Sex and Length as Predictors of Vertical Movements in Smalltooth Sawfish (Pristis pectinata)

by Taylor Mogavero

Abstract: Smalltooth sawfish (*Pristis pectinata*) are a marine species of high concern since they are listed as critically endangered species by the International Union for Conservation of Nature (IUCN) and listed as endangered under the U.S. Endangered Species Act (ESA). Smalltooth sawfish are extremely vulnerable to being caught as bycatch due to their long, toothed rostrum that can easily become entangled in fishing nets, especially in shrimp trawling fisheries. Several studies have been conducted on smalltooth sawfish since being listed under the ESA in 2003, but their vertical movements and use of depth have still not been thoroughly studied. Until recently, sawfish were thought to stay at a depth of 10 m or less, but studies have now shown that they occupy much deeper depths. Due to these conflicting findings in the literature, depth was chosen to be the focus of this study. Furthermore, this study investigates whether sex or individual total length has an influence on the percentage of time a sawfish spends at a particular depth. Satellite telemetry was used to track the movements of the tagged sawfish (n=14). The data collected from the pop-off archiving satellite tags (PSATs) showed smalltooth sawfish spend most of their time in shallow water (between 0-8 m), but do frequently occupy deeper depths. Sex was found to be a significant factor, while total length was not. Females were found to spend more time at deeper depths than males. Understanding how sawfish use depth is important in order to predict population trends and dynamics. Knowing the factors that affect a sawfish's depth use would be beneficial to efforts that manage and conserve this species. With the decline of smalltooth sawfish and their vulnerability to population loss, more research needs to be conducted to create more effective management and recovery plans.

Introduction

Sawfish are large rays in the Chondrichthyes class and are known for their long, toothed "saw" or rostrum (Harrison & Dulvy, 2014). Their rostrum is an elongated snout with horizontal rostral teeth that is used for feeding and defense (Poulakis & Seitz, 2004; Whitty et al., 2009). About 20-28% of a sawfish's body length comes from its rostrum, and it serves a vital role for capturing and detecting prey (Harrison & Dulvy 2014). The rostrum is able to find and catch prey due to extensive sensory organs that detect minute electrical signals emitted by other animals. A sawfish can also use its rostrum to stunt or kill fish by slashing its toothed side into its prey (Harrison & Dulvy, 2014). The species live in coastal tropical and subtropical waters in both estuaries and freshwater. They can be found across the world, but the only sawfish species currently found in the U.S. is the smalltooth sawfish (*Pristis pectinata*).

The average size at birth for a smalltooth sawfish is 80 cm total length (TL). The size at maturity is 370 cm TL for females and 340 cm TL for males (Brame et al., 2019). Their age of maturity is estimated to be 7-11 years for males and females (Carlson & Simpfendorfer, 2015), with a total lifespan around 30 years. Smalltooth sawfish are yolk-sac viviparous, meaning young are nourished in utero by an external yolk sac and are then born live. It is presumed that their reproduction occurs biennially and their average litter size is 7-14 pups (Feldheim et al., 2017). Due to their long lifespans and late maturity, sawfish have a slow population growth rate, therefore increasing their vulnerability to and difficulty recovering from population loss.

Many of the areas where sawfish reside are highly threatened habitats such as mangroves or seagrasses, two habitats that have seen a great decline in range over the years. Their coastal preference also tends to overlap with large cities and areas of high human population density where more activities like fishing occur (Dulvy et al., 2016). The current geographical distribution of *P. pectinata* is mainly in the western Atlantic, but they have also been found in the eastern Atlantic (Harrison et al., 2014), and the largest population is found along the southwest coast of Florida (Poulakis & Seitz, 2004). Smalltooth sawfish were historically found along the coast of the United States as far north as the Carolinas, in the Gulf of Mexico, the Caribbean Sea, and along the coast as far south as Uruguay (Carlson et al., 2014; Dulvy et al., 2016; Feldheim et al., 2017; Simpfendorfer, 2001; Wiley & Simpfendorfer, 2010). The smalltooth sawfish is currently found in less than 20% of its historic range (Dulvy et al., 2016). Now smalltooth sawfish are only consistently found in the coastal waters of southern Florida with a slow increase or stable population growth, and an estimated population size of only a few thousand (Carlson et al., 2014; Feldheim et al., 2017; Wiley & Simpfendorfer, 2010). Exact population reduction rates are hard to calculate due to limited scientific data, but it has been estimated that the population may have declined as much as 95% from the historic stock size (Wiley & Simpfendorfer, 2010).

Smalltooth sawfish tend to stay near or within mangroves and seagrass beds as juveniles (Dulvy et al., 2016; Wiley & Simpfendorfer, 2010). Sawfish are known to occupy shallow coastal waters typically 10 m deep or less (Carlson et al., 2014), but they can occupy depths deeper than 10 m and can be found at depths up to 122 m (Poulakis & Seitz, 2004). It has been postulated that smaller and immature sawfish are more commonly found in shallow water (Poulakis & Seitz, 2004; Wiley & Simpfendorfer, 2010; Whitty et al., 2009; Simpfendorfer, 2001). They also prefer warm water temperatures, mainly 22–28°C, and their lower thermal tolerance is predicted to be around 20°C (Carlson et al., 2014). Smalltooth sawfish often feed on schooling fish such as clupeids, carangids, mugilids, elopids, sparids, and belonids, as well as dasyatids stingrays (Poulakis et al., 2017). They obtain their prey by slashing their rostrum sideways through a school and impaling the fish on their rostral teeth. After caught, they ingest their prey whole. Most of their prey are coastal or estuarine species that are typically found at or near the surface.

There has been evidence for sexual segregation in elasmobranchs and sawfish may be included among those. Sexual segregation is the separation of males and females of the same species; this separation may be spatial as well as temporal in nature, for example, occurring only during the non-breeding season (Wearmouth & Sims, 2010). It is important to understand the habitat use of different sexes in order to predict population trends and dynamics. This would provide data that may be useful to the successful management and conservation of this species, as these spatial dynamics often overlap with area-focused human activities like fishing.

There has never been a large-scale fishery that directly targeted smalltooth sawfish, but it is very common for a sawfish to get entangled in fishing nets due to their long-toothed rostrum, and therefore they are often caught as bycatch. The main threat responsible for the decline in smalltooth sawfish has been and remains commercial and recreational fisheries. Shrimp trawl fisheries present a major concern due to the high bycatch mortality of large, mature sawfish, which could reduce the population's reproductive potential. Fortunately, sawfish are expected to suffer less and recover quicker when caught and released by longlines as opposed to trawls and gill nets (Brame et al., 2019).

Smalltooth sawfish are said to be one of the world's most vulnerable marine fishes (Dulvy et al., 2016; Feldheim et al., 2017). The United States population of smalltooth sawfish was listed as endangered under the U.S. Endangered Species Act in April 2003 (Poulakis & Seitz, 2004). Penalties such as imprisonment or steep fines could be given to anyone who harasses, harms, or kills any animal listed on the U.S. Endangered Species Act. Smalltooth sawfish are classified as critically endangered by the International Union for Conservation of Nature (IUCN). This is the highest level of alert—the closest to extinction—set by the IUCN and is defined by them as "a species facing an *extremely* high risk of extinction in the wild." The IUCN Red List states their population trend is still decreasing (Carlson et al., 2013).

Pop-off archiving satellite tags (PSATs) are a relatively new electronic tagging technology. PSATs detach from the tagged animal after a predetermined time, float to the surface, and transmit the archived data to satellites which provide the data to the researcher. This technology allows tracking the movements of pelagic fish in their natural environment to be much more accessible and economical. PSATs can sample temperature, depth, and light levels at user-defined time intervals, and then store and process these data (Luo et al., 2006). It has become more common to use PSATs to gather data on horizontal and vertical movements of pelagic fishes, especially since the vertical movement of PSAT-tagged fishes in sea water has a high degree of accuracy and precision (depth and temperature resolution are claimed to be 0.5 m and 0.05°C, respectively) (Luo et al., 2006).

Why we need to study and protect sawfish

The U.S. Endangered Species Act requires by law that critical habitat must be designated for any listed species. To date, critical habitat has only been designated for small juvenile smalltooth sawfish. Satellite tagging of sawfish adults was done for the following reasons: 1) to aid in defining critical habitat for adults and vertical space use; 2) to determine potential aggregation sites for mating and areas where males and females overlap in depth; and 3) to determine if the U.S. population is distinct from adjacent populations (e.g. Bahamas, Cuba) by determining if sawfish frequently traverse deep water (up to 800 m depths). With the decline of sawfish, more research needs to be conducted in order to create more effective status assessments, management measures, and recovery plans (Dulvy et al., 2016). Fishery management, where it does occur, focuses mostly on commercially valuable fish populations, so populations like sawfish are rarely the main concern. It is difficult to develop recovery strategies for species that do not have a sufficient amount of scientific data concerning their distribution and habitat use, especially if they are widely dispersed (Wiley & Simpfendorfer, 2010). More research must be conducted on sawfish so adequate recovery plans can be developed. The purpose of this study is to assess whether sex or length has an influence on the percent time a smalltooth sawfish spends at a particular depth. Conducting research on how sawfish use depth could help predict population trends and dynamics. Knowing the factors that affect a sawfish's depth would allow for the successful management and conservation of this species, so it is important that these factors are studied and considered.

Methods

Pop-off archival satellite tagging data was collected from 2011 to 2017 and forty-seven sawfish were tagged. The sawfish were caught using a research vessel and a bottom longline of 50 or 100 16/0 hooks baited with ladyfish, *Elops saurus*. Longline stations were selected based on being potential habitats suitable for smalltooth sawfish and historic encounter records. Tagging was conducted in the Florida Bay and the Florida Keys. Most of the sites had coordinates around 25°N 81°W (Figure 1). Satellite telemetry was used to track the movements of the tagged sawfish. Pop-off archiving satellite tags (PSATs), which record depth (m), temperature (°Celsius), time, and light levels, were attached externally to the sawfish first dorsal fin. Three different models of PSATs (all manufactured by Wildlife Computers, Inc.) were used: Mini-PAT, MK10, and PATF. Three different models of PSATs were used because multiple research institutions contributed to tagging the sawfish. The tags were programmed to detach from the animals after a certain number of days (depending on the tag type) and transmit the archived data to a satellite. The PSATs use light-based geolocation where the spatial track is based on the timing of local noon (used to estimate longitude) and day length (used to estimate latitude) and corrected for temperature (Luo et al., 2006). Depth data were collected every four hours. Each satellite tag or PTT (Platform Transmitting Terminal) was assigned a PTT number.

For this study, data was available for fourteen satellite tags (Wildlife Computers, Inc.), spanning a deployment period from March 2011 to March 2017. Six of the tags were MK10 tags (programmed for 150 days), five were PATF tags (tracked for 60 days), and three were Mini-PAT tags (programmed for 105 days).

Choosing viable data

The GPE2 program from Wildlife Computers was opened using iGOR Pro 6.37 software. The graphs that displayed viable data (daily depths measurements for at least a duration of two weeks) were chosen to examine further. Further examination was done by looking at the specific depth measures in the Excel sheets for each of those tags. Only depths with an error of 4 m or less were considered, since that was the most accurate reading recorded by any tag. Anything with a higher error than 4 m was considered to be inaccurate.

Used data

In total, forty-three satellite tags were inspected for data use. Only fourteen of those tags were analyzed due to some tags failing to report or record enough data to make it viable. Eight of these were males and six were females. Statistics for each analyzed sawfish can be seen in Table 1. Any negative minimum depths were regarded as 0 m (at the surface).

Creating histograms of percentage time-at-depth

All of the recorded depth measurements, with an error of 4 m or less, for an individual sawfish were considered. Depth bins were created in 8 m intervals (0-8, 9-16, 17-24, etc.), since the recorded data were expressed in increments of 8 m (0, 8, 16, 24, etc.). The percent of time each sawfish spent in each depth bin was calculated and made into a histogram in Excel.

Average maximum depth

Excel was used to calculate the average maximum depth of each sawfish. The average maximum depth of each day was found, then all of these calculations were averaged together.

Model choice

Akaike's Information Criteria (AIC) is a log-likelihood that penalizes any superfluous parameters in the model. AIC estimates the quality of each entered model, relative to each of the other models. AICc has small-sample correction. A low AIC value indicates the model is a good fit; the model with the lowest AIC is considered the best fit. If the delta AIC is lower than 2, it can be said to have substantial support. Various linear mixed-effects models were tested. The entered model that was the simplest was chosen by comparing AICc values to determine which model has a better fit. Due to the principle of parsimony, all the factors that did not cause a significant increase in deviance were removed from the model to form a minimal adequate model.

Linear mixed-effects model

R Statistical Computing (R Core Team, 2019) and lme4 (Bates, Maechler, Bolker & Walker, 2015) were used to perform a linear mixed effects analysis of the relationship between percent time and depth. A mixed-effects model was chosen because the data had both random and fixed effects due to temporal pseudoreplication resulting from repeated measurements on the same individuals. As the random effect, the sawfish PTT number was entered (without interaction term) into the model. Intercepts for depth and sex were fixed effects, as well as by-subject and by-item random slopes for the effect of depth. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality for sex. The function "lmer()" was used, as it allows for non-normal errors and non-constant variance with the same error as a generalized linear model.

Results

Histograms of percentage time-at-depth

The results of the histograms can be seen in Figure 2. These histograms showed the percentage of time a sawfish spent at a specific depth by analyzing all of the data recorded on that sawfish's tag. Every sawfish was seen at a depth of 0-8 m for the majority of the time; however, a few sawfish (14%) were recorded to go as deep as 88 m. Most tagged (n = 12) sawfish spent over 60% of their time at 0-8 m, but two sawfish (one male and one female) spent over 50% of their recorded time at depths deeper than the 0-8 m bin. As depth increases, there is no pattern of depth use. When a sawfish is found at a depth deeper than 8 m, there is not a favored depth, and their preference for a depth did not consistently decrease with increasing depth. Sex-dependent trends were apparent, however. All of the females spent time in at least six other depth bins, while half of the males solely spent time in 0-8 m.

Which sex has a greater maximum depth?

This t-test compared the average maximum depth each sawfish occupied each day, which shows the deepest depth a sawfish occupies on average. The average maximum depth occupied by males was 5.736 m (standard error = 2.475) and 22.61 m (standard error = 5.118) for females. An unpaired student t-test was performed and the two-tailed p-value equaled 0.0068, suggesting there was a significant difference between the means (t = 3.3985; df = 10 ; standard error of difference = 4.965).

Model choice

The lowest AICc value indicated the most parsimonious model, relative to the other model fits with a higher AICc value (best model: *lmer(Percent. Time ~ Depth + Sex + (1|Sawfish))*). The best model to explain the influence of percent of time at depth indicated sex was relevant, while length was not. The minimal adequate model showed a common slope for percent time against depth with two intercepts, one for each sex. The delta AICc of the best linear mixed-effects model was between 0-2 and therefore can be said to have substantial support.

Linear mixed-effects model

The variables that were tested were depth, length, and sex to address the following question: Does total length and/or sex have an effect on the percent-of-time a sawfish spent at a particular depth? Since length fell out of the model, it is not considered a significant factor. The percent time each sex stays at a specific depth is shown in Figure 3. In this figure, it is clear that sawfish spend more time at shallow depths, but definitely spend a considerable amount of time in deeper water. Due to the model choice conducted with AICc, both the male and female isoclines were given the same slope. Males spend a much greater time at shallower depths than females. This is consistent with the average maximum depth t-test results that show females have a significantly deeper average depth than males. This shows that females are expected to be found at deeper depths than males.

Discussion

The goal of this study was to assess whether sex or length influences the percent of time a smalltooth sawfish spends at a specific depth. Knowing what factors determine the depth of sawfish will help further understand the habits of sawfish and could help with conservation management for this critically endangered species. The results concluded that both male and female sawfish spend more time in shallow depths over deeper depths, as expected from previous sawfish literature (Carlson et al., 2014; Poulakis & Seitz, 2004; Simpfendorfer, 2001; Wiley & Simpfendorfer, 2010). This knowledge is important to comprehend in order to understand their habitats and apply them to conservation practices. Expecting shallower depths to be favored, the main focus of this study was to see which sex spent more time occupying deeper depths. The results showed females tend to spend more time at deeper depths than males, and males spend more time at shallower depths than females. Two males did go relatively deep (65-72 m), and two females only occupied shallow water (0-8 m), but the general trend showed females spending more time at deeper depths than males. This was seen in the histograms of percentage time-at-depth (Figure 2), the t-test conducted for greatest maximum depth, and the linear mixed-effects model (Figure 3).

Trends in the histograms (Figure 2) reveal that despite sex differences, all sawfish analyzed spent the majority of their time at 0-8 m. Therefore, this area of the water column should still be the main concern for conservation and management practices. However, it is important to know that sawfish do also frequently occupy deeper depths, and deeper waters still need to be considered for management measures to support population increases of this critically endangered species.

These results mean we can expect to find females at greater depths than males and could potentially affect the way female, especially pregnant, sawfish are protected. Females are very important for population dynamics since they give birth to pups. In order to ensure the sawfish population grows, females must be protected. If females have different depth preferences than males, this could change the way the conservation of female sawfish is managed. It may be more important to ensure female survival, so this information can help tailor sawfish conservation more towards females. Further research on whether sexual maturity or reproductive state affects the depth a sawfish occupies would add to scientific knowledge and management, helping to ensure these individuals are protected, therefore promoting the growth of the sawfish population.

Improvements to this model could include adding factors such as seasonality. Month was considered when sorting the data, but seasonality was not analyzed. Upon visual inspection of the data, it appears sawfish mostly occupied deeper depths during the late summer months. The deepening of the thermocline during the summer months may be a reason for sawfish to go deeper. Further analysis regarding month and the breeding season would need to be calculated to see if sex is only segregating at certain times of the year. Differences in depth between males and females could also be due to the reproductive cycle of females (Carlson et al., 2014). This could be counterintuitive since females are more often found at nurseries, which occur in shallow water areas like estuaries, and would not support the data showing females spend more time at deeper depths than males (Feldheim et al., 2017). However, this could potentially be evidence of sexual segregation, where females are actively avoiding males during non-reproductive seasons. Further studies that track the exact seasons during which female sawfish mate would have to be conducted in order to see if this could be a factor.

Other factors that may affect the distribution of sexes could be due to feeding behavior or thermoregulation (Carlson et al., 2014). There has been evidence of sex-specific dietary requirements, such as females eating more than males of the same size. Sex-specific temperature preferences may also occur if a female is pregnant, as warm waters can help an embryo develop (Wearmouth & Sims, 2010). Feeding behavior and temperature preference could be different among sexes, but more data collection and analysis would need to be done to see if these factors have an effect on percent of time at a particular depth. Depth could also depend on the time of day. Sawfish have been recorded to move into shallower waters at night and deeper waters during the day, so diurnal movements could be a factor (Carlson et al., 2014). Total length was not a significant factor when considering what depth a sawfish occupies, but modeling length and depth could still be useful to see if any visual trends are spotted, especially if this work was extended to include juveniles as well as adult sawfish. It's important to note that the analyzed sawfish in this study did not have much size variety (ranging from 279-428 cm); therefore, length may be a significant factor, but the study may not have had enough statistical power to show any variation. Further testing with sawfish of greater size variety could be done to see if increasing the statistical power of length creates a difference. Overall, there are several potentially confounding variables that could have influenced the results of this study. Additional data and analyses would need to be collected and completed in order to see if these variables cause a significant difference.

Understanding how sawfish use depth is important in order to predict population trends and dynamics. Knowing the factors that affect a sawfish's depth preferences would allow for the successful management and conservation of this species, since these spatial dynamics often overlap with area-focused human activities like fishing. Until recently, sawfish were thought to stay at a depth of 10 m or less (Simpfendorfer, 2001), so data on their depth use is limited, but important to know in order to fully understand their full vertical range. Understanding their depth range could help with the conservation and recovery efforts of this critically endangered species. With the decline of sawfish, more research needs to be conducted in order to create more effective status assessments, management measures, and recovery plans (Dulvy et al., 2016). With the knowledge from this study, hopefully more effective recovery plans can be developed and key areas of research that still need to be conducted can be identified.

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Figures and Tables

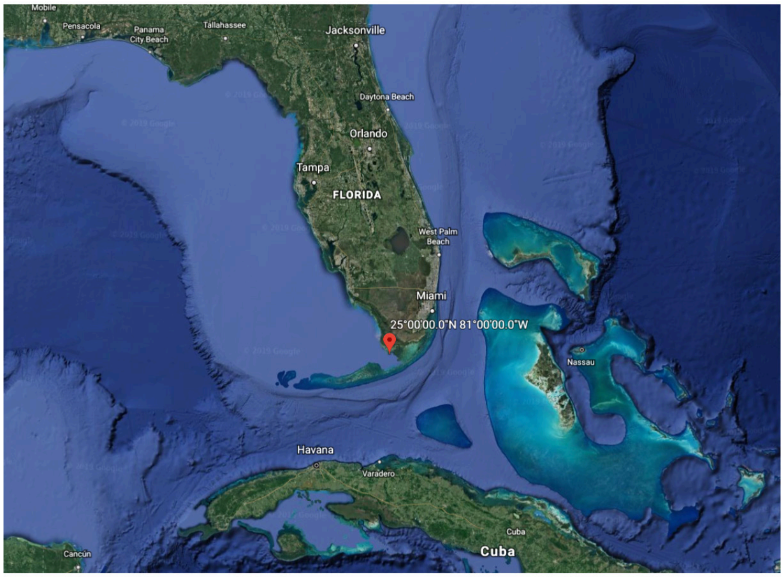

Figure 1. Map of the approximate location where most of the sawfish were tagged.

Table 1. Statistics for each sawfish that was used in the analysis. Sawfish numbers are their PTT numbers. STL means stretched total length. The location with the asterisk was adrift for 55 days before reporting data. Females are highlighted in red.

Sawfish number	Tag type	Days Analyzed	Sex	STL	Tagging date	Tagging location	Pop up date	Pop up location
103429	MK10	151	M	427	4/24/13	25.098N 80.958W	9/22/13	25.307N 81.795W
103430	MK10	141	M	371	7/21/11	24.440N 82.083W	12/16/11	25.078N 80.423W
103432	MK10	55	M	409	5/1/11	25.130N 81.810W	6/23/11	25.012N 81.453W
103434	PATF	140	M	381	7/18/11	24.458N 82.087W	10/5/11	24.872N 82.242W
103435	PATF	46	M	399	3/13/12	25.035N 80.977W	4/28/12	25.112N 80.890W
103438	PATF	84	F	368	7/19/11	24.439N 82.087W	10/11/11	24.422N 81.749W
119906	MK10	150	M	412	8/11/13	25.105N 81.041W	1/9/14	N/A
127594	Mini-PAT	121	F	428	1/30/15	24.782N 80.657W	5/31/15	25.326N 80.267W
60745	PATF	62	M	395	4/24/13	25.098N 80.960W	6/24/13	28.293N 83.286W
60746	PATF	61	M	395	4/25/13	24.839N 80.610W	6/24/13	26.464N 82.064W
60749	MK10	138	F	323	7/17/11	24.455N 81.810W	1/27/12	24.013N 81.497W
60750	MK10	156	F	352	7/17/11	24.455N 81.810W	12/20/11	32.599N* 73.797W
136409	Mini-PAT	141	F	279	3/17/14	25.129N 81.066W	8/5/14	25.337N 81.240W
136410	Mini-PAT	133	F	283	9/6/14	25.124N 81.067W	1/17/15	25.110N 81.065W

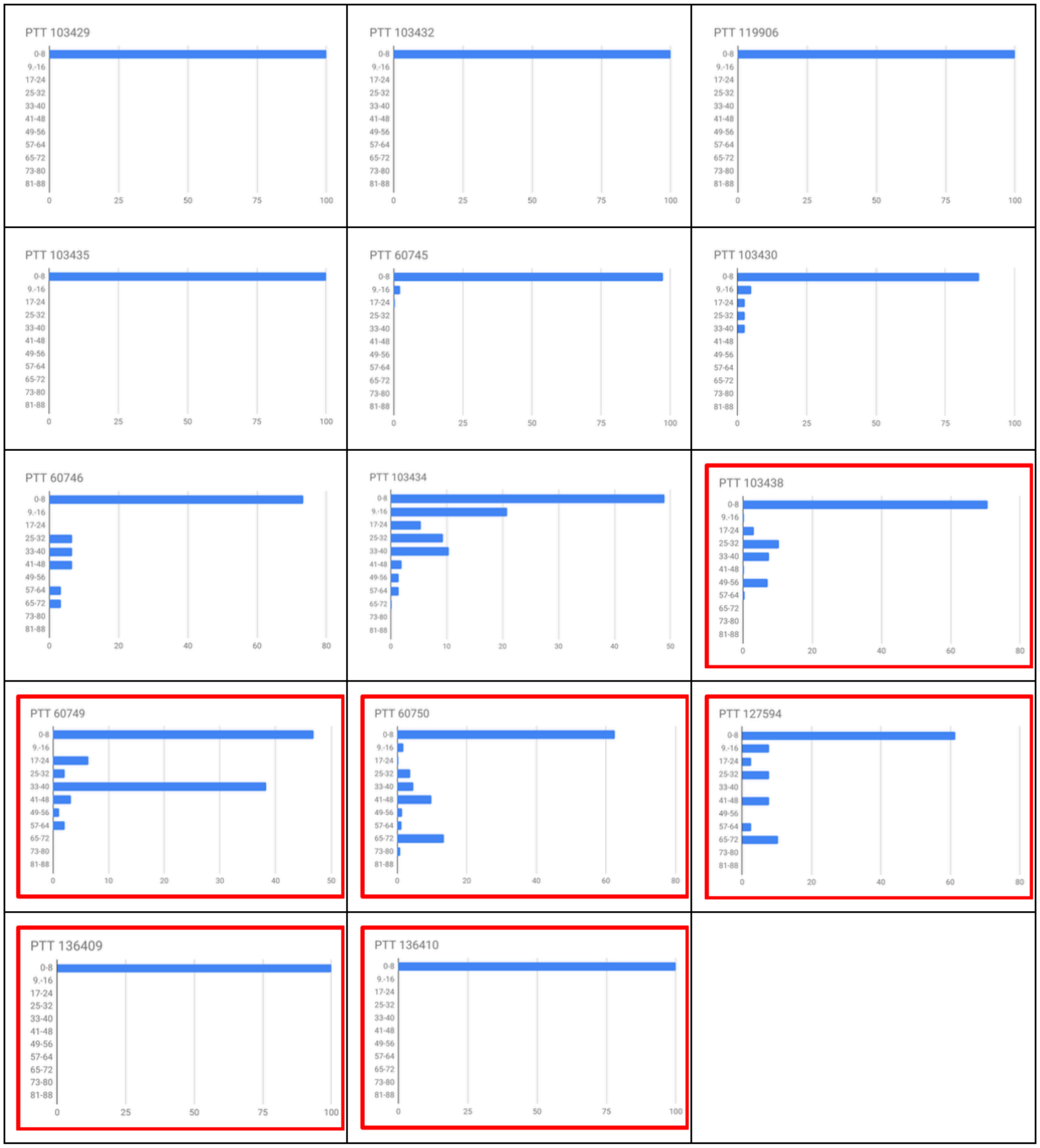

Figure 2. Histograms of percentage time-at-depth for all of the analyzed sawfish. X-axis is “Percent of Time” and y-axis is “Depth (m).” Females are highlighted in red.

Table 2. Table of the tested linear mixed-effects models and corresponding AICc and Delta AICc values. The lowest AICc value indicated the most parsimonious model, relative to the other model fits with a higher AICc value. The delta AICc of the best linear mixed-effects model between 0-2 can be said to have substantial support.

Model- function:lmer()	AICc	Delta AICc
Percent.Time ~ Sex + Depth + (1|Sawfish)	58.25	0.00
Percent.Time ~ Length + Depth + (1|Sawfish)	66.93	8.67
Percent.Time ~ Depth * Sex + (1|Sawfish)	69.82	11.56
Percent.Time ~ Length + Depth + Sex + (1|Sawfish)	72.76	14.51
Percent.Time ~ Length * Depth + (1|Sawfish)	87.28	29.03
Percent.Time ~ 1 + (1|Sawfish)	115.48	57.23
Percent.Time ~ 1	115.48	57.23
Percent.Time ~ Length * Depth * Sex + (1|Sawfish)	123.87	65.62
Percent.Time ~ Length + Sex + (1|Sawfish)	132.52	74.27
Percent.Time ~ Length * Sex + (1|Sawfish)	139.54	81.29

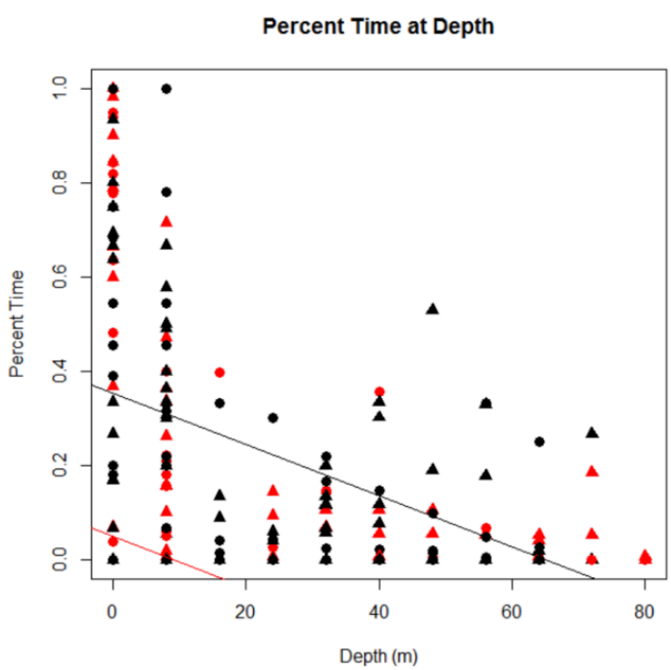

Figure 3. The model shows the percent time a sawfish stays at a specific depth. Black = females, red = males.