mean  $\pm$  S.E sagittal weight of  $0.526 \pm 0.021$  mg. The fork length (cm) to sagittal weight (mg) relationship for female Dolphinfish can be described by the equation:  $SW = 0.3654 - 0.0064*FL + 0.0002*FL^2$  (Figure 13). For female Dolphinfish a total of 131 left sagittal rostrum diameter measurements (RD) were recorded with a minimum sagittal rostrum diameter of 1.542 mm, a maximum sagittal rostrum diameter of 3.249 mm and a mean  $\pm$  S.E sagittal rostrum diameter of  $2.000 \pm 0.025$  mm. The fork length (cm) to left sagittal rostrum diameter measurement (mm) relationship for female Dolphinfish can be described by the equation:  $RD = 1.0489 + 0.0168*FL$  (Figure 16). For female Dolphinfish a total of 133 left sagittal antirostrum diameter measurements (AD) were recorded with a minimum sagittal antirostrum diameter of 1.037 mm, a maximum sagittal antirostrum diameter of 1.037 mm and a mean  $\pm$  S.E sagittal antirostrum diameter of  $1.501 \pm 0.019$  mm. The fork length (cm) to left sagittal antirostrum diameter measurement (mm) relationship for

female Dolphinfish can be described by the equation:  $AD = .8162 + 0.0121*FL$  (Figure 19). For female Dolphinfish a total of 126 left sagittal rostrum radial measurements (RR) were recorded with a minimum sagittal rostrum radius of 0.908 mm, a maximum sagittal rostrum radius of 2.207 mm and a mean  $\pm$  S.E sagittal rostrum radius of  $1.258 \pm 0.018$  mm. The fork length (cm) to left sagittal rostrum radial measurement (mm) relationship for female Dolphinfish can be described by the equation:  $RR = .6625 + 0.0105*FL$  (Figure 22). For female Dolphinfish a total of 58 left sagittal daily rings (DR) were counted with a minimum of 81 daily rings, a maximum of 364 daily rings and a mean  $\pm$  S.E of  $141.2 \pm 6.63$  daily rings. The fork length (cm) to left sagittal daily rings relationship for female Dolphinfish can be described by the equation:  $DR = 20.37 + 2.14*FL$  (Figure 25).

For male Dolphinfish of the northwestern Gulf of Mexico, a total of 83 left sagittal otolith weights (SW) were recorded with a minimum sagittal weight of 0.210 mg, a maximum sagittal weight of 2.507 mg and a mean  $\pm$  S.E sagittal weight of  $0.674 \pm 0.047$  mg. The fork length (cm) to sagittal weight (mg) relationship for male Dolphinfish can be described by the equation:  $SW = 0.2144 - 0.0019*FL + 0.0001*FL^2$  (Figure 14). For male Dolphinfish a total of 81 left sagittal rostrum diameter measurements (RD) were recorded with a minimum sagittal rostrum diameter of 1.503 mm, a maximum sagittal rostrum diameter of 4.006 mm and a mean  $\pm$  S.E sagittal rostrum diameter of  $2.185 \pm 0.050$  mm. The fork length (cm) to left sagittal rostrum diameter measurement (mm) relationship for male Dolphinfish can be described by the equation:  $RD = 0.9991 + 0.0200*FL$  (Figure 17). For male Dolphinfish a total of 81 left sagittal antirostrum diameter measurements (AD) were recorded with a minimum sagittal antirostrum

diameter of 1.174 mm, a maximum sagittal antirostrum diameter of 2.714 mm and a mean  $\pm$  S.E sagittal antirostrum diameter of  $1.612 \pm 0.037$  mm. The fork length (cm) to left sagittal antirostrum diameter measurement (mm) relationship for male Dolphinfish can be described by the equation:  $AD = .7538 + 0.0145*FL$  (Figure 20). For male Dolphinfish a total of 81 left sagittal rostrum radial measurements (RR) were recorded with a minimum sagittal rostrum radius of 0.960 mm, a maximum sagittal rostrum radius of 2.343 mm and a mean  $\pm$  S.E sagittal rostrum radius of  $1.380 \pm 0.029$  mm. The fork length (cm) to left sagittal rostrum radial measurement (mm) relationship for male Dolphinfish can be described by the equation:  $RR = .7124 + 0.0113*FL$  (Figure 23). For male Dolphinfish a total of 40 left sagittal daily rings (DR) were counted with a minimum of 67 daily rings, a maximum of 258 daily rings and a mean  $\pm$  S.E of  $143.4 \pm 8.57$  daily rings. The fork length (cm) to left sagittal daily rings relationship for male Dolphinfish can be described by the equation:  $DR = 33.88 + 1.82*FL$  (Figure 26). The p-value for all reported regression lines are:  $p(x) < 0.0001$ .

Table 2. A summary of the regression equations for relationships between somatic, and otolith parameters, and fork length (cm) for combined male, female, and unknown sex Dolphinfish collected in the northwestern Gulf of Mexico, and their respective figure and page numbers. For more details regarding these regressions as well as the sex specific regression equations and figures, refer to the results section of this document.

| <b>Fig.</b> | <b>y</b>         | <b>x</b>    | <b>regression equation</b>                       | <b>r<sup>2</sup></b> |
|-------------|------------------|-------------|--|----------------------|
| 7           | standard length  | fork length | SL = 0.4603 + 0.9405*FL                          | 0.9971               |
| 7           | total length     | fork length | TL = -0.8918 + 1.2243*FL                         | 0.9956               |
| 8           | whole weight     | fork length | WW=1.5696 -0.0915*FL + 0.0017*FL <sup>2</sup>    | 0.9374               |
| 9           | carcass weight   | fork length | CW=1.8665 -0.0847*FL+ 0.0012*FL <sup>2</sup>     | 0.9357               |
| 12          | otolith weight   | fork length | SW = 0.3011 - 0.0052*FL + 0.0002*FL <sup>2</sup> | 0.8572               |
| 15          | rostrum dia.     | fork length | RD = .9603 + 0.0193*FL                           | 0.7729               |
| 18          | antirostrum dia. | fork length | AD = .7383 + 0.0140*FL                           | 0.7353               |
| 21          | rostrum radius   | fork length | RR = .6310 + 0.0118*FL                           | 0.7179               |
| 24          | daily rings      | fork length | DR = 26.16 + 1.986*FL                            | 0.6860               |
| 36          | fork length      | daily rings | FL = 8.91+0.245*DR                               | 0.6860               |

### *Age at maturity*

Age at 50% maturity for Dolphinfish in the northwestern Gulf of Mexico was calculated using a generalized linear model (GLM). Individual maturity was converted into a binary response where “success” (mature=1) or a “failure” (immature=0). Specimens were classified as mature or immature according to Beardsley’s (1967) method of categorization. The probability of maturity at age (x) is expressed by the equation:  $\log(p/1-p) = \alpha + \beta_1 * x$ . In this case daily otolith rings were used as age. This model was used to estimate age at 50% maturity for combined male, female and Dolphinfish of unknown sex, as well as for the individual sexes (Table 3). Fifty percent of the combined male, female and unknown sex Dolphinfish were estimated to have reached maturity by the age of 112 days (Figure 27). Fifty percent of the female Dolphinfish were estimated to have reached maturity by the age of 114 days (Figure 28). Fifty percent of the male Dolphinfish were estimated to have reached maturity by the age of 137 days (Figure 29).

### *Length at maturity*

Length at 50% maturity for Dolphinfish in the northwestern Gulf of Mexico was calculated using a generalized linear model (GLM). For the model individuals in the sample must be classified as either a “success” (mature) or a “failure” (immature). Again specimens were classified as mature or immature according to Beardsley’s (1967) method of categorization. The probability of maturity at length (x) is expressed by the equation:  $\log(p/1-p) = \alpha + \beta_1 * x$ . In this case fork length (cm) was used. This model was used to estimate length at 50% maturity for male, female and unknown sex Dolphinfish,

as well as for the individual sexes (Table 3). Fifty percent of the 332 combined male, female and unknown sex Dolphinfish were estimated to have reached maturity at a fork length of 44.88 cm (Figure 30). Fifty percent of the 200 female Dolphinfish were estimated to have reached maturity at a fork length of 41.43 cm (Figure 31). Fifty percent of the 130 male Dolphinfish were estimated to have reached maturity at a fork length of 49.87 cm (Figure 32).

Table 3. A summary of the estimated coefficients, standard errors, z-values, p-values, residual deviances (rd), degrees of freedom (df) and Akaike information criterion (AIC) for the generalized linear models (GLM) used to estimate age at 50% maturity and length at 50% maturity for Dolphinfish in the Gulf of Mexico.

| <b>Maturity~Daily</b>      |                    |                 |           |              | <b>z</b>           |           |           |            |
|----------------------------|--------------------|-----------------|-----------|--------------|--------------------|-----------|-----------|------------|
| <b>Age</b>                 | <b>coefficient</b> | <b>estimate</b> | <b>SE</b> | <b>value</b> | <b>Pr(&gt; z )</b> | <b>rd</b> | <b>df</b> | <b>AIC</b> |
| GLM all sexes<br>(n=96)    | (Intercept)        | -7.02           | 1.55      | -4.53        | 5.97E-06           | 68.0      | 94        | 72         |
|                            | daily age          | 0.06            | 0.01      | 4.57         | 4.86E-06           |           |           |            |
| GLM males<br>(n=40)        | (Intercept)        | -7.04           | 1.96      | -3.59        | 3.30E-04           | 26.7      | 38        | 31         |
|                            | daily age          | 0.05            | 0.01      | 3.57         | 3.52E-04           |           |           |            |
| GLM females<br>(n=56)      | (Intercept)        | -16.52          | 5.87      | -2.81        | 4.89E-03           | 23.1      | 54        | 27         |
|                            | daily age          | 0.16            | 0.06      | 2.81         | 4.95E-03           |           |           |            |
| <b>Maturity~Length</b>     |                    |                 |           |              | <b>z</b>           |           |           |            |
|                            | <b>coefficient</b> | <b>estimate</b> | <b>SE</b> | <b>value</b> | <b>Pr(&gt; z )</b> | <b>rd</b> | <b>df</b> | <b>AIC</b> |
| GLM all sexes<br>(n=332)   | (Intercept)        | -13.44          | 1.89      | -7.13        | 1.04E-12           | 161.9     | 330       | 165        |
|                            | fork length        | 0.30            | 0.04      | 7.55         | 4.53E-14           |           |           |            |
| GLM for males<br>(n=131)   | (Intercept)        | -16.54          | 3.54      | -4.68        | 2.92E-06           | 61.6      | 129       | 65         |
|                            | fork length        | 0.33            | 0.07      | 4.69         | 2.77E-06           |           |           |            |
| GLM for females<br>(n=202) | (Intercept)        | -14.83          | 3.26      | -4.56        | 5.23E-06           | 58.5      | 199       | 62         |
|                            | fork length        | 0.36            | 0.07      | 4.93         | 8.40E-07           |           |           |            |

*Von Bertalanffy growth functions*

To estimate von Bertalanffy growth functions for Dolphinfish collected in the northwestern Gulf of Mexico, the following equation was used:  $L_t = L_\infty * [1 - e^{-K(t-t_0)}]$ , where  $L_t$  = fork length at time (years),  $L_\infty$  = maximum theoretical attainable fork length (cm),  $K$  = growth coefficient ( $\text{year}^{-1}$ ) and  $t_0$  = time (years) when length would theoretically be equal to zero (Von Bertalanffy 1957). Sagittal otolith daily rings counts were converted into years and fork length (cm) was used for length. Von Bertalanffy growth functions were estimated for the combined sexes and for male and female Dolphinfish separately (**Error! Reference source not found.**). The estimated von Bertalanffy growth parameters for combined male, female and unknown sex ( $N = 103$ ) Dolphinfish are  $L_\infty$  (asymptotic length) = 207.44 cm FL,  $K$  (growth coefficient) = 0.902  $\text{year}^{-1}$ , and  $t_0$  (time at length 0) = 0.017 yrs (Figure 33). The estimated von Bertalanffy growth parameters for female ( $N = 58$ ) Dolphinfish are  $L_\infty$  (asymptotic length) = 157.06 cm FL,  $K$  (growth coefficient) = 1.25  $\text{year}^{-1}$ , and  $t_0$  (time at length 0) = 0.018 yrs (Figure 34). The estimated von Bertalanffy growth parameters for male ( $N = 39$ ) Dolphinfish are  $L_\infty$  (asymptotic length) = 571.70 cm FL,  $K$  (growth coefficient) = 0.300  $\text{year}^{-1}$ , and  $t_0$  (time at length 0) = 0.022 yr (Figure 35).

Table 4. A summary of the von Bertalanffy parameter estimates, the standard error of those estimates, t-based confidence intervals and  $r^2$  for combined sexes, and male and female Dolphinfish separately. The equation:  $L_t = L_\infty * [1 - e^{-K(t-t_0)}]$ , where  $L_t$  = fork length at time (years),  $L_\infty$  = maximum theoretical attainable fork length (cm),  $K$  = growth coefficient and  $t_0$  = time (years) when length would theoretically be equal to zero, was used to calculate the parameters.

| Sex and<br>Parameter | Estimate | SE      | t-based confidence interval |         | r <sup>2</sup> |
|----------------------|----------|---------|-----------------------------|---------|----------------|
|                      |          |         | 0.025                       | 0.975   |                |
| Combined Sexes       |          |         |                             |         | 0.69           |
| $L_\infty$           | 207.44   | 106.60  | -4.06                       | 418.94  |                |
| K                    | 0.90     | 0.68    | -0.44                       | 2.25    |                |
| $t_0$                | 0.02     | 0.05    | -0.09                       | 0.12    |                |
| Females              |          |         |                             |         | 0.66           |
| $L_\infty$           | 157.06   | 65.80   | 25.19                       | 288.92  |                |
| K                    | 1.25     | 0.90    | -0.55                       | 3.04    |                |
| $t_0$                | 0.02     | 0.07    | -0.12                       | 0.16    |                |
| Males                |          |         |                             |         | 0.75           |
| $L_\infty$           | 571.70   | 2467.00 | -4430.71                    | 5574.18 |                |
| K                    | 0.30     | 1.46    | -2.66                       | 3.26    |                |
| $t_0$                | 0.02     | 0.11    | -0.19                       | 0.24    |                |

### *Estimated growth rate*

An alternative method for estimating a growth rate is to plot sagittal daily growth rings as a function of fork length and take the slope of that linear regression line as an estimate daily growth rate (Bentivoglio 1989; Oxenford and Hunte 1983). Combined female, male and unknown sex Dolphinfish of the northwestern Gulf of Mexico were estimated to have a growth rate  $\pm$  S.E. of  $3.45 \pm 0.02$  mm FL day<sup>-1</sup> (Figure 36). Female Dolphinfish were estimated to have a growth rate  $\pm$  S.E of  $3.01 \pm 0.03$  mm FL day<sup>-1</sup> (Figure 37). Male Dolphinfish were estimated to have a growth rate  $\pm$  S.E of  $4.03 \pm 0.04$ mm FL day<sup>-1</sup> (Figure 38).

### *Estimating age using biological parameters*

Based on the information collected in this study, a multiple regression model was developed for the purpose of estimating the age of an individual fish using biological parameters. The main purpose of this model was to estimate age of individual fish using easily accessible biological parameters: fork length and carcass weight. With this goal in mind, a linear multiple regression model was developed using backward elimination stepwise regression. This method determined the  $r^2$  value for the multiple regression model, where age is explained by fork length and carcass weight, was 0.71. The  $r^2$  value for age as explained by fork length alone was 0.68, and the  $r^2$  value for age as explained by carcass weight alone was 0.50, indicating that the multiple regression model is a better fit for predicting age, than either coefficient alone. The equation for the multiple regression model is:  $(\text{daily age})_i = -7.53 + 2.82 * FL_i - 8.19 * CW_i$ . Confidence intervals,

analysis of variance, and non-parametric bootstrapping was done on the coefficients of the models to assess overall goodness of fit (Table 5).

Table 5. A summary of the multiple regression model coefficients, confidence intervals, analysis of variance table, and bootstrapping results for predicting Dolphinfish age using carcass weight and fork length.

| <b>Model: daily rings as predicted by fl + cw</b> |          |            |            |          |          |
|---|----------|------------|------------|----------|----------|
|   | Estimate | Std. Error | t value    | Pr(> t ) |          |
| (Intercept)                                       | -7.53    | 16.08      | -0.47      | 0.64     |          |
| fl  | 2.82     | 0.36       | 7.84       | 8.8E-12  |          |
| cw  | -8.19    | 3.54       | -2.31      | 0.02     |          |
| <b>Confidence intervals</b>                       |          |            |            |          |          |
|   | 2.50%    | 97.50%     |            |          |          |
| (Intercept)                                       | -39.47   | 24.41      |            |          |          |
| fl  | 2.11     | 3.54       |            |          |          |
| cw  | -15.22   | -1.16      |            |          |          |
| <b>Analysis of Variance Table</b>                 |          |            |            |          |          |
|   | Df       | Sum Sq     | Mean Sq    | F Value  | Pr(>F)   |
| fl  | 1        | 173489     | 173489     | 209.78   | 2.00E-16 |
| cw  | 1        | 4429       | 4429       | 5.3558   | 0.02293  |
| Residuals   | 90       | 74430      | 827        |          |          |
| <b>Bootstrap Statistics (2014 Replicates)</b>     |          |            |            |          |          |
|   | original | bias       | std. error |          |          |
| (Intercept)                                       | -7.53    | -0.25      | 19.28      |          |          |
| fl  | 2.82     | 0.00       | 0.48       |          |          |
| cw  | -8.19    | 0.19       | 5.67       |          |          |

*Length at age key*

An estimated length at age key was created using the daily ages and fork lengths for Dolphinfish in the Gulf of Mexico, observed in this study. To create an age category, the estimated daily ages were converted into months by dividing the daily age by 30. Dolphinfish with ages were then categorized into length categories of 10 cm fork lengths to create a contingency table that calculated the probability of age for each length category. These probabilities were then used to assign ages for all Dolphinfish with a recorded fork length (Figure 39). The results of the estimated ages for all Dolphinfish in the dataset were then converted back to years to estimate the von Bertalanffy growth equations for the entire dataset (Figure 40). Using the length-age key to estimate ages for the entire data set, the re-estimated von Bertalanffy growth parameters for combined male, female, and unknown sex Dolphinfish (N = 352) in the northwestern Gulf of Mexico are  $L_{\infty}$  (asymptotic length) = 202.94 cm FL, K (growth coefficient) = 0.746 year<sup>-1</sup>, and  $t_0$  (time at length 0) = 0.076 yrs ( $r^2 = 0.550$ ).

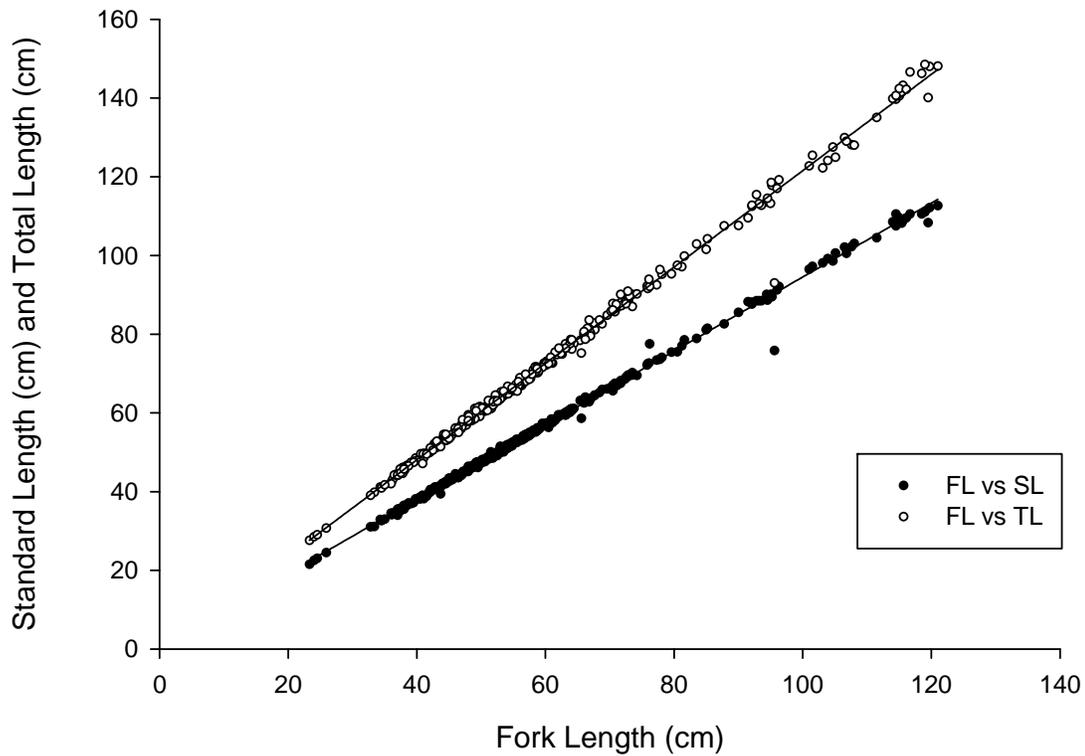


Figure 7. Fork length (cm) to standard length (cm) ( $N = 356$ ), and fork length (cm) to total length (cm) ( $N = 356$ ) relationships for combined male, female, and unknown sex Dolphinfish collected in the northwestern Gulf of Mexico.

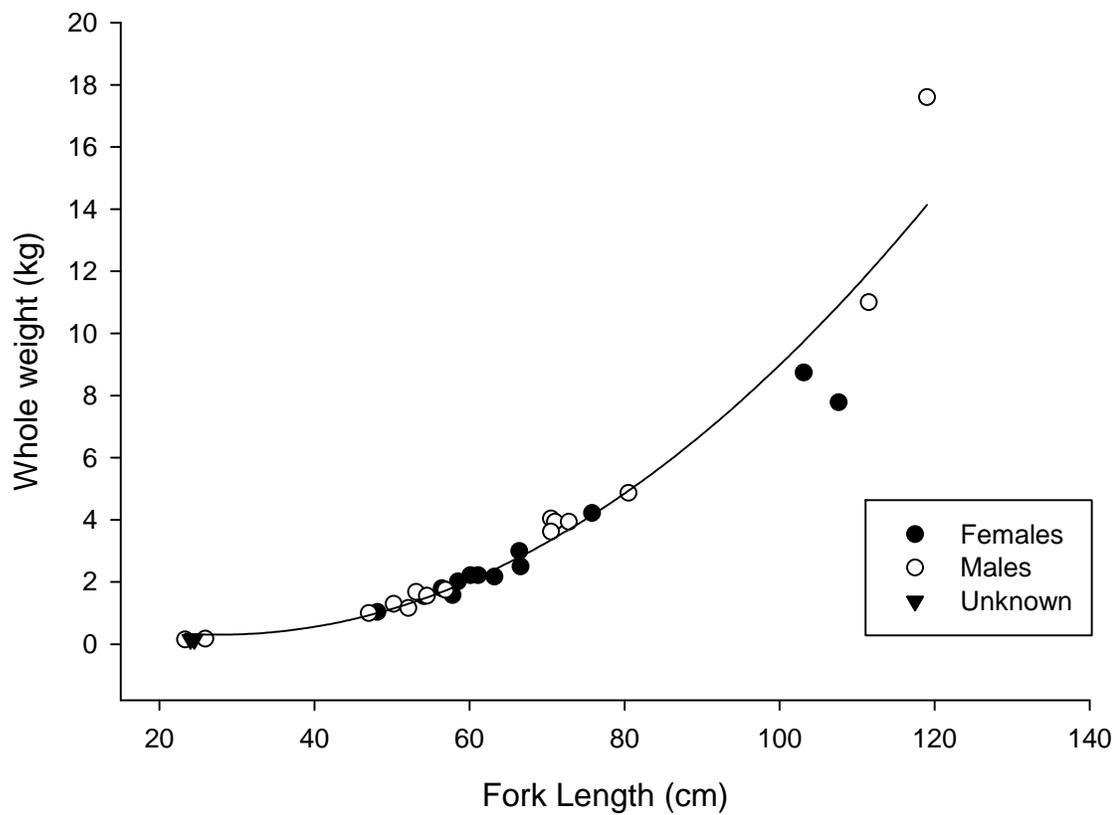


Figure 8. Fork length (cm) to whole weight (kg) relationships for combined male, female, and unknown sex Dolphinfish (N = 31) collected in the northwestern Gulf of Mexico.

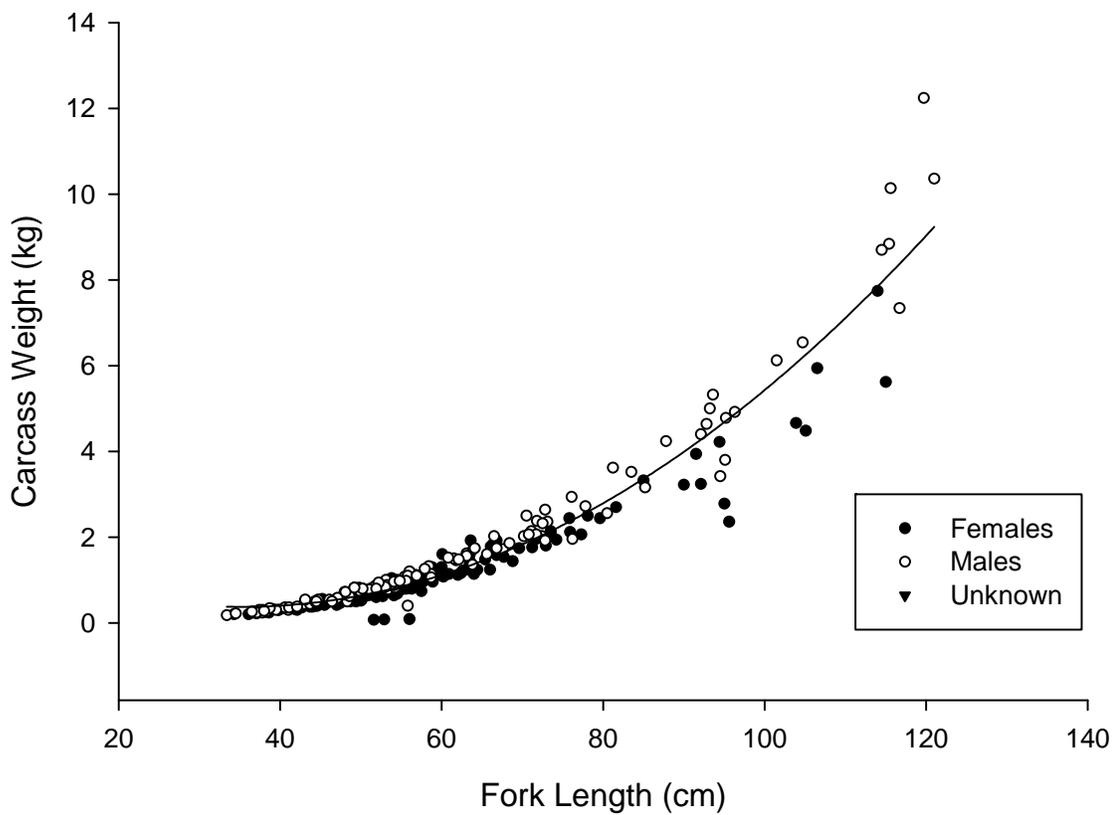


Figure 9. Fork length (cm) to carcass weight (kg) relationships for combined male, female and Dolphinfish of unknown sex (N = 290) collected in the northwestern Gulf of Mexico.

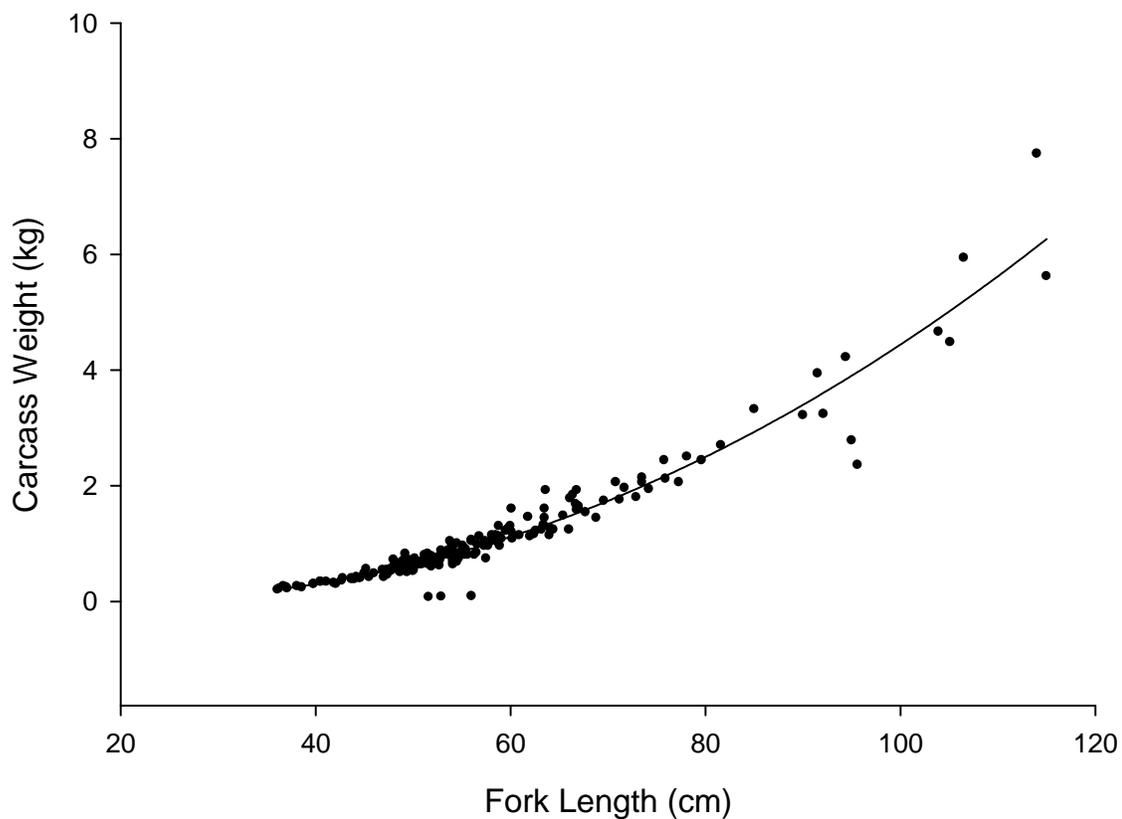


Figure 10. Fork length (cm) to carcass weight (kg) relationship for female Dolphinfish ( $N = 174$ ;  $r^2 = 0.9372$ ) collected in the northwestern Gulf of Mexico.

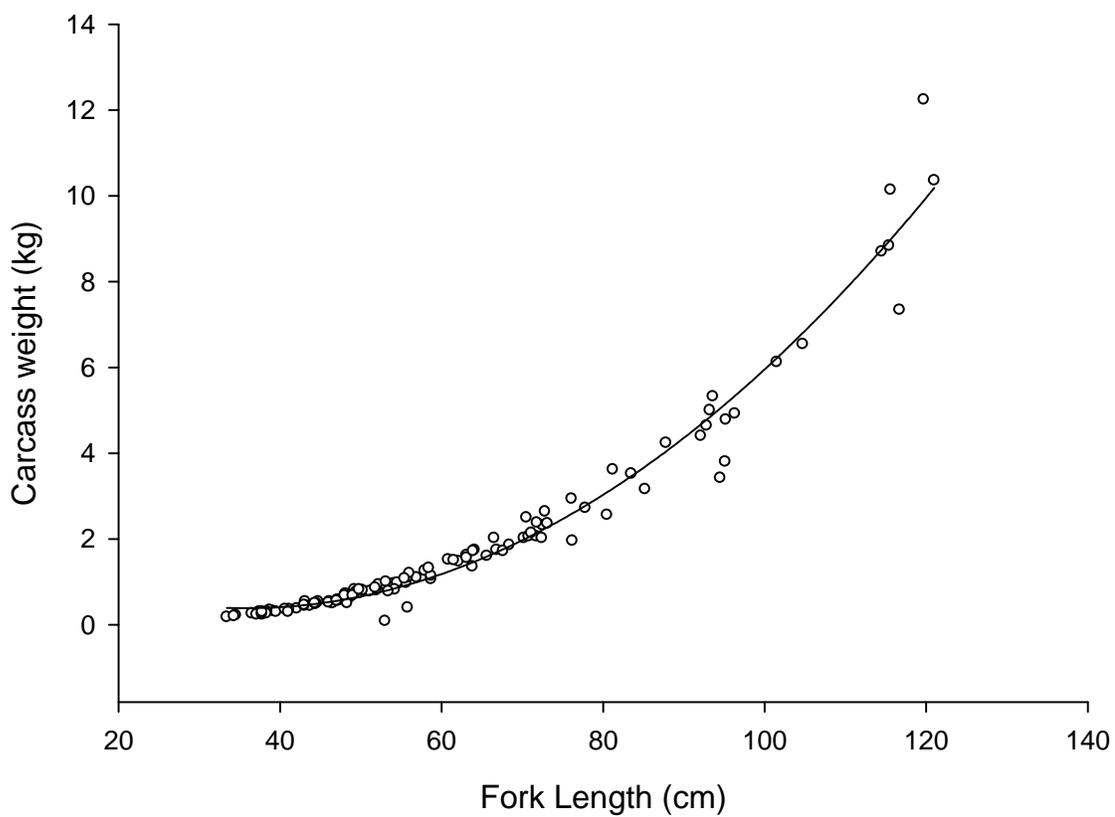


Figure 11. Fork length (cm) to carcass weight (kg) relationship for male Dolphin fish ( $N = 116$ ;  $r^2 = 0.9677$ ) collected in the northwestern Gulf of Mexico.

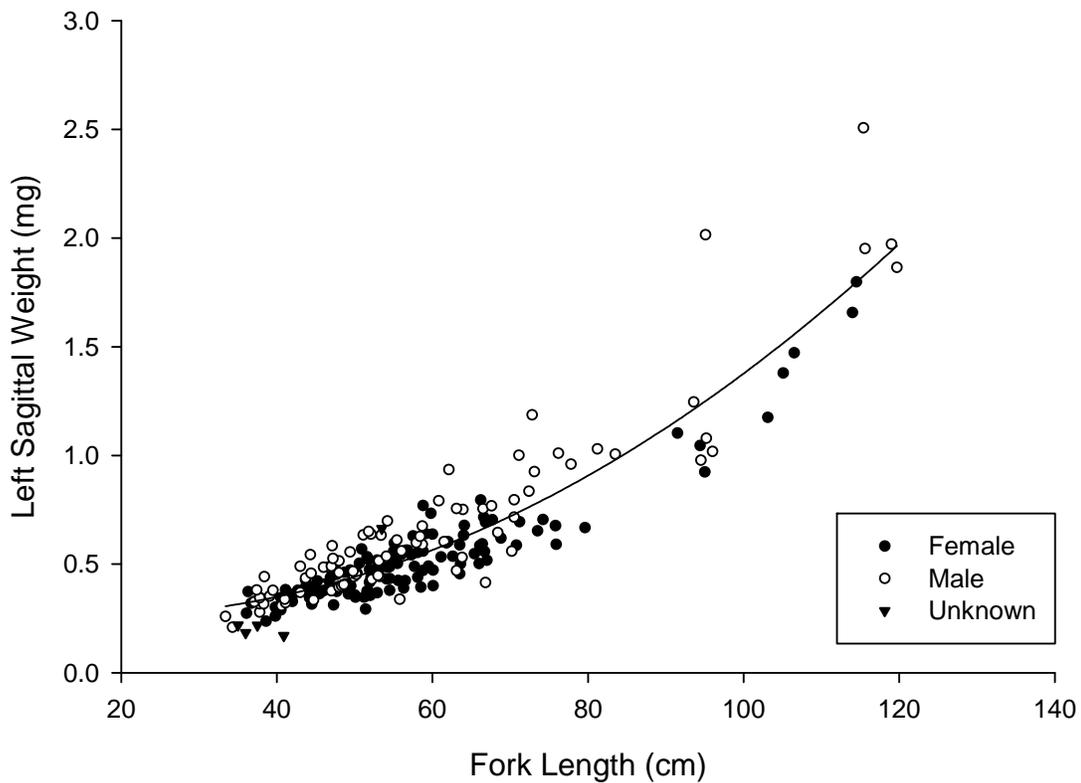


Figure 12. Fork length (cm) to left sagittal weight (mg) relationship for combined male, female and unknown sex Dolphinfish (N = 225) collected in the northwestern Gulf of Mexico.

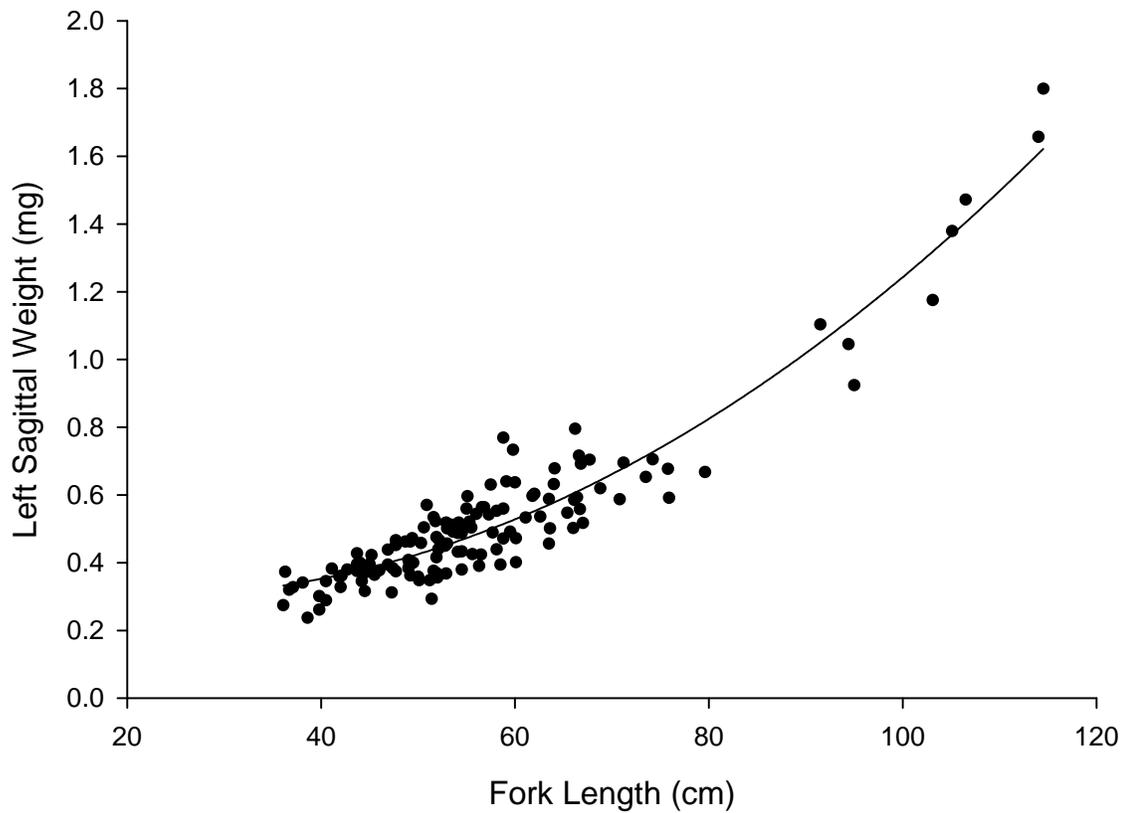


Figure 13. Fork length (cm) to left sagittal weight (mg) relationship for female Dolphinfish ( $N = 135$ ;  $r^2 = 0.9016$ ) collected in the northwestern Gulf of Mexico.

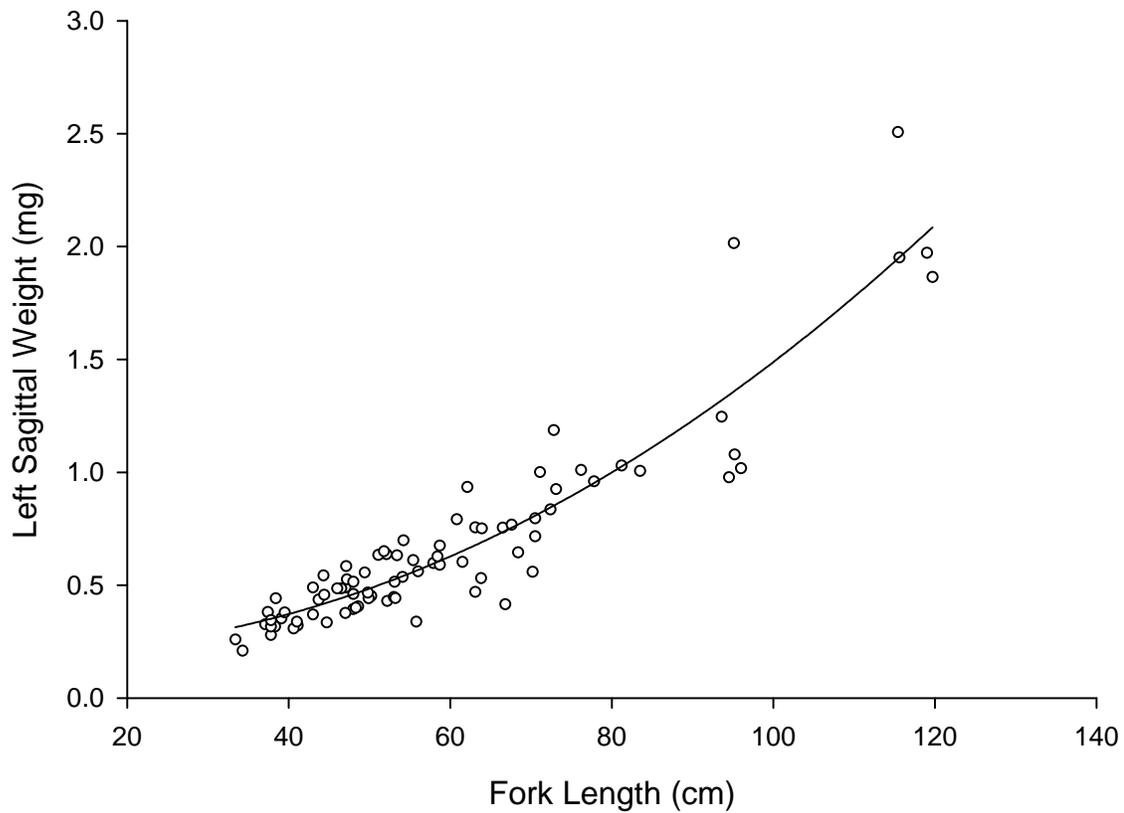


Figure 14. Fork length (cm) to left sagittal weight (mg) relationship for male Dolphinfish ( $N = 83$ ;  $r^2 = 0.8664$ ) collected in the northwestern Gulf of Mexico.

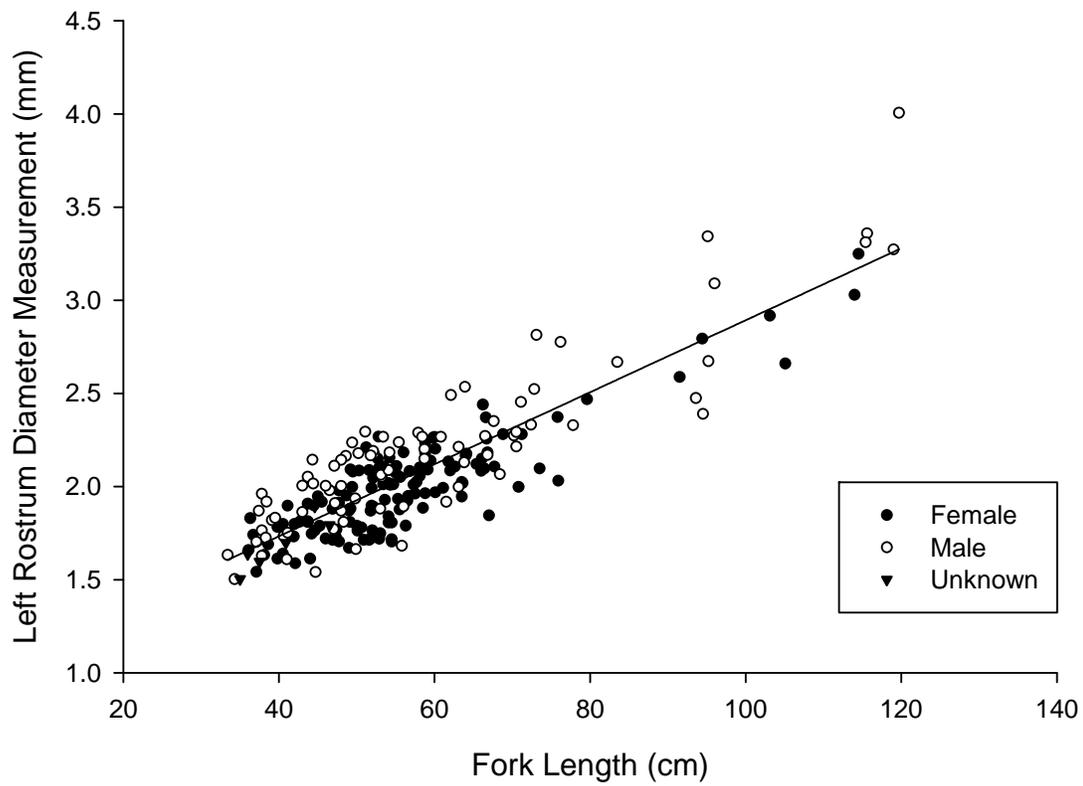


Figure 15. Fork length (cm) to left sagittal rostrum diameter measurement (mm) relationship for combined male, female and unknown sex Dolphinfish ( $N = 218$ ;  $r^2 = 0.7729$ ) collected in the northwestern Gulf of Mexico.

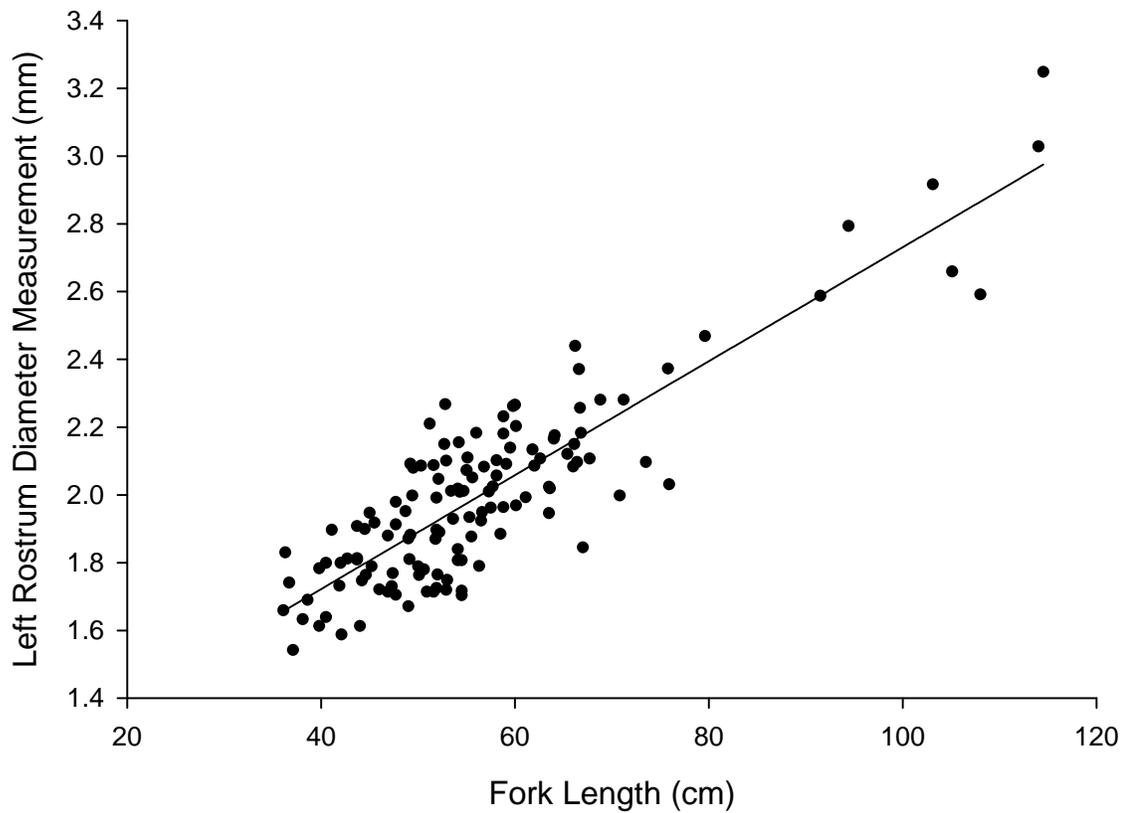


Figure 16. Fork length (cm) to left sagittal rostrum diameter measurement (mm) relationship for female Dolphinfish ( $N = 131$ ;  $r^2 = 0.7624$ ) collected in the northwestern Gulf of Mexico.

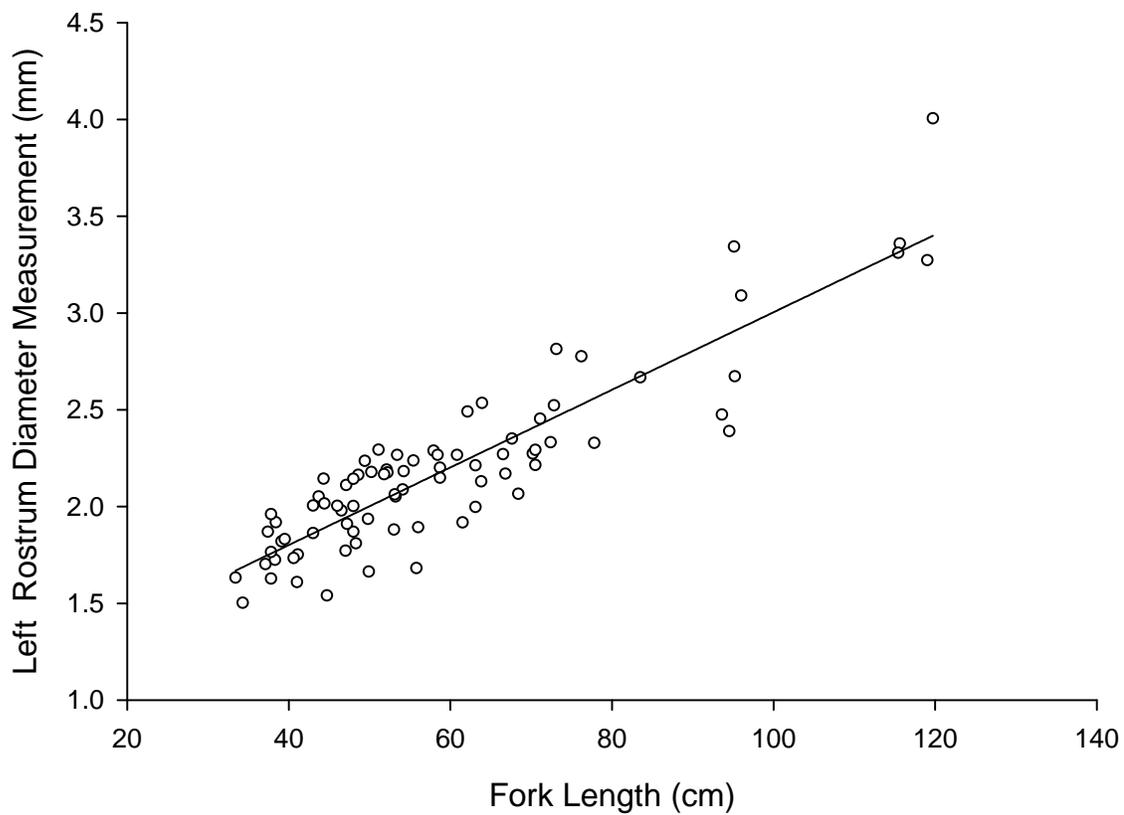


Figure 17. Fork length (cm) to left sagittal rostrum diameter measurement (mm) relationship for male Dolphinfish ( $N = 81$ ;  $r^2 = 0.8046$ ) collected in the northwestern Gulf of Mexico.

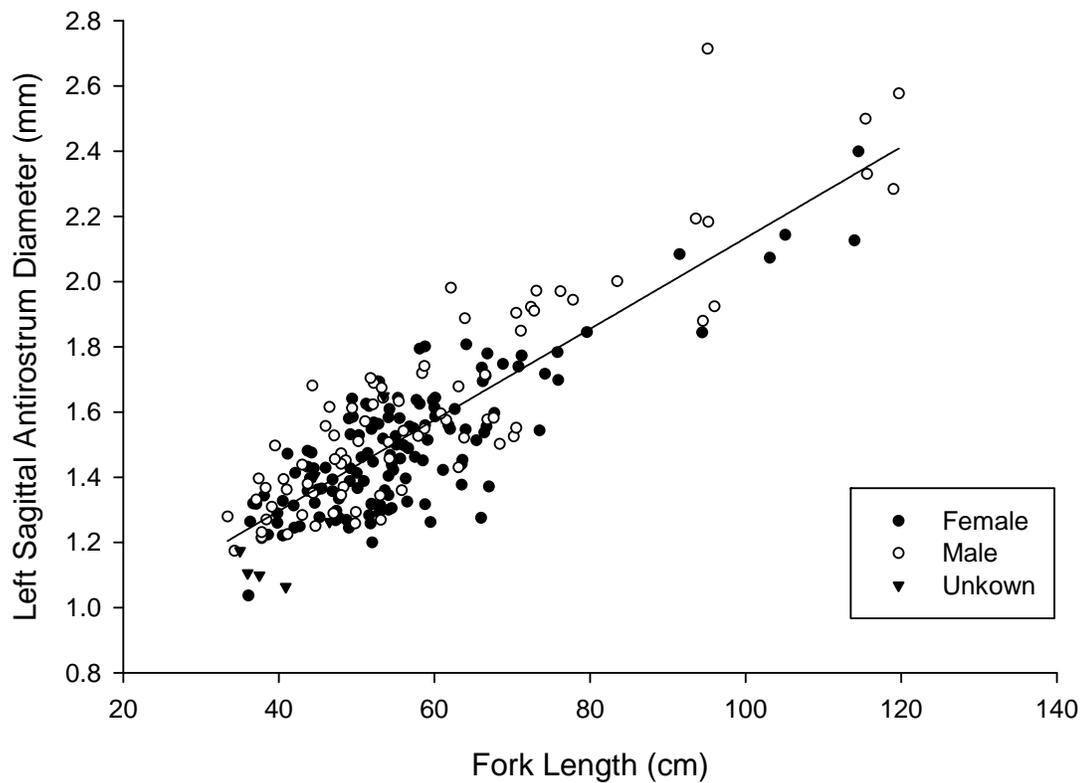


Figure 18. Fork length (cm) to left sagittal antirostrum diameter measurement (mm) relationship for combined male, female and unknown sex Dolphinfish (N = 220) collected in the northwestern Gulf of Mexico.

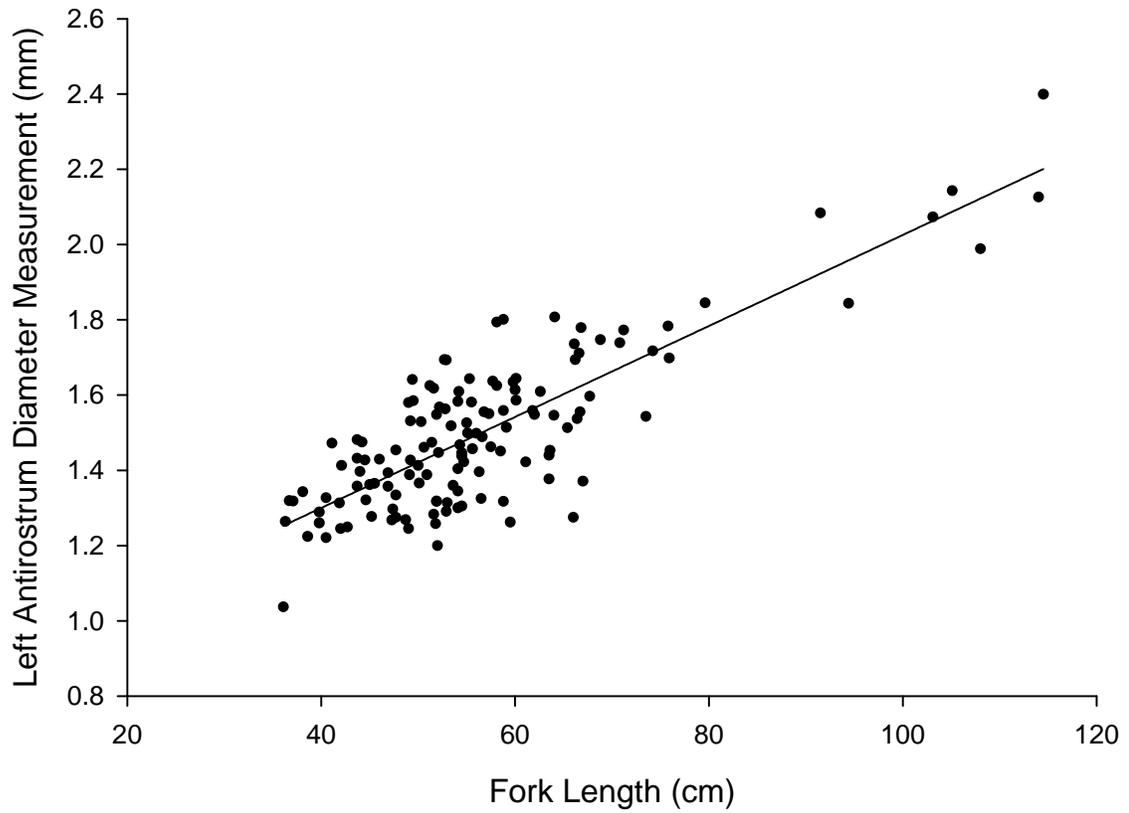


Figure 19. Fork length (cm) to left sagittal antirostrum diameter measurement (mm) relationship for female Dolphinfish ( $N = 133$ ;  $r^2 = 0.6788$ ) collected in the northwestern Gulf of Mexico.

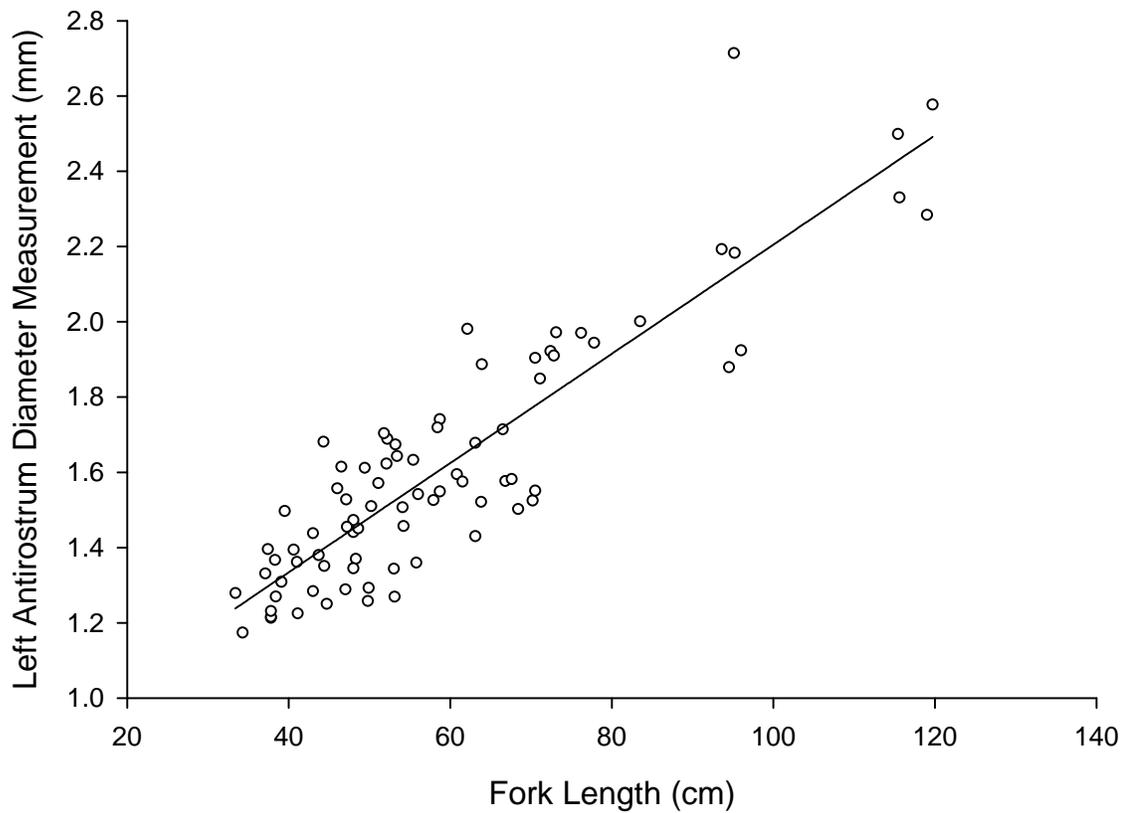


Figure 20. Fork length (cm) to left sagittal antirostrum diameter measurement (mm) relationship for male Dolphinfish ( $N = 81$ ;  $r^2 = 0.7926$ ) collected in the northwestern Gulf of Mexico.

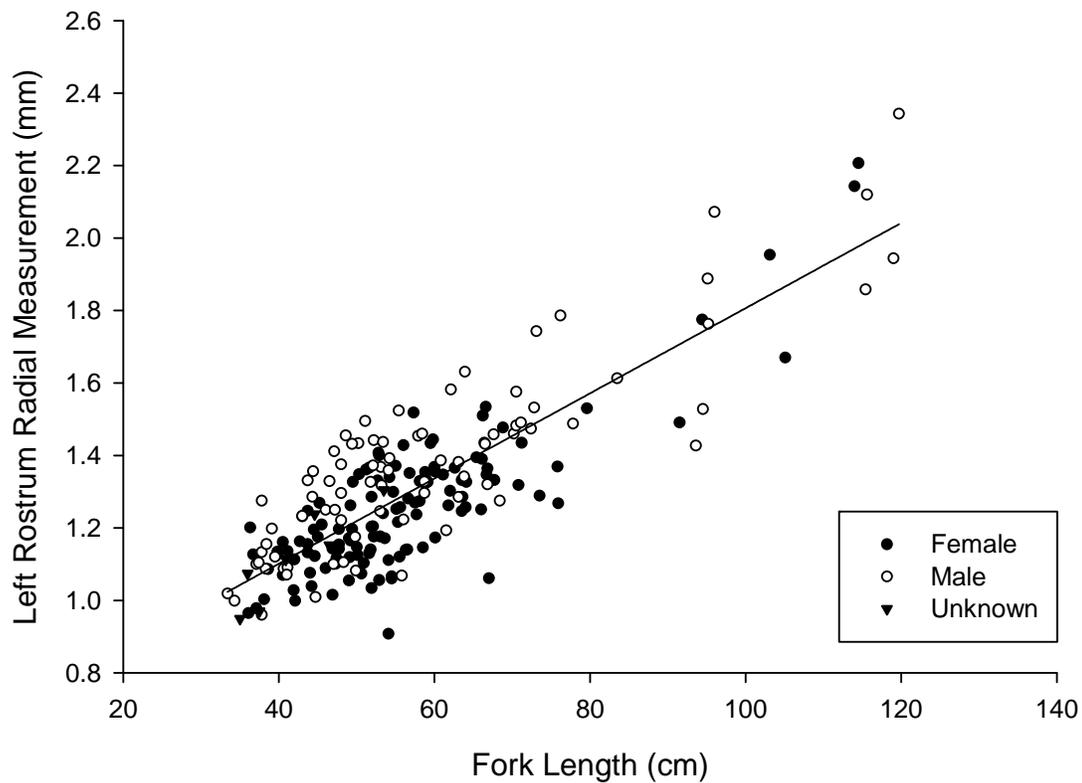


Figure 21. Fork length (cm) to left sagittal rostrum radial measurement (mm) relationship for combined male, female and unknown sex Dolphinfish (N = 213) collected in the northwestern Gulf of Mexico.

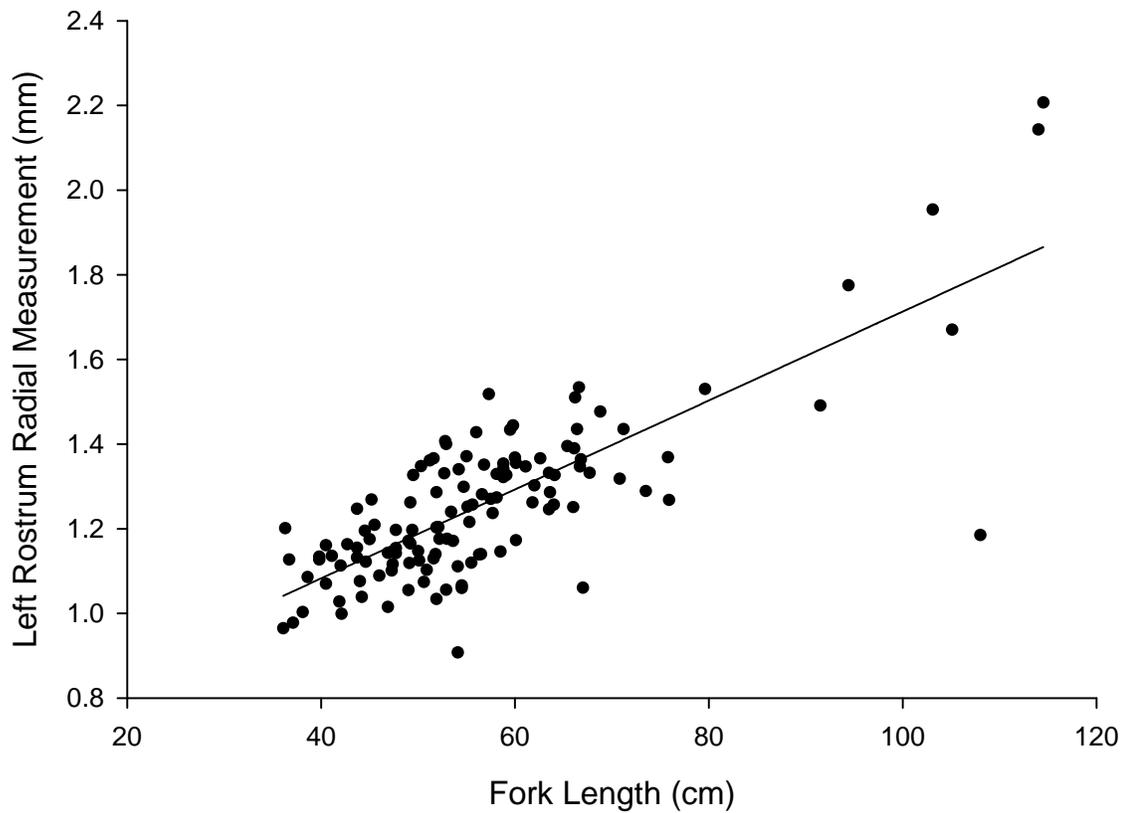


Figure 22. Fork length (cm) to left sagittal rostrum radial measurement (mm) relationship for female Dolphinfish ( $N = 126$ ;  $r^2 = 0.6196$ ) collected in the northwestern Gulf of Mexico.

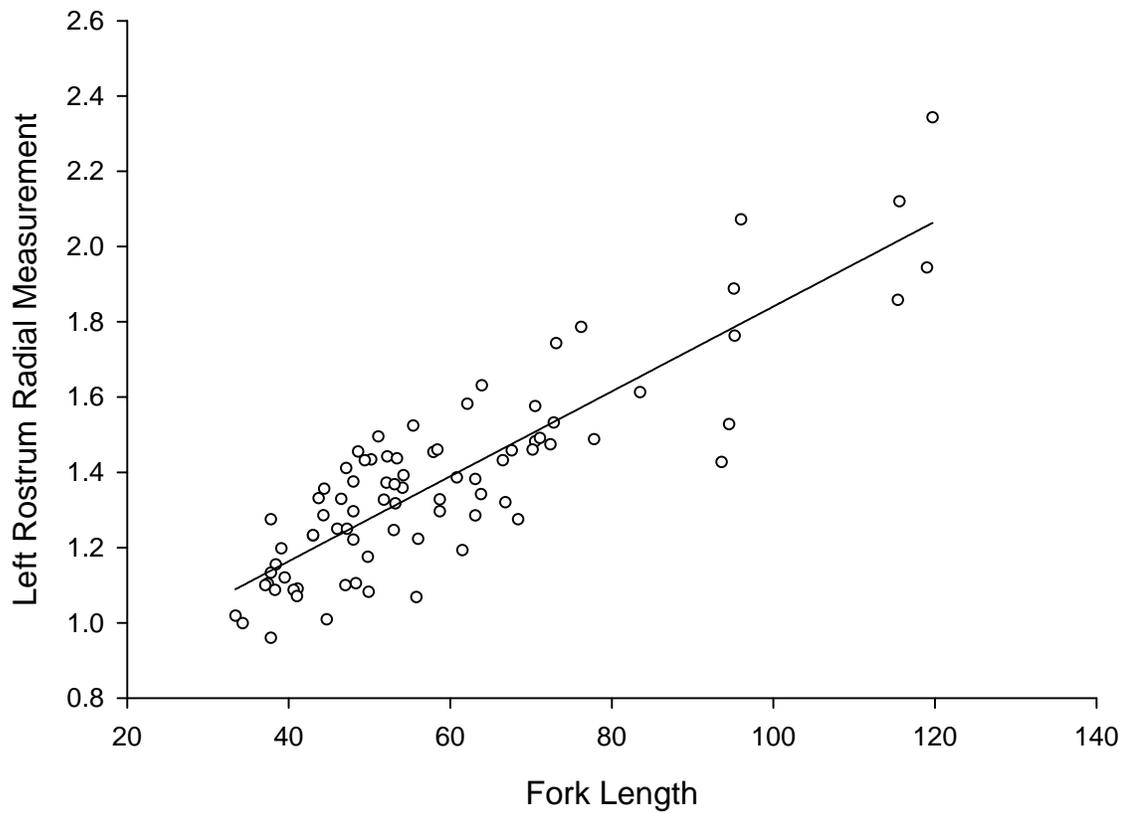


Figure 23. Fork length (cm) to left sagittal rostrum radial measurement (mm) relationship for male Dolphinfish ( $N = 81$ ;  $r^2 = 0.7501$ ) collected in the northwestern Gulf of Mexico.

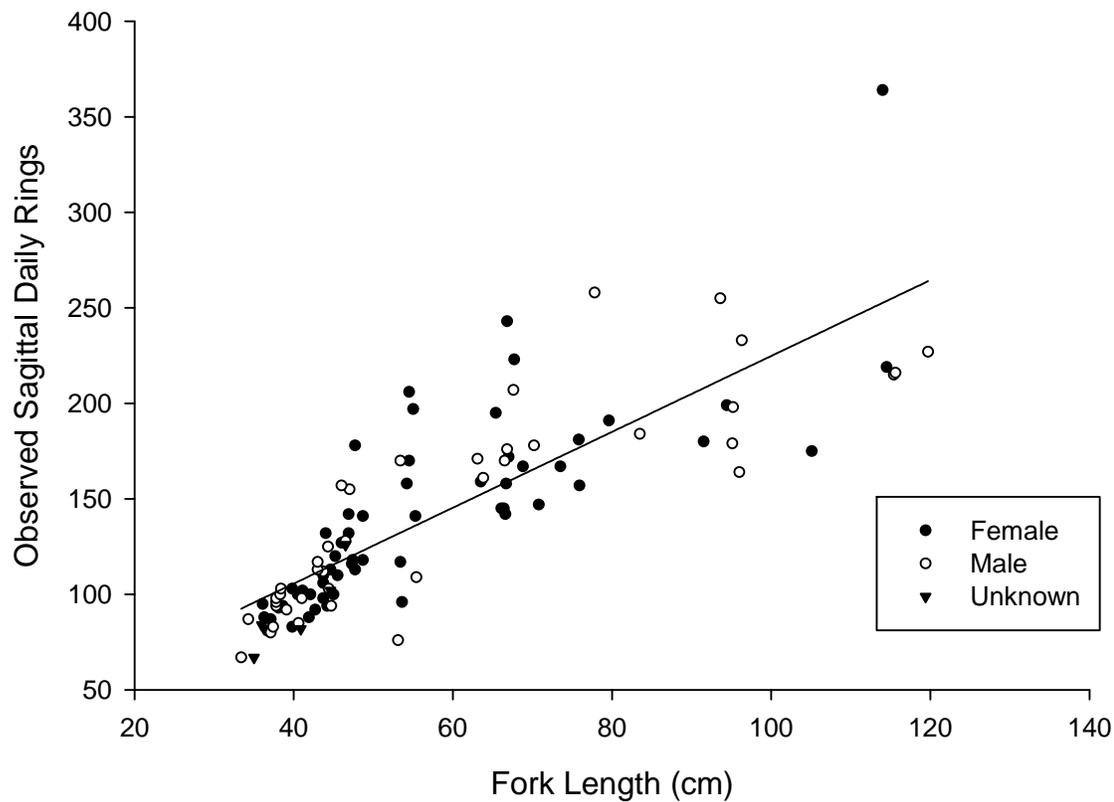


Figure 24. Fork length (cm) to counted daily sagittal otolith rings relationship for combined male, female, and unknown sex Dolphinfish (N = 103) collected in the northwestern Gulf of Mexico.

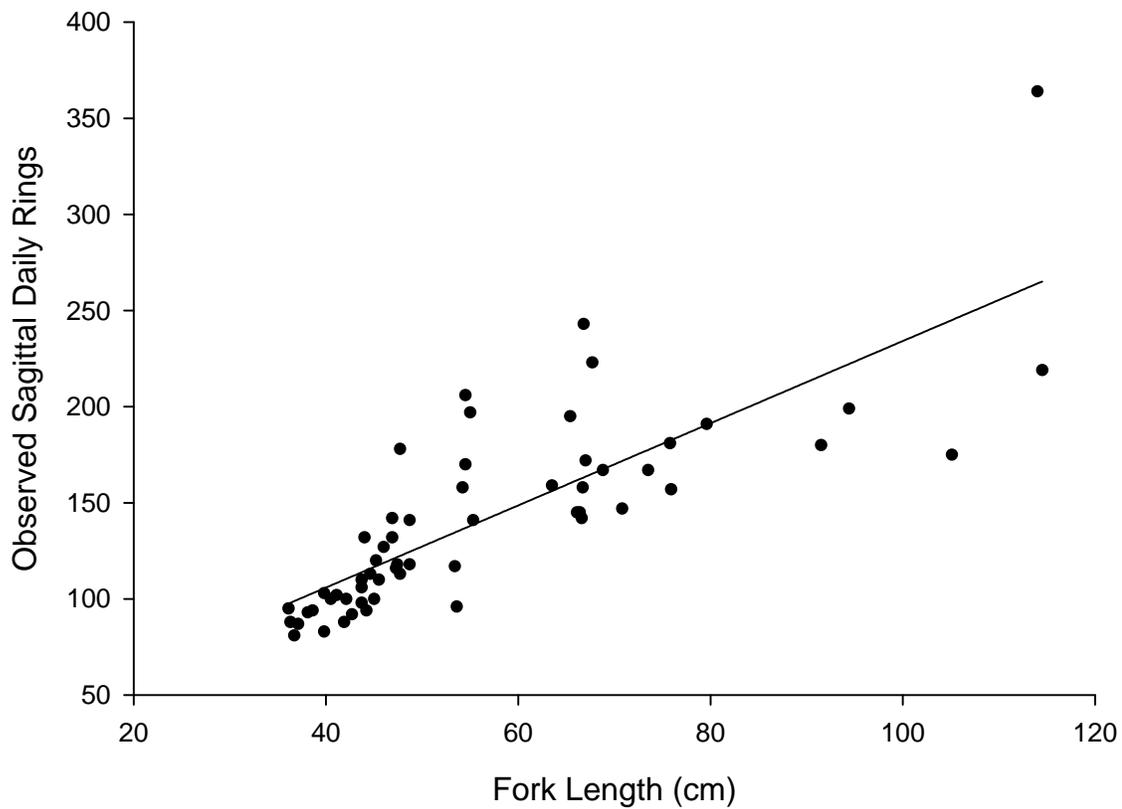


Figure 25. Fork length (cm) to counted daily sagittal otolith rings relationship for female Dolphinfish ( $N = 58$ ;  $r^2 = 0.6434$ ) collected in the northwestern Gulf of Mexico.

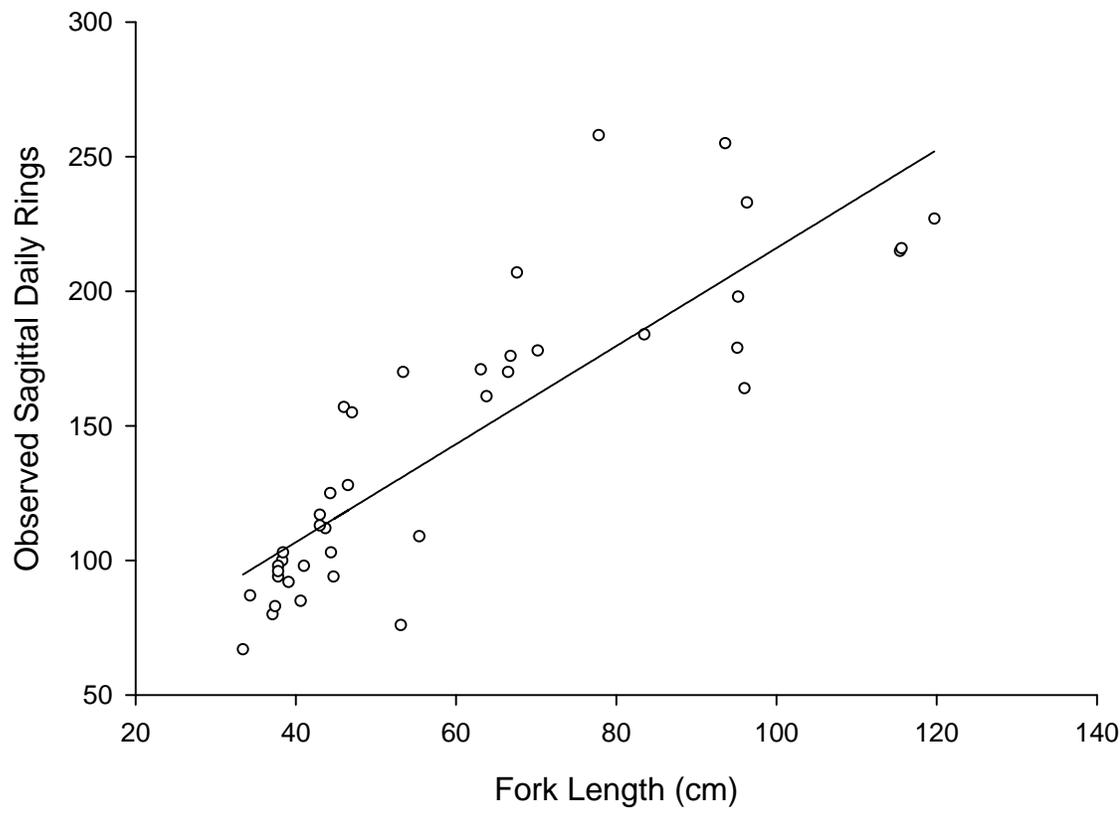


Figure 26. Fork length (cm) to counted daily sagittal otolith rings relationship for male Dolphinfish (N = 40;  $r^2 = 0.7335$ ) collected in the northwestern Gulf of Mexico.

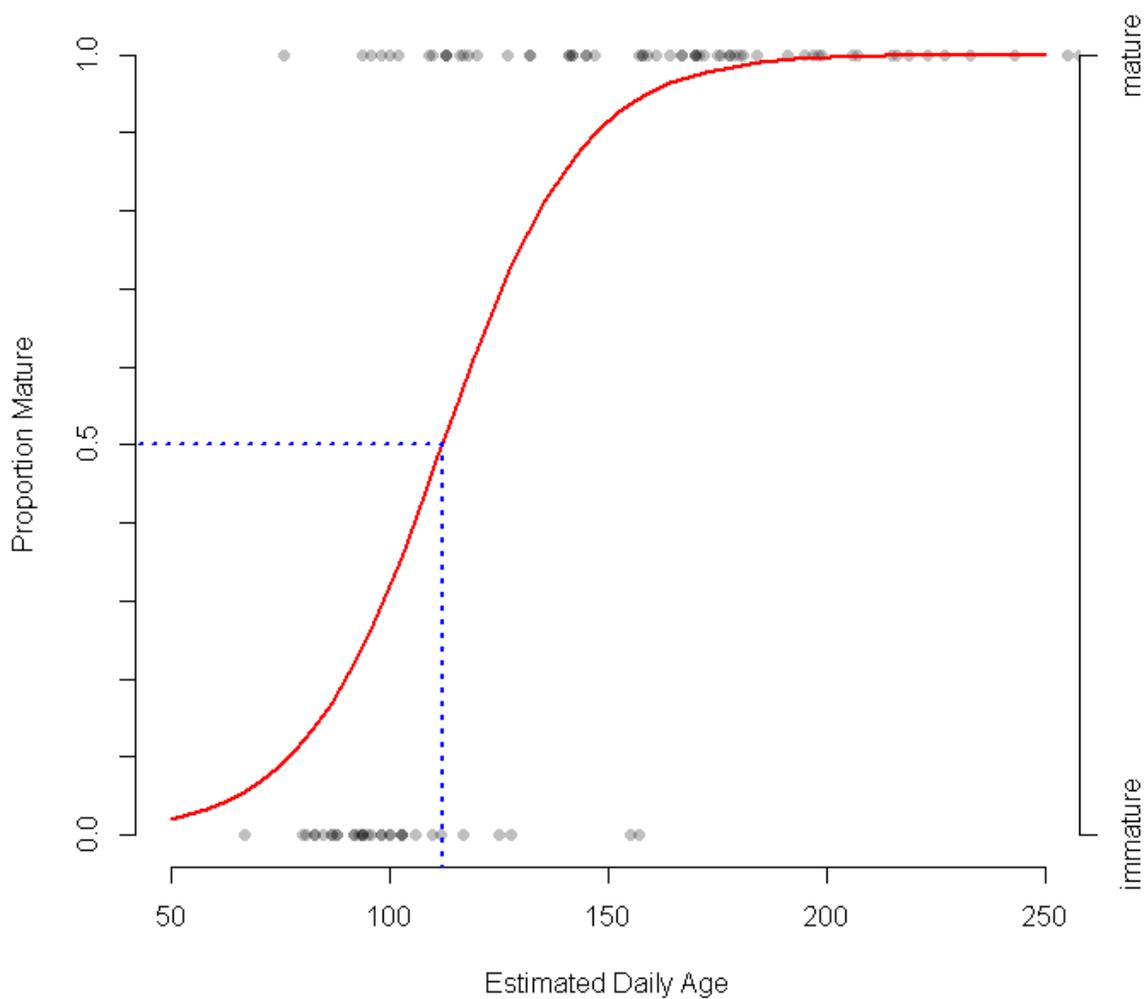


Figure 27. Fitted logistic regression illustrating the proportion of mature male, female and unknown sex Dolphinfish against estimated daily age where 50% of combined Dolphinfish were estimated to be sexually mature by the estimated age of 112 days (n=96).

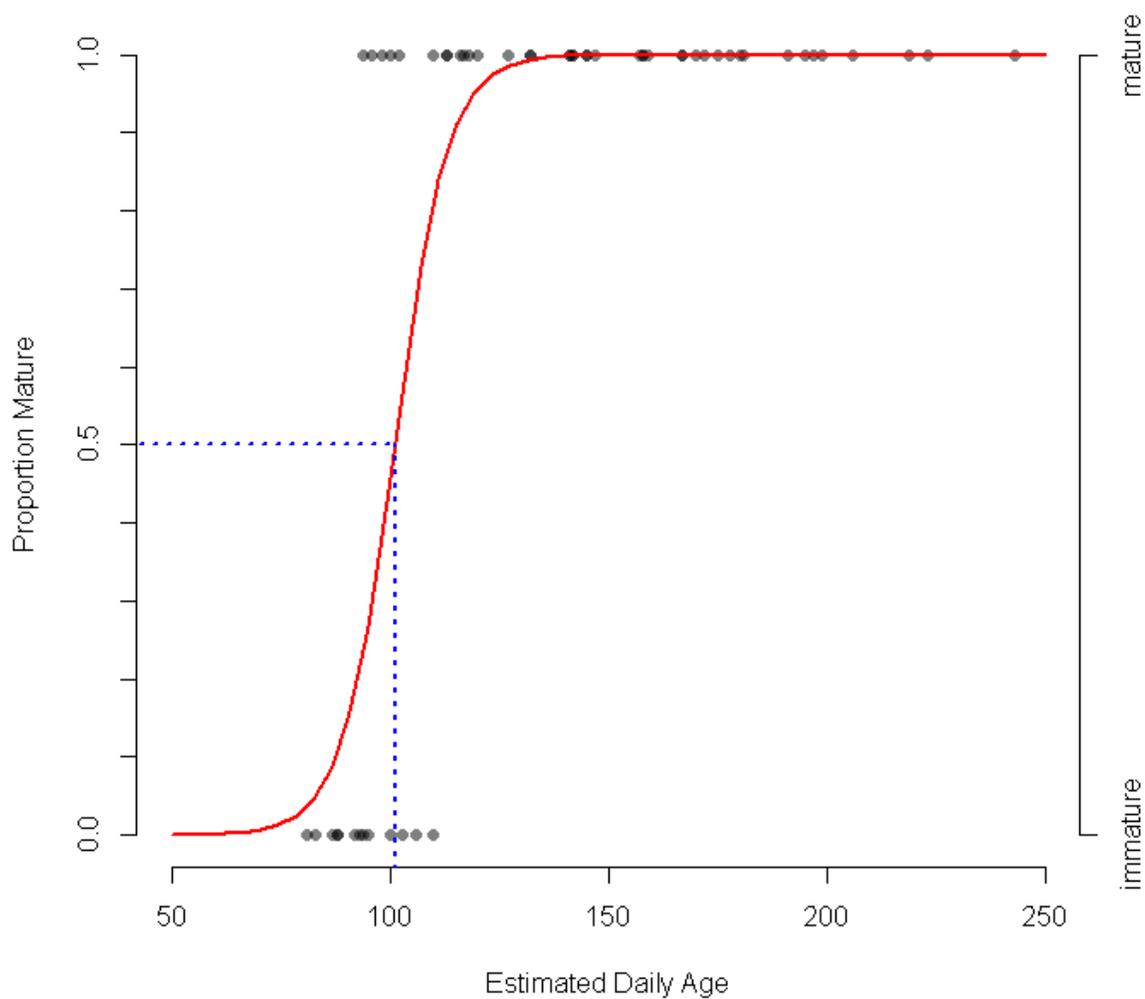


Figure 28. Fitted logistic regression illustrating the proportion of mature female Dolphinfish against the estimated daily age where 50% of female Dolphinfish were estimated to be sexually mature by the estimated age of 114 days (n=56).

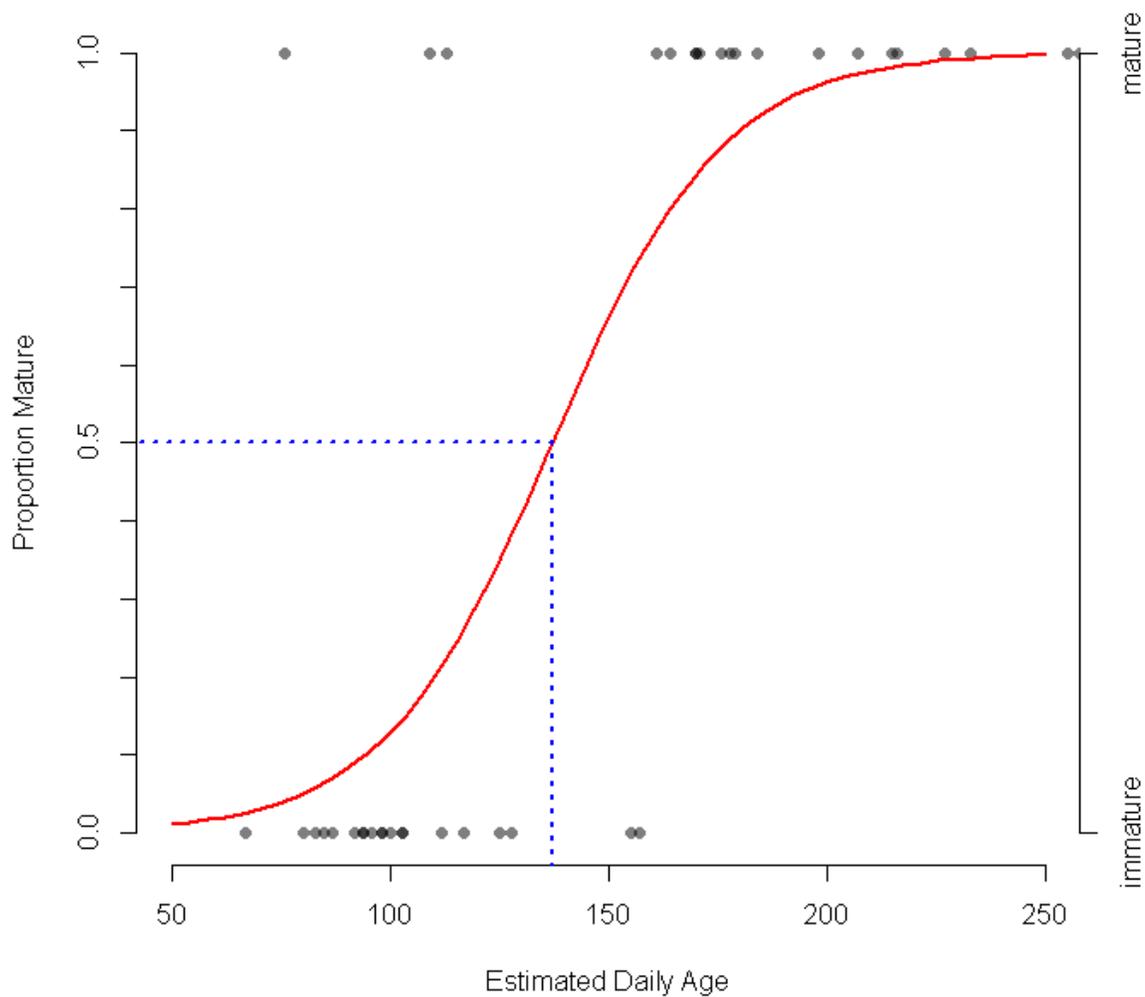


Figure 29. Fitted logistic regression illustrating the proportion of mature male Dolphinfish against the estimated daily age where 50% of male Dolphinfish were estimated to be sexually mature by the estimated age of 137 days (n=40).

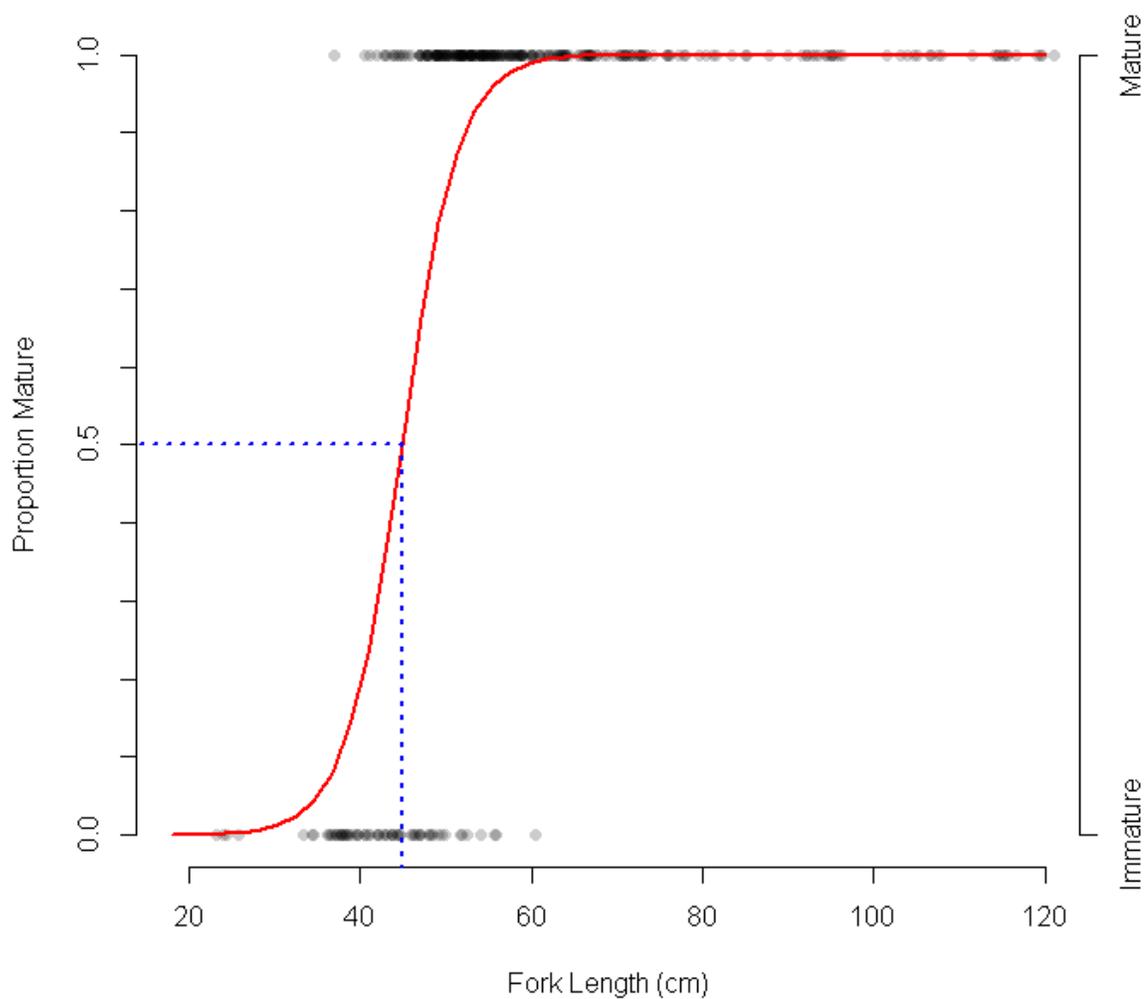


Figure 30. Fitted logistic regression illustrating the proportion of mature male, female, and unknown sex Dolphinfish against fork length (cm) where 50% of combined Dolphinfish were estimated to be sexually mature at a fork length of 44.88 cm (n=332).

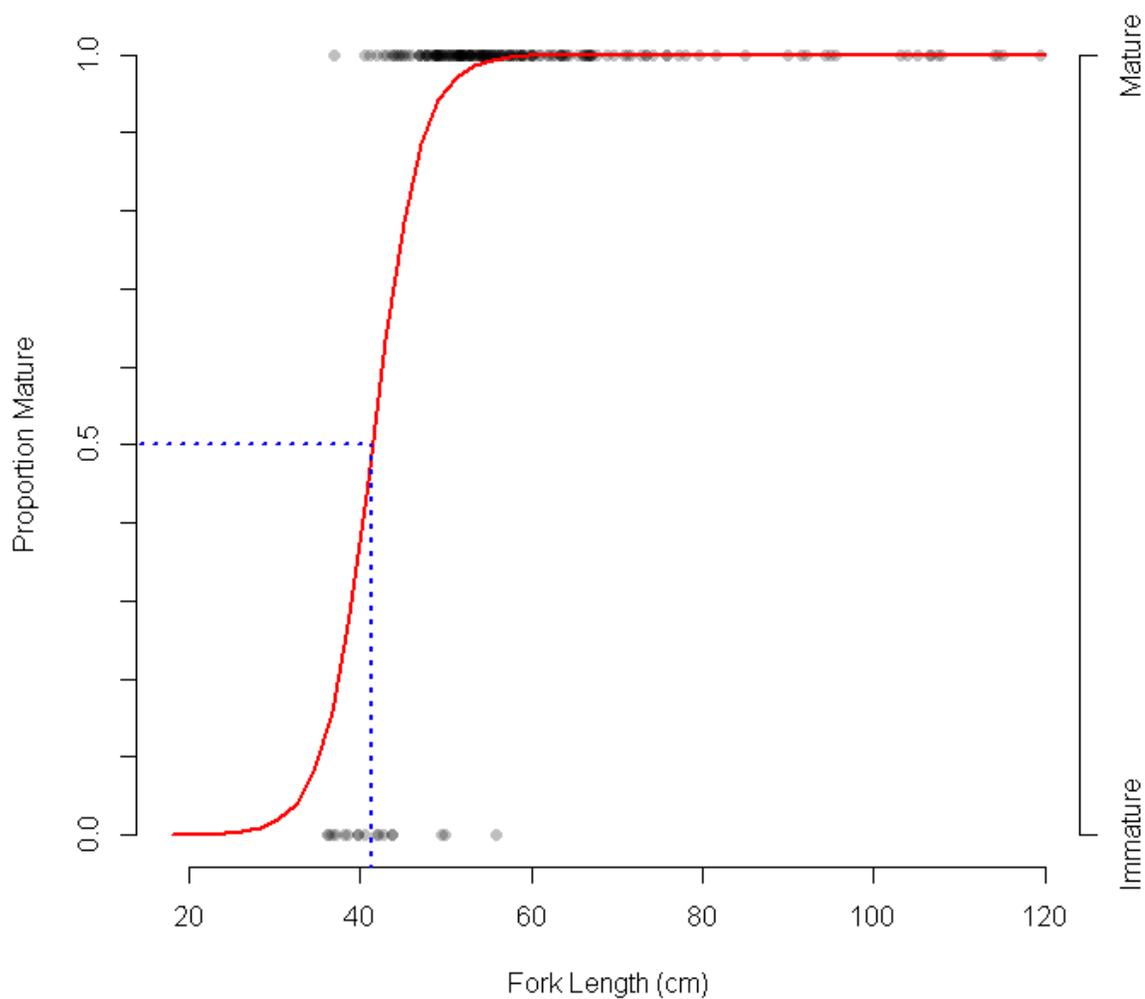


Figure 31. Fitted logistic regression illustrating the proportion of mature female Dolphinfish against fork length (cm) where 50% of Dolphinfish were estimated to be sexually mature at fork length 41.43 cm (n=200).

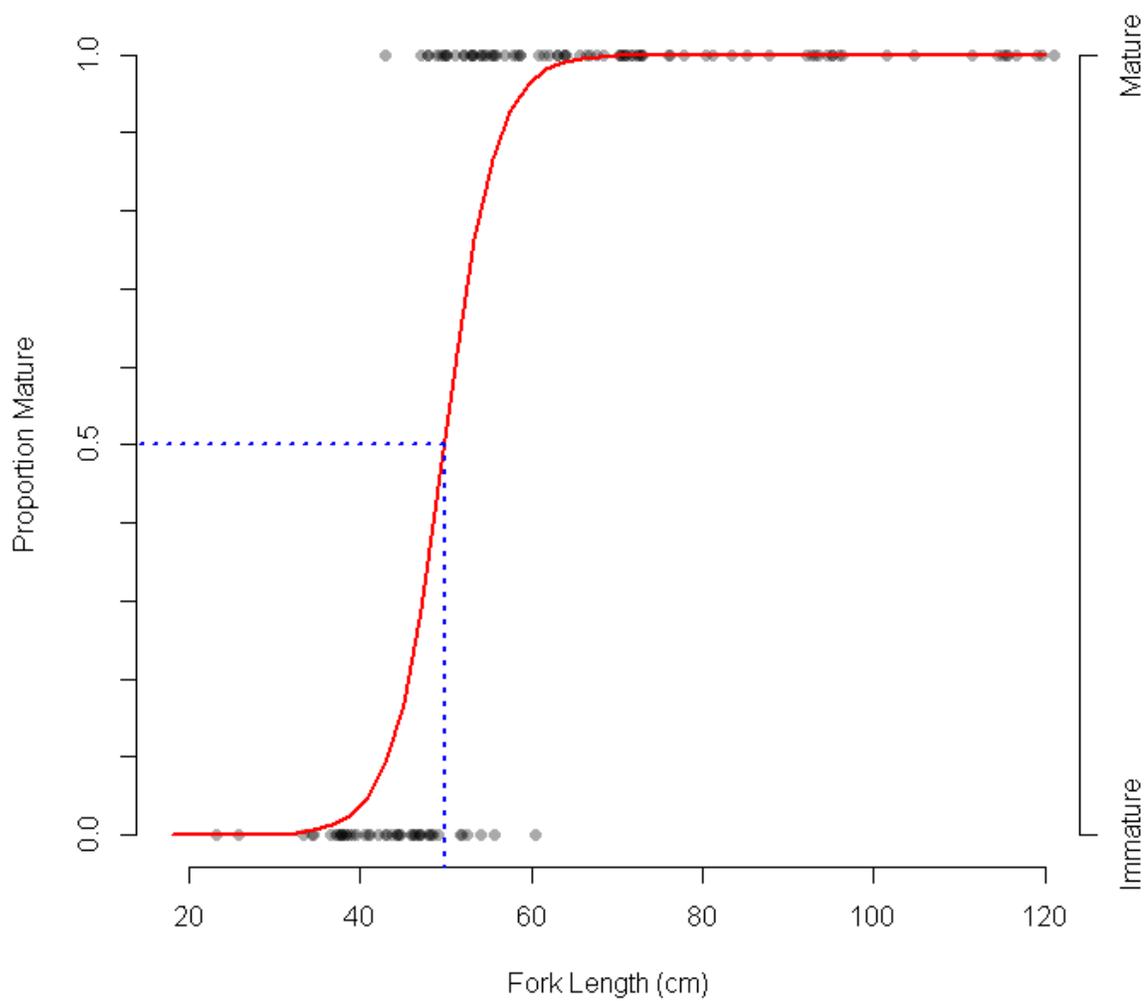


Figure 32. Fitted logistic regression illustrating the proportion of mature male Dolphinfish against fork length (cm) where 50% of Dolphinfish were estimated to be sexually mature at fork length 49.87 cm (n=130).

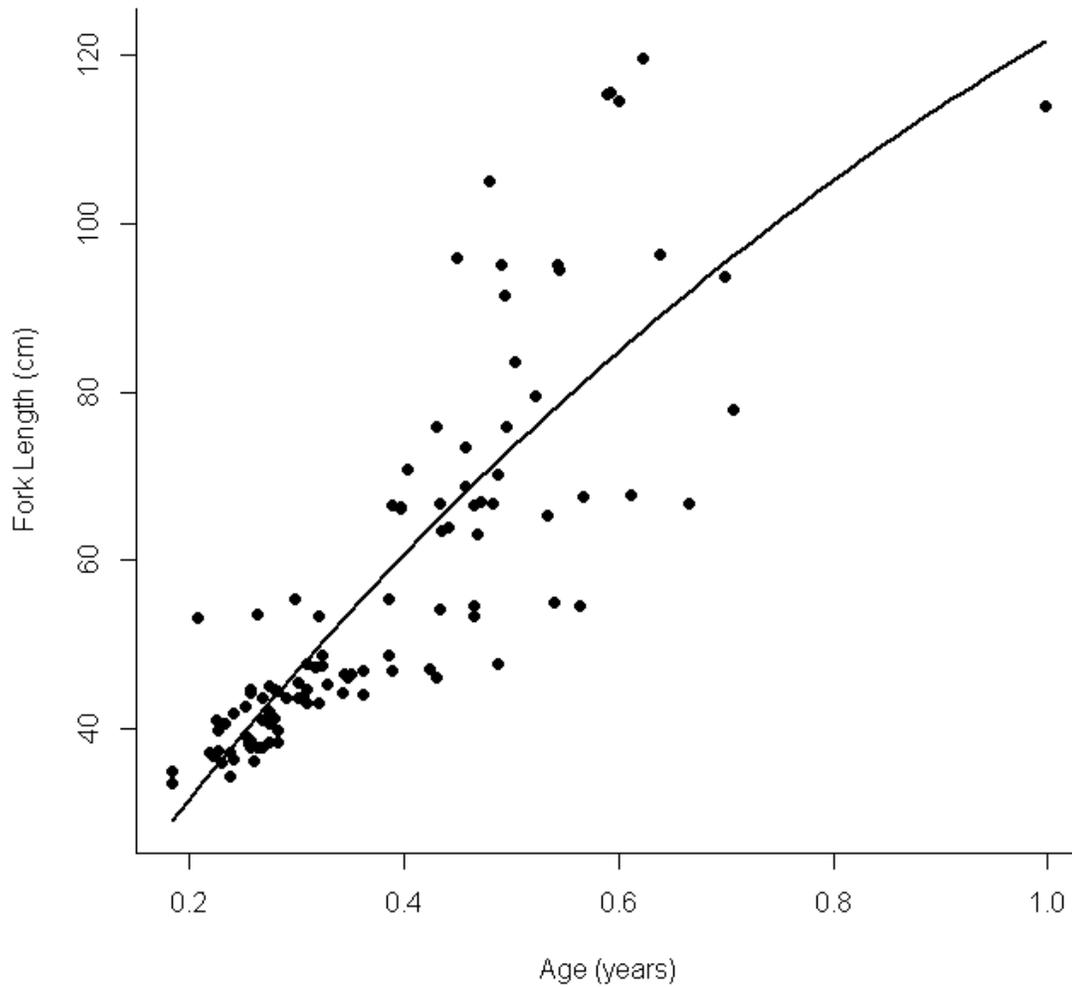


Figure 33. The von Bertalanffy growth parameters for combined male, female, and unknown sex Dolphinfish ( $N = 103$ ) in the northwestern Gulf of Mexico are  $L_{\infty}$  (asymptotic length) = 207.44 cm FL,  $K$  (growth coefficient) =  $0.902 \text{ year}^{-1}$ , and  $t_0$  (time at length 0) =  $0.017 \text{ yr}$  ( $r^2 = 0.694$ ).

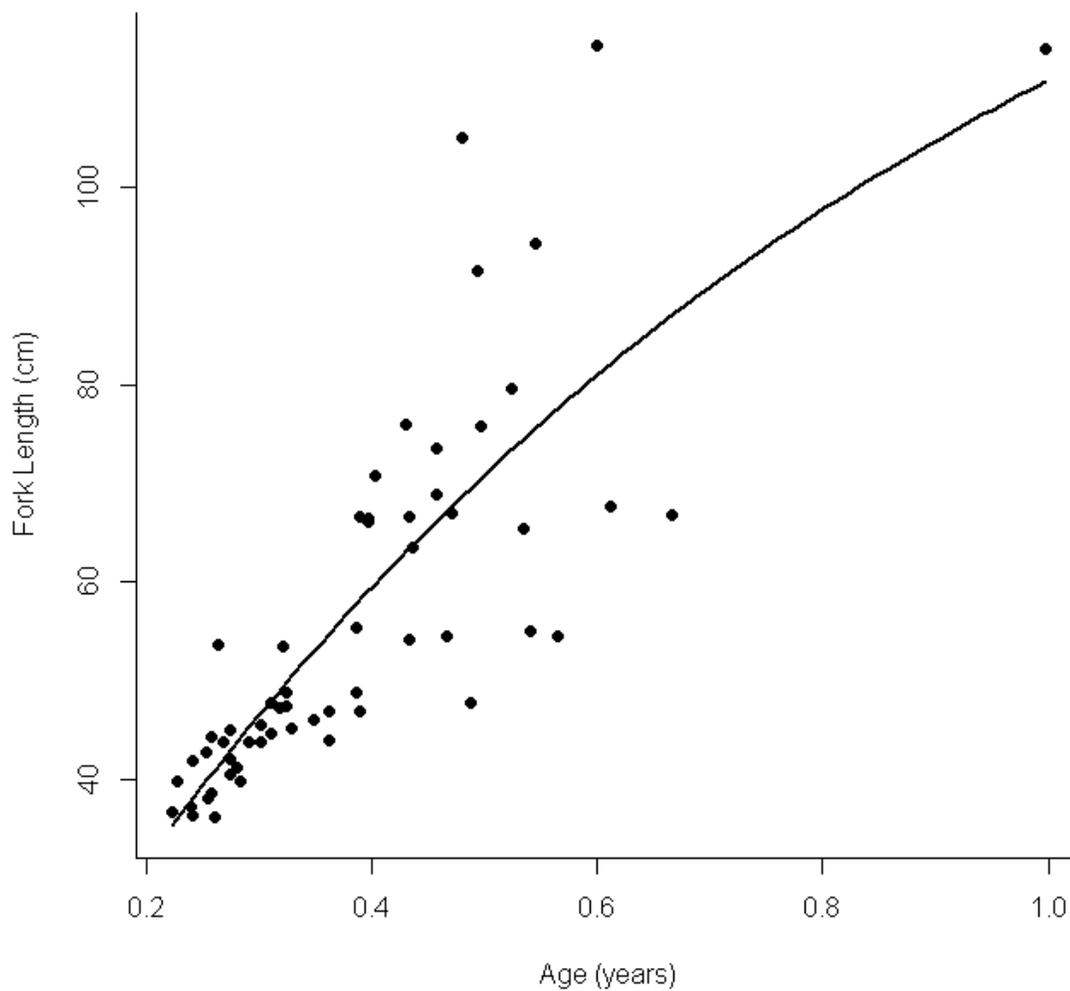


Figure 34. The von Bertalanffy growth parameters for female ( $N = 58$ ) Dolphinfish in the northwestern Gulf of Mexico are  $L_{\infty}$  (asymptotic length) = 157.06 cm FL,  $K$  (growth coefficient) =  $1.25 \text{ year}^{-1}$ , and  $t_0$  (time at length 0) = 0.018 yr ( $r^2 = 0.658$ ).

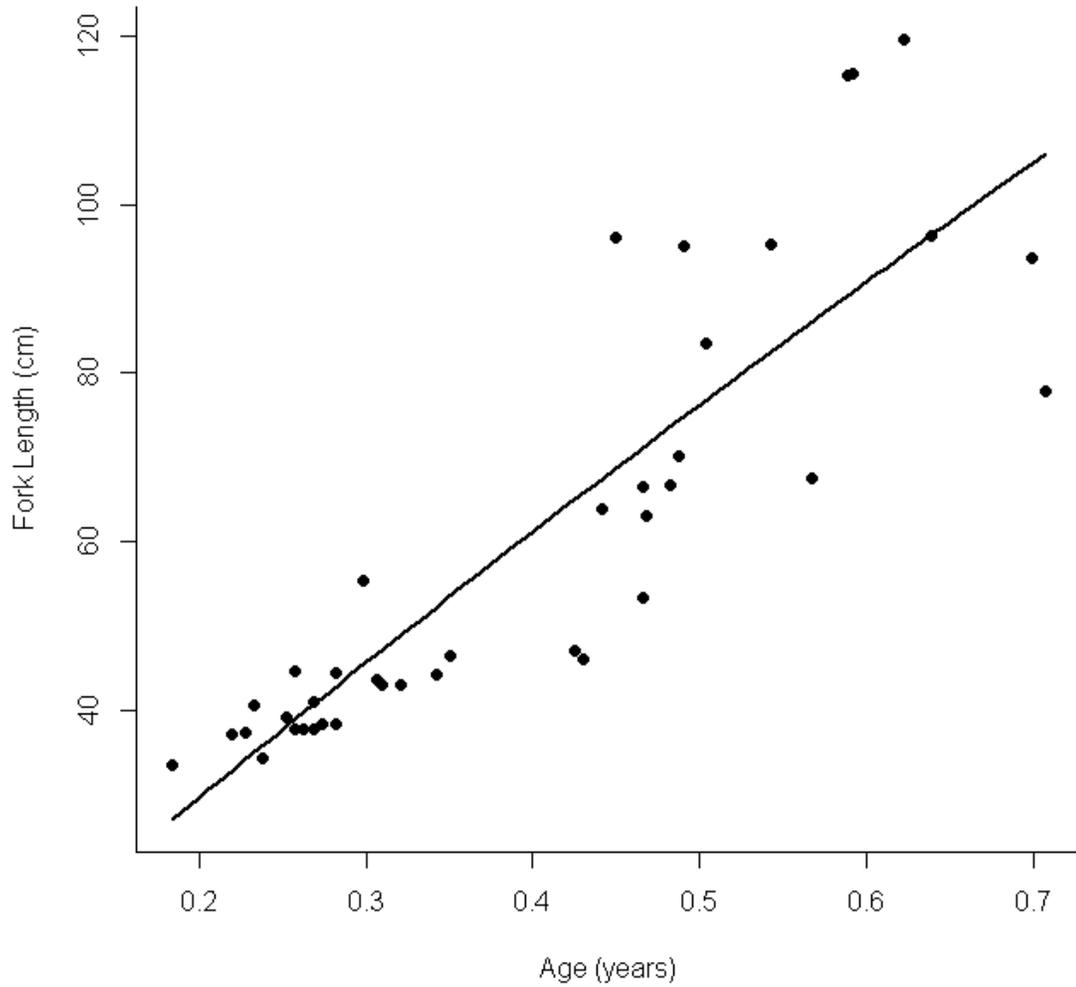


Figure 35. The von Bertalanffy growth parameters for male (N = 39) Dolphinfish in the northwestern Gulf of Mexico are  $L_{\infty}$  (asymptotic length) = 571.70 cm FL, K (growth coefficient) = 0.300 year<sup>-1</sup>, and  $t_0$  (time at length 0) = 0.022 yr ( $r^2 = 0.751$ ).



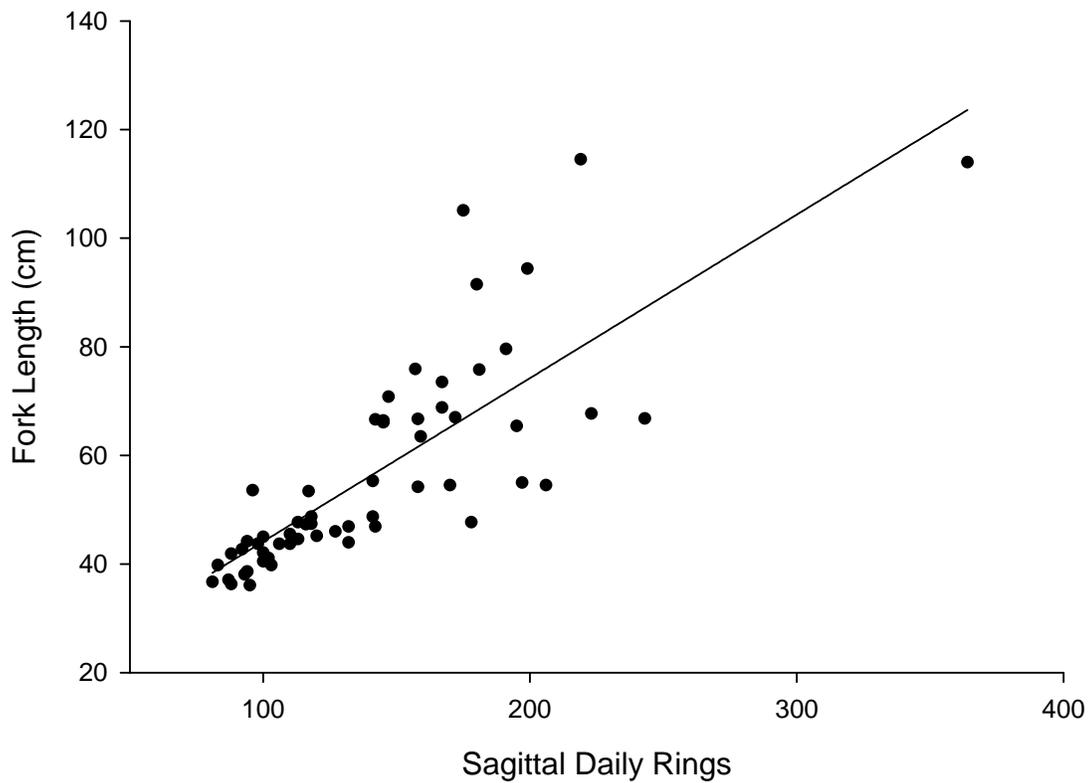


Figure 37. Sagittal daily rings to fork length (cm) relationship for female Dolphinfish ( $N = 58$ ;  $r^2 = 0.6434$ ) collected in the northwestern Gulf of Mexico. Female Dolphinfish are estimated to have a growth rate of  $3.01 \text{ mm FL day}^{-1}$ .

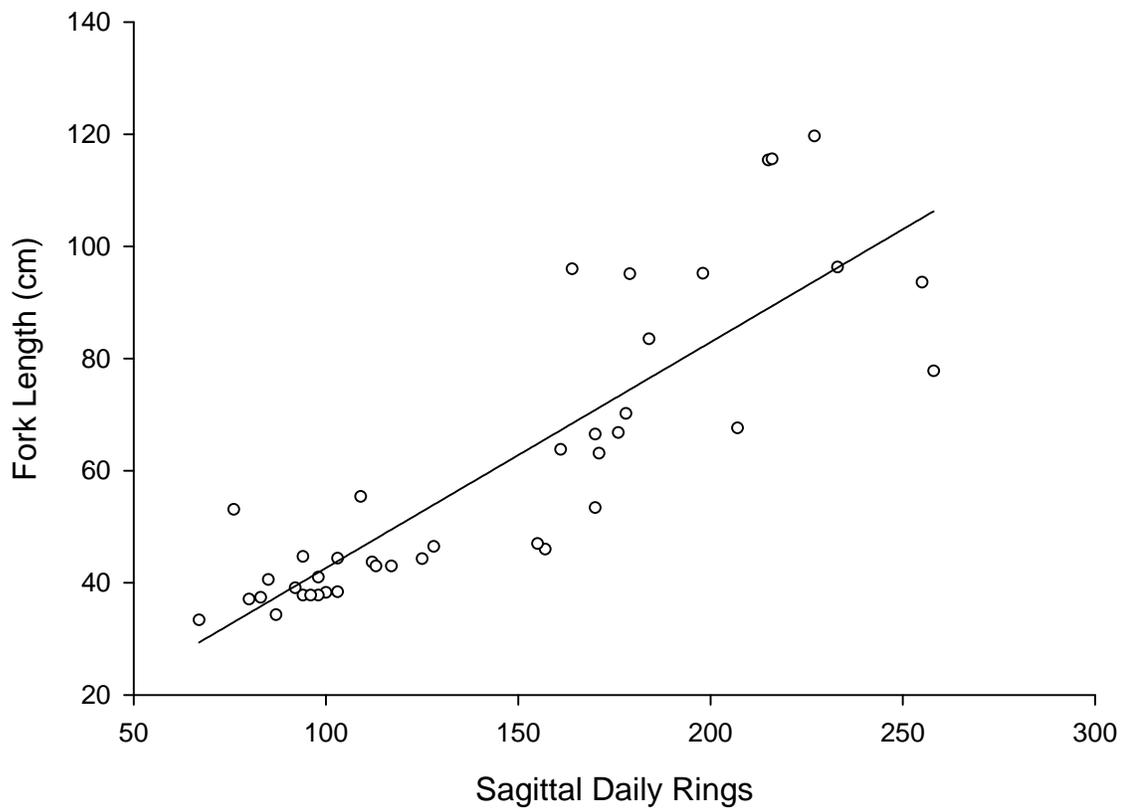


Figure 38. Sagittal daily rings to fork length (cm) relationship for male Dolphinfish ( $N = 40$ ;  $r^2 = 0.7335$ ) collected in the northwestern Gulf of Mexico. Male Dolphinfish were estimated to have a growth rate of  $4.03 \text{ mm FL day}^{-1}$ .

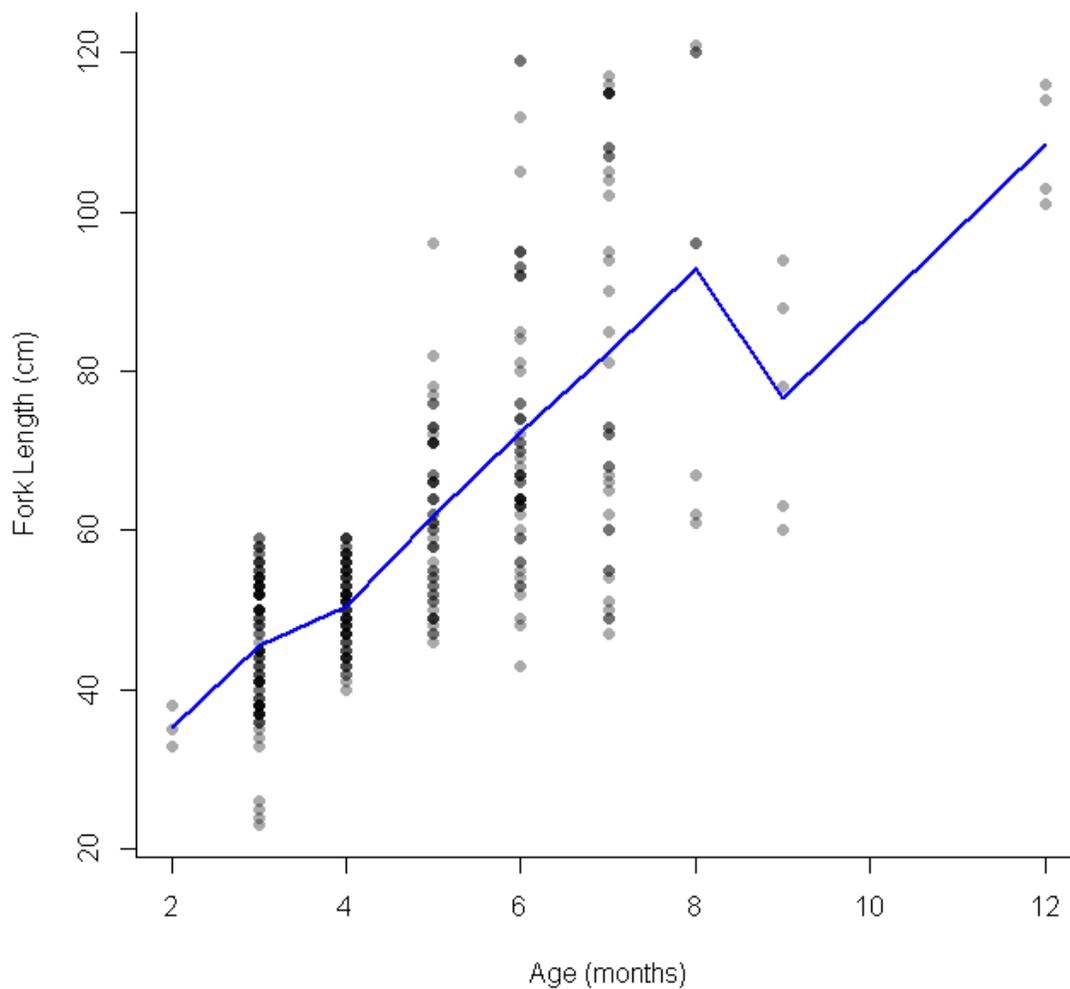


Figure 39. Plot of the estimated length at age key for Dolphinfish collected in the northwestern Gulf of Mexico. The blue line represents the average mean length at age for each length category.

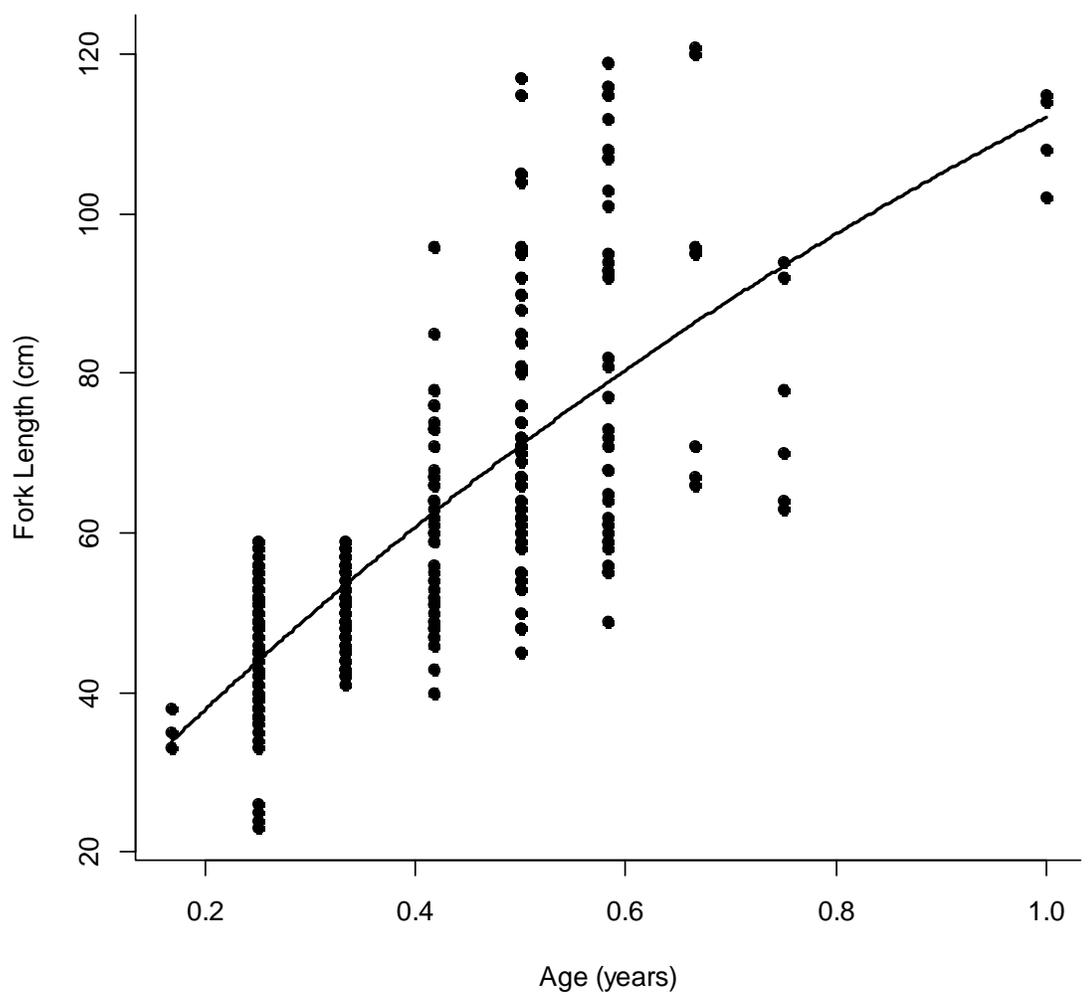


Figure 40. The von Bertalanffy growth parameters, based on age-length key, for combined male, female, and unknown sex Dolphin fish (N = 352) in the northwestern Gulf of Mexico are  $L_{\infty}$  (asymptotic length) = 202.94 cm FL, K (growth coefficient) = 0.746/yr, and  $t_0$  (time at length 0) = 0.076 yrs ( $r^2 = 0.550$ ).

## DISCUSSION

This study examined biological parameters of Dolphinfish in the northwestern Gulf of Mexico to generate an understanding of their growth and migration patterns. The rapid growth rate and early maturation of Dolphinfish confirm they are an r-selected-type species capable of withstanding a reasonable amount of exploitation (Adams 1980). The relationships between otolith parameters and somatic growth for Dolphinfish show that otolith parameters are highly correlated with somatic growth and are a valid method for estimating age. These results serve as a foundation for fisheries managers, researchers, interest groups, recreational anglers, and the general public to build a management strategy that serves the dual purpose of both enjoying and ultimately ensuring the survival of this unique fish.

### *Otolith parameters and somatic growth*

This study determined a strong correlation between otolith morphology and somatic growth in Dolphinfish in the Gulf of Mexico. Daily sagittal increment formations in Dolphinfish in the northwestern Gulf of Mexico appear to be periodic considering their correlation with somatic growth (Bentivoglio 1989; Massuti et al. 1999; Oxenford and Hunte 1983; Schwenke and Buckel 2008). The daily age estimates for Dolphinfish in the northwestern Gulf of Mexico are supported by the methods and findings of previous works, the correlation between ring estimates and somatic growth, and the correlations between otolith morphological measurements and somatic growth found in this study (Massuti et al. 1999; Oxenford and Hunte 1983; Secor et al. 1990). These findings provide baseline knowledge that can be used to generate more data by

estimating the age of Gulf of Mexico Dolphinfish using only fork length and carcass weight.

The findings of this study provide a means for age estimation using biological parameters alone, offering an important economic alternative for future generation of much needed data on Dolphinfish in the Gulf of Mexico. The determination of these parameters is a costly and labor intensive process requiring access to many technological resources. Obtaining accurate estimates for the otolith weights, radial and diameter measurements, and daily age required care and precision in technique as microscopic otoliths are extremely fragile and difficult to handle. Gloves had to be worn at all times to prevent skin oils from interfering with the otolith handling instruments and tare slide. The microbalance used to weigh the otoliths would not function without a dust cover to prevent any stray air flows or dust particles from interfering with the accuracy of the weights. Photographing and conducting morphological measurements of the sagittal otoliths required the use of costly and powerful microscopes fitted with digital cameras and computer software to run the programs. In contrast, collecting fork length measurements and carcass weights of Dolphinfish and using the regressions found in this study to estimate age is a relatively cheap process with much less overhead. Thus, the findings of this study are utilitarian because they can be used in the future to generate a broader base of knowledge for Dolphinfish in the Gulf of Mexico.

No annular rings were detected on the sagittal otoliths of Dolphinfish from the northwestern Gulf of Mexico, and at present no annular rings have ever been reported on Dolphinfish sagittal otoliths (Schwenke and Buckel 2008). The lack of annular rings on the sagittae of Dolphinfish is most likely due to their migratory nature but did not prevent

assignment of daily age. Dolphinfish spend the majority of their time in tropical and subtropical waters with more stable environmental parameters, as compared to temperate species. As poikilotherms migrating within water masses that typically do not drop below 20°C, it is likely that the rate of somatic growth for Dolphinfish would remain more stable relative to their surrounding environment and thus no annular increment formation. Data retrieved from satellite tagging studies on Dolphinfish reported a thermal range of 16.2 °C-30.87 °C, and the reported average temperature was 27.34 °C among four Dolphinfish fitted with satellite tags, where two were tagged off the Florida coast, one off the coast of South Carolina, and one from the Yucatan straight (Hammond 2008). This is also supported by findings from studies conducted on captive Dolphinfish in North Carolina where Dolphinfish tolerated temperatures from 15 °C to 29 °C but would stop feeding at 18 °C (Hassler and Hogarth 1977). In fish of temperate climates, seasonal changes in salinity, temperature, and food sources have been shown to affect the rate of daily incremental otolith deposition leading to the formation of opaque and translucent zones which are interpreted as annuli (Brothers et al. 1976; Jones 1993; Secor and Dean 1989; Wright et al. 2002). The notion of Dolphinfish migrating within warmer water bodies is further supported by the historical seasonal abundance of Dolphinfish in the northwestern Gulf of Mexico. Anecdotal evidence and observations made during this study indicate that during the winter months Dolphinfish are typically only encountered in the deeper warmer waters off the continental shelf. As these warmer waters are pushed coastward by seasonal winds and currents in the spring and summer the Dolphinfish were encountered as close as 19 km from land. The lack of annular rings on Dolphinfish

sagittae is likely due to their migratory nature within water bodies with fewer environmental fluctuations.

No large scale incremental formations were observed in Dolphinfish sagittae, however, small scale periodic groupings of incremental formations were observed in sagittal otoliths from Dolphinfish collected in the northwestern Gulf of Mexico. The observed smaller scale periodic incremental formations appeared as alternating translucent and opaque zones comprised of between 7-30 daily increments. These observed changes in otolith deposition rates have been attributed to lunar growth rhythms in studies where similar periodic incremental formations were observed in Dolphinfish sagittae (Massuti et al. 1999). Although the effects of lunar phase on virtually every organism on this planet have been widely speculated upon since Aristotle, the coupling of lunar phase with Dolphinfish otolith increment formation is not overtly clear (Hagman et al. 1998). While it is well known that lunar phase exerts an effect on global ocean tides, the linkages between lunar affect on tides, ocean currents and Dolphinfish behavior are also unknown. One potential explanation for the link between lunar phase and patterns of otolith increment formation could be a lunar driven shift in Dolphinfish behavior in relation to prey availability. Satellite tag data analyzed by lunar phase for two Dolphinfish in the western Central Atlantic suggested that Dolphinfish shift vertically from surface to at-depth feeding strategies to prey upon aggregating epipelagic and mesopelagic prey, diving at different average depths between full and new moons (Merten et al. 2014c). Diving in response to lunar periodicity has been shown in other pelagic species, particularly white marlin. Forty seven white marlin fitted with satellite tags in the North Atlantic illustrated deeper dives in correlation with brighter moon

phases and the authors speculated that the fish were using the increased light to get below their prey, a behavior known as silhouetting (Horodysky et al. 2007). More research is needed to directly link diving behaviors in response to lunar phase and somatic growth, however lunar phase has been shown to affect Galapagos fur seal body mass and, diving and foraging behavior where the seals were shown to dive deeper during the full moon than during the new moon, incurring body mass losses and suggesting a reduction in foraging efficiency (Horning and Trillmich 1999). Although the results of satellite tagging studies are intriguing and Dolphinfish have been recorded as diving as deep as 123 meters, it is apparent that the findings of these studies are limited by the cost of the satellite tag technology, the fact that the size of the satellite tags restricting researchers to studying only the largest of Dolphinfish, and the fact that larger Dolphinfish are extremely difficult work with (Hammond 2008).

The correlation coefficients from the relationships between Dolphinfish somatic growth and otolith parameters exhibit differences inherent to both otolith variability and to the methods of measure of each parameter. The highest correlation coefficient was found between fork length and sagittal otolith weights, while the lowest correlation coefficient was found between fork length and daily ring counts. When weighing a sagittal otolith, one is quantifying the amount of otolith material on the scale, regardless of shape or structure, the weight of an otolith is uncoupled from the shape of the actual otolith. In contrast when examining an otolith to count daily sagittal rings, one is attempting to both qualify and quantify the otolith material under the scope. To further understand the difference between otolith weights, morphological measurements, and ring counts, we must consider the structure of the otolith.

Otolith formations and growth depositions are three dimensional in their nature and crystalline in their structure (Secor et al. 1990). While most Dolphinfish otoliths have relatively similar shapes, there appears to be variation in both the overall structure of each individual otolith, and the manner in which each otolith grows. These overall shape differences among individuals are so pronounced that the use of image analysis and multishape descriptors have been combined with DNA analysis to successfully discriminate separate Dolphinfish stocks off the coast of Brazil (Duarte-Neto et al. 2008). Cycling through various fine focuses under a high power microscope, a Dolphinfish otolith takes on the appearance of a monolith. Some Dolphinfish otoliths appear to grow outward in a flat and even manner while some otoliths have many more rises and drops. A few otoliths had no consecutive ring structure, and had the formative appearance of knotted burl that is highly prized in trees. One major consequence of these differences in otolith appearance is that they make the daily ring counting of some otoliths more difficult, if not impossible.

The notion of inherent variability in otolith shape is also supported by the fact that the rostrum radial measurement had the lowest correlation coefficient with somatic growth, of the linear otolith measurements taken. The rostrum and antirostrum measurements were able to explain more variation because the measurements taken from the anterior to the posterior end of the otolith are more encompassing of the total otolith shape. The rostrum radial measurement, restricted to measuring from the primordium to the anterior end of the rostrum, is less encompassing of the overall otolith shape, and therefore explains less of the inherent variation. The higher correlation coefficient shown between sagittal otolith weight and fork length within the same dataset is indicative of a

strong relationship between otolith morphology, and somatic growth in Dolphinfish. There is potential for a higher correlation coefficient to be discovered between somatic growth and daily sagittal otolith rings. One way to possibly accomplish this would be to develop a successful method for preparing the microscopic otoliths for transverse cross sectioning using a specialized isomet low speed saw fitted with a microscope, as was done by Schwenke and Buckel (2008).

An additional factor in explaining the difference between weighing sagittal otolith weights and ring counts is that the ring counting process itself is conducted by the human eye and is therefore more subject to human bias versus the use of a precision scale. As the formation of an individual otolith is unique, the use of automated technology is limited in its application and judgment calls are often needed to interpret otolith increments (Secor et al. 1990). When counting daily otolith increments, the easiest path from the primordium to the outer margin often requires the use of reference rings (Oxenford and Hunte 1983). A reference ring is where the reader counts the increments in one clearly defined section of the otolith and then follows a single reference ring around the otolith to resume counting in another clearly defined portion of the otolith. In addition to precision in technique, additional steps must be taken to reduce both inherent and introduced reader bias (Secor et al. 1990). One method used in this study to reduce bias was to use microscopic cameras to capture digital images for analysis. This allows the otolith image to be “frozen in time” for more accurate ring counts when obtaining multiple readings over time, as otoliths are known to degrade in immersion oil (Secor et al. 1990). The use of digital otolith images also aided in reduction of reader bias by allowing multiple blind reading counts to be conducted on the exact same images. This

reduced reader bias as changes in focus and light have been shown to change the appearance of and therefore the interpretation of daily ring estimates (Secor et al. 1990).

In conclusion, this study determined a strong correlation between otolith formation and somatic growth. The daily age estimates for Dolphinfish in the northwestern Gulf of Mexico are supported by the methods and findings of previous works, the correlation between ring estimates and somatic growth, and the correlations between otolith morphological measurements and somatic growth. The findings of this study provide a baseline of knowledge contributing to the future generation of data on Dolphinfish in the Gulf of Mexico.

*Growth rates, von Bertalanffy coefficients, and length at age*

The findings of this study show that Dolphinfish in Gulf of Mexico grow at a very fast rate. An overall estimated growth rate of  $3.54 \text{ mm FL day}^{-1}$  for Dolphinfish of the northwestern Gulf of Mexico is similar to the overall estimated growth rate of  $3.78 \text{ mm FL day}^{-1}$ , for Dolphinfish off the coast of North Carolina (Schwenke and Buckel 2008). The similar growth rates support the methodologies used in this study to estimate the daily age of Dolphinfish and suggest the possibility of similar stocks. Linear regression as a method to estimate growth rate for Dolphinfish is useful because it is a simple way to illustrate the average amount of growth per day needed for a specific age Dolphinfish to reach their measured length. One limitation in using linear regression to estimate growth rate is that linear regression, by calculation, assumes a constant growth rate for the life of the fish. The growth of fish is not assumed to be constant over time and growth has been shown to slow as fish approach an estimated maximum mean length (Pauly 1978). Fish approaching a maximum mean length over time is addressed by estimating the von

Bertalanffy growth parameter:  $L_{\infty}$  or asymptotic length. The estimated asymptotic mean fork length of 207 cm for Dolphinfish in the northwestern Gulf of Mexico is closest to the mean asymptotic fork length of 194 cm, estimated for Dolphinfish collected offshore of Alabama and Florida, and for Dolphinfish off the Pacific coast of Columbia and Panama (Bentivoglio 1989; Lasso and Zapata 1999). The explanations in the literature for comparing differences in estimated von Bertalanffy parameters between studies vary. Geographic region is considered an important factor influencing the von Bertalanffy parameter estimates. The results from this study and others show that Dolphinfish from the Caribbean and Gulf of Mexico typically have higher asymptotic fork lengths and growth coefficients, as compared to Dolphinfish from Florida and North Carolina (Chang and Maunder 2012; Oxenford 1999). Explanations other than region must exist, as the highest reported asymptotic fork length was 236 cm for Dolphinfish in St. Lucia, while one of the lowest reported asymptotic fork lengths was 132 cm for Dolphinfish in Barbados, only 175 km away, and over 5 times closer than the distance between Port Aransas and Dauphin Island, Alabama (Oxenford 1999).

Methods and source of aging material i.e. otoliths, scales, vertebrae, or length are another determinant for discrepancies between von Bertalanffy parameters (Chang and Maunder 2012). The observed disparity in coefficient estimates between methods is not surprising given that the oldest fish found in this study was estimated at 1 year old while aging studies using scales have estimated Dolphinfish to be as old as 4 years (Beardsley 1967). Previous Dolphinfish studies using otoliths to estimate daily age consistently reported higher growth coefficient estimates while studies using scales to estimate annual ages consistently reported lower growth coefficient estimates (Chang and Maunder 2012;

Schwenke and Buckel 2008). But the estimated growth coefficient of  $0.92 \text{ year}^{-1}$  seen in this study is relatively low compared to the findings of 42 previous studies that reported growth coefficients ranging from  $0.17\text{-}9.94 \text{ year}^{-1}$  (Chang and Maunder 2012). In examination of multiple Dolphinfish studies, there has been a clear and decided call to conformity in regard to aging method and materials of Dolphinfish. While many studies have ascertained that scales provide the best estimate of annual age in Dolphinfish, the fact remains that the use of scales has never been adequately validated. More confounding is the rationale for the formulation of a winter annulus on a scale is purported to be caused by a reduction in growth associated with a seasonal drop in water temperature in the Gulf Stream. This is problematic because by that rationale, a dramatic change in growth rate would likely lead to the formation of an annulus in the otoliths as well, given the well established relationship between otoliths and somatic growth.

In the von Bertalanffy equation, the estimated asymptotic mean and the growth coefficient are negatively correlated and restrictions in age ranges and sample size have been shown to increase the estimate of the asymptotic mean while decreasing the estimate of the growth coefficient. Fewer representatives of older fish in the length categories for the non-linear models in this study may have influenced the estimation of the von Bertalanffy growth coefficients. The difficulties in collecting and aging older, larger fish have been well established. Fish abundance decreases with age, and growth tends to slow as fish approach the estimated asymptote creating difficulties in aging older fish as rings in otoliths and scales grow increasingly closer together. By re-estimating the von Bertalanffy growth coefficients using the mean length at age key, this effect was exaggerated, explaining the slight increase in re-estimated asymptotic mean and resulting

decrease in the re-estimated growth coefficient. Small sample size with restrictions in age range might also explain the unrealistically high estimated asymptotic mean for male Dolphinfish in this study. The lower numbers of older fish in the larger length categories are also evident in the mean length at age line as it dips down at around 9 months and 90 cm (Figure 39). Because of their fast growth rate, many Dolphinfish attained greater lengths than 90 cm at a younger age, but because of a decreased number of older fish in the larger ages, the resulting mean length at age line drops down at 90 cm instead of leveling off or continuing up. This change in mean length at age may be due to the fewer numbers of older fish in the sample, although another plausible biological explanation could be the presence of more than one stock within the sample. Stock differences yielding fish of different growth rates within the same sample have been suggested in previous studies, but the analysis needed to support this idea is not within the scope of this study (Betancourt 1994; Oxenford and Hunte 1986). As the Dolphinfish in this study were collected over a wide range of dates, another plausible biological explanation could be seasonality, incurring slight differences in water temperature or food abundance. The mean fork length of 60 cm for Dolphinfish collected in this study suggests an overall decrease in abundance of older and larger Dolphinfish, and is most likely the leading explanation for the lower numbers of older fish. In conclusion, the growth rates estimated for Dolphinfish in the Gulf of Mexico are well within the expected estimates as compared to similar studies. Further the reasonable growth rate estimates for Dolphinfish found in this study support the methods and materials used to estimate the ages of Dolphinfish in the Gulf of Mexico.

### *Age and length at maturity*

Dolphinfish in the northwestern Gulf of Mexico quickly reach maturity where 50% of the Dolphinfish in this study were mature at 44.88 cm FL, or by the estimated age of just 112 days. Similar to Dolphinfish off the coast of North Carolina, female Dolphinfish reach maturity at a smaller size than that of male Dolphinfish (Schwenke and Buckel 2008). Rapid maturity of female Dolphinfish is explained by natural selection favoring females who can reproduce as quickly as possible in a less stable environment (Moyle and Cech). As Dolphinfish are a known food source for a variety of predators, natural selection would favor also favor rapid growth to escape predation.

### *Tagging summary*

Although limited to just two tag returns, the findings of the tagging portion of this study indicate that Dolphinfish of the northwestern Gulf of Mexico are a highly migratory species capable of traveling 5 kilometers per day. By comparison, from 2002-2011 Dolphinfish of the SC tagging project showed average travel rates from as low as 4.32 km/day within the South Atlantic Bight to average travel rates as high as 44.67 km/day migrating from Florida to the South Atlantic Bight (Merten et al. 2014a). There are several inferences that may be drawn from the comparison of these two tagging efforts. First, while the efforts of 17 boats tagging a total of 261 Dolphinfish in a single season are commendable, these numbers are not anywhere close to the number of fish needed to produce viable migration study results for this species. The SC tagging project reports a 2.2% rate of return on tags over a ten year period. This means that the SC tagging project participants tagged at least 13,909 Dolphinfish over a ten year period, averaging 1390 tagged fish per season, for ten years. Second, in comparing the numbers of these two tagging efforts, the fact that this study showed any tag returns in only one

year of tagging is fortunate but a tag return rate of 2% should have yielded at least 5 returns instead of just 2.

Considering that 99.3% of the tagged fish from this study were never recovered suggests the possibility of a complex migratory pattern. Perhaps the best explanation for understanding the difference between tagging Dolphinfinch in the northwestern Gulf of Mexico and tagging Dolphinfinch off the east coast is the shape of the coastlines involved and their interaction with the Gulf Stream. The Gulf of Mexico is considered a shallow sea while the east coast is an abrupt drop off along the edge of the Atlantic Ocean. During the Dolphinfinch season on the east coast, the Gulf Stream flows mainly northward along the coast and many tagging participants all along the coast simply run to the edge of the Gulf Stream and fish for pelagic species, such as dolphin. The affects of the Gulf Stream on the waters of the northwest Gulf of Mexico are much less straightforward. During the Dolphinfinch season in the northwestern Gulf of Mexico, counter-clockwise meanders break off from the loop current in the central Gulf of Mexico where they eventually spin off and die (Huang and Hsueh 2001; Walker 2009). The biological effects of these loop current meanders or frontal eddies are somewhat understood as the edges of these eddies are known as induce upwelling and serve as an important driver of biological activity in the northwestern Gulf of Mexico (Richards et al. 1993). The majority of the disparity between these two tagging studies can be explained by the unpredictable nature of the loop current eddies and their potential effect on Dolphinfinch migration. Dolphinfinch tagged along the coast of Florida have been shown to migrate northward, along the east coast as far north as New York. Dolphinfinch tagged off the coast of Texas may migrate eastward, as seen in this study, but at some point they may be

expected to encounter a frontal eddy that could potentially drive them offshore, away from the coast. In summary, tagged Dolphinfinh are migrating in the Gulf Stream in a relatively straightforward manner along a well populated coastline with higher chances of recapture. Tagged Dolphinfinh in the northwestern Gulf of Mexico are migrating in waters with a less sparsely populated coastline within a highly variable, circular current system that is affected by frontal eddies likely to drive them away from the coastline thus lessening their odds of recapture before their life span has expired. One way to overcome these factors would be to use satellite tags in Dolphinfinh to get a better idea of the overall direction of migration of Dolphinfinh in the Gulf of Mexico and build a tag and recapture study based on these findings.

The mean total length of 63.91 cm for tagged Dolphinfinh in the Gulf of Mexico, as reported by recreational anglers is lower than the mean total length of 72.22 cm for Dolphinfinh collected for age and growth portion of this study. One explanation for this difference may be the fact that the participants in the tagging study were selecting smaller Dolphinfinh for release while retaining the larger Dolphinfinh for consumption. Another explanation could be that the self-reported data provided by the recreational anglers was inaccurate. While using recreational anglers for participation in scientific study is excellent for generating a base of support for the study, the results of such findings must be viewed with caution. One issue is that recreational anglers are not properly trained in the best method of measure. Further, by incorporating more individuals into a method of measure, there is the possibility of incorporating more individual bias with the addition of each individual. Another plausible issue is the possibility that some recreational anglers may forgo measuring altogether and simply generate information simply to qualify for

the incentive. Finally, it may be that some recreational anglers simply don't realize the importance of their individual contributions may have on the study. An exact location was not reported by the angler for the recapture of the two Dolphinfish. The angler knew enough to call in the tags, but did not realize at the time the importance of writing down the exact location of the recaptures. Not all of this falls onto the angler however, as even more public outreach could have possibly prevented this situation whereby the angler would have already known about the study, prior to the recapture event. In conclusion, the benefits of using recreational anglers to participate in scientific tag and recapture studies far outweigh the drawbacks in the amount of participants, the potential for increasing the number of tags and therefore tag returns and in the overall generation of public support for the project.

#### *Recreational anglers and civic science*

One of the secondary goals of this study was to demonstrate the utility of recreational anglers for participation in a scientific study. Specifically, to gather as much data as possible and to generate a public base of support for this project, I wanted to utilize the recreational sector for participation in the tagging portion of this study. The first major challenge that arises when recruiting the general public for participation in a scientific study is addressing the dogma that marine fisheries studies automatically lead to increased regulations for the recreational angler. Over the course of this study, this singular belief and general mistrust of the scientific community often arose when recruiting anglers for participation. As a member of both the scientific community and sportfishing community, I wanted to address this issue directly and help resolve this conflict for this study and future studies. In personal conversations with numerous

captains and boat owners, I felt it was important to listen to and acknowledge the concerns of the recreational anglers while at the same time offering them an insight on the role of scientific studies in species management and conservation. In general, I would assert that while it may be true that most fisheries regulations are typically based on information obtained from scientific studies, it is also likely that without such regulations the fisheries resource that we currently enjoy would be severely depleted, at best. Moreover, I would contend that regulation without adequate information is likely the leading cause of mistrust in the scientific process among anglers. At this point, I would emphasize the opportunity given to recreational anglers to participate in such a study whereby their own contributions would ultimately lead to a broader base of knowledge about Dolphinfish and ultimately conservation of this important species. With this level of understanding, the recruited angler is likely to have a more vested interest in participation in the project.

In recruiting the general public for participation in a scientific study the first step is to disseminate information about the study in a presentable and attractive format. Equally important is attracting a large number of participants in an ethical manner. Following the format used by the SC tagging project which capitalizes on the competitive nature of recreational anglers, the HRI, The Center for Sportfish Research and I hosted a Dolphinfish tagging contest (Hammond 2006). As incentive, prizes and t-shirts were awarded to boats and participants as well as those who successfully measured and tagged the most Dolphinfish. Since participation in this study was open to the public, I wanted to make information about the study, the results and participants as accessible and unambiguous as possible while also providing a platform to launch the tagging contest.

Using this website as a link on the main Fisheries and Ocean Health page I was able to create a webpage that would inform potential recruits about my study as well as provide them with information about this study and Dolphinfish in general. I was also able to post specific instructions with photos on how to properly handle, tag, collect data and release healthy Dolphinfish. Additionally, the website served as an optional platform for reporting tag and recapture data as well as thanking the numerous sponsors and participants involved in the study and tagging contest. Building the website before engaging the general public became a crucial part of the recruiting portion of the project as the website served as a platform for delivering information that was available to the target audience 24 hours a day. It was also helpful when engaging the general public to have the website as a platform to direct people to learn more information about the project at their leisure. Additional recruiting for the tagging study was conducted in Port Aransas by going dock to dock, and engaging previous and new contacts, informing them of the study and recruiting them for the project. As information spread, momentum began to build and people began to call and email me directly wanting to know how to get involved in the project.

#### *Conclusions, management implications, and future studies*

In conclusion, I have examined biological parameters of Dolphinfish in the northwestern Gulf of Mexico and generated baseline information toward an understanding of their life history strategy. I have shown that the rapid growth rate and early maturation of Dolphinfish may indicate their ability to withstand a reasonable amount of exploitation. There was a clear relationship between otolith parameters and somatic growth and I demonstrated that otolith parameters are highly correlated with

somatic growth and that otolith rings counts are a valid method for estimating age. The findings of my study are intended for fisheries managers, researchers, interest groups, recreational anglers, and the general public to build a management strategy that serves the dual purpose of both enjoying and ultimately ensuring the survival of this unique fish.

The findings of this study impose three major management implications: the r-selected-type life history strategy of Dolphinfish makes them less susceptible to overexploitation, the highly migratory nature of Dolphinfish require regional management strategies, and that the incorporation of recreational angler participation in this study is a clear advantage. The first implication shown by this study is that the fast growth rate and early maturation rate of Dolphinfish in the northwestern Gulf of Mexico make them less susceptible to overfishing by hook and line technique. However, declaring a species as resistant to exploitation should be viewed with caution. While their migratory nature and serial spawning strategy make Dolphinfish highly resilient, the rapidly growing recreational sector combined with the technological advancements in marine electronics and transducers, increased access to satellite imagery, and the development of bigger faster boats with more range will only continue to apply pressure to this fishery. While it is unlikely that hook and line technique alone could severely deplete the Dolphinfish population, it is certainly plausible that hook and line technique combined with an environmental disaster could damage a resilient population. For this reason, more data is needed regarding estimates of abundance and migration patterns so that the population can be properly monitored.

Effective management of a migratory species with unknown range is difficult and will require the adoption of regional management techniques. This difficulty is perhaps

one of the reasons why Dolphinfish are not currently under federal regulation and why the Fisheries Management Plans that include the Gulf of Mexico do not include Dolphinfish. Management of a species is also impossible without adequate data. Using the multiple regression model developed in this study, a relationships between fork length and/or carcass weight could be used estimated the age of thousands of Dolphinfish along the Texas coast. Estimating the age of a large number of Dolphinfish carcasses at the docks over a number of years would potentially provide the necessary data for estimating relative abundances, fishing mortality estimates, and other general information needed to form a management strategy for Dolphinfish in the northwestern Gulf of Mexico. Generating data for all major sectors of the Gulf, including international sectors would be the first step in adopting a regional management strategy. With the necessary data, Dolphinfish regional management could ultimately be addressed by incorporating their management in the International Commission for the Conservation of Atlantic Tuna (ICCAT) policies.

The final management implication of this study involves the advantage in incorporating recreational anglers into the realm of fisheries science. As shown by this study, generating a broad base of support for evaluating the population a public resource is not overly difficult provided there is some measure of persistence and incentive. Stake holder buy in and public participation will become increasingly important in the realm of fisheries science in the future as increasing population levels will continue to put more pressure on fisheries resources. Public buy in is especially important in resource management because the resources are considered public. Or, as one author wrote: “In the wake of the declining public trust in scientific expertise, civic science has been

advanced as a solution to reverse the growing public distrust in science” (Bäckstrand 2003).

In conclusion, there is clear need for future studies to provide answers to the many lingering questions than answers about Dolphinfish. Given their range and rate of migration, perhaps the biggest question concerning Dolphinfish is discerning stock structure to establish connectivity. This will allow science to answer questions such as, are Dolphinfish of the northwestern Gulf of Mexico more related to Dolphinfish found off the Yucatan, or Puerto Rico, or Florida, or are they a separate stock? Or are all the Dolphinfish in the Atlantic one intermingled stock? As the cost of DNA analysis goes down, and satellite tag technology improves surely it is only a matter of time before the fiscal burdens of this question are outweighed by the need to know the answer. Future studies incorporating the general public, satellite tagging data, DNA analysis, scale validation, and standardized age estimation techniques would provide the data necessary for the formation of a comprehensive regional management strategy needed to ensure the survival of this important and unique species.

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