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Snook (*Centropomus undecimalis*) Behavior and Accelerometer Telemetry in the Bahia Grande of Texas

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SNOOK (*CENTROPOMUS UNDECIMALIS*) BEHAVIOR AND ACCELEROMETER TELEMETRY IN THE BAHIA GRANDE OF TEXAS

A Thesis

by

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ABSTRACT

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In this study, behavioral patterns and activity levels of Common Snook *(Centropomus undecimalis)* in the Lower Laguna Madre were measured utilizing accelerometer telemetry tags at nine different sites. Twenty-three Common Snook were surgically implanted with accelerometer tags and monitored with acoustic receivers. Telemetry receivers were placed in man-made channels, tidal creeks, on seagrass flats, and mangrove shorelines in the Bahia Grande and nearby sites in the Lower Laguna Madre in order to monitor snook in different habitat types. Occurrence and acceleration data was collected and analyzed with environmental factors in order to determine their effect on snook activity and behavior. Understanding how activity levels and behavioral differences are affected by environmental factors is essential for developing strategies for properly managing snook. Water temperature, diel period, barometric pressure, and tide height had significant effects on snook presence. Tagged snook completely vacated the Bahia Grande in response to colder water temperatures (below 23° C) for the winter months and returning in warmer months. Differing behaviors were observed at habitat types within the Bahia Grande. Water temperature, hour of the day, and tide height, all had significant effects on the snook ODBA levels.

DEDICATION

To my parents, who encouraged my curiosity in the natural world, instilled in me a love for wild places, and gave me the opportunities to enjoy them.

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CHAPTER I

INTRODUCTION

Snook

Common Snook (*Centropomus undecimalis*) occur in the western Atlantic, Gulf of Mexico, and Caribbean from 34N to 25S. They are stenothermic, and their range is primarily limited by an intolerance of cold temperatures (Adams et al. 2012). This results in their northern limit occurring around the 14° C isotherm (Pope et al. 2006) which includes areas north of the Laguna Madre in Texas. As a tropical fish limited by temperature, the Texas-Mexico population of snook finds their northernmost limit for permanent establishment at the Laguna Madre (Pope et al 2006). Snook can be found north of the Laguna Madre but experience heavy mortality during winter freezes when water temperatures drop below 14° C (Howells et al 1990).

Common Snook are a large ambush predator feeding primarily on smaller fish species and crustaceans (Blewett et al. 2006). They are opportunistic predators that will feed throughout the entire water column in a variety of habitats (Blewett et al. 2006) and as top predators they are ecologically important in the ecosystems they occupy.

Common Snook are a recreationally important fish, especially in Florida. Restoring a healthy snook fishery to the Lower Laguna Madre could have significant cultural and economic benefits on south Texas and the Rio Grande Valley. For example, in Florida, snook are a major part of the attraction to an Everglades fishery valued at $1.2 billion annually (Eggenberger et al. 2019).

Genetic stocks of snook are somewhat isolated throughout their range. The Florida Gulf and Atlantic populations of snook demonstrate their genetic isolation from one another by significantly different rates of growth (Tringali et al. 1999). The Lower Laguna Madre's snook population is part of the Texas-Mexico genetic stock (Pope et al. 2006, Anderson et al. 2020). Understanding the movement and habitat utilization of the Lower Laguna Madre's snook population will bring understanding of the population dynamics of the Texas-Mexico snook population and how to best manage them. Anderson et al. (2020) as well as Getz et al. (2021) noted that snook seem to be expanding their range northward over time from data collected in Texas. Snook spawning remains largely uncharacterized, and recruitment may still be inconsistent in the Texas population. (Getz et al. 2021)

Snook are protandrous hermaphrodites that mature initially as males around the age of one before transitioning to females between the ages of one and seven years old and sizes ranging from 240-824 mm (Grier & Taylor 1998) (Taylor et al. 2000) (Roberts et al. 1999). In Florida, snook migrate to passes, inlets, estuary mouths, beaches, and river mouths to spawn in spring, summer, and fall (Taylor et al. 1998, Trotter et al. 2012). Snook spawning activity is influenced by several factors such as water temperature, salinity, moon phase, and tidal current. Snook spawning generally occurs at salinities above 27 psu, in Florida (Lowerre-Barbierri et al. 2014, Taylor et al. 1998).

Snook in the early larval stages spend very little time in open water before moving into nursery habitats, which include mangrove shoreline, riverine backwaters, and salt marshes (Peters et al. 1998). Juveniles are often found in lagoons and canals characterized by moderately sloping shorelines with sufficient fringe vegetation and underwater structure (Peters et al. 1998). Juvenile and adult snook primarily utilize mangrove shorelines, seagrass meadow habitat, passes, channels, and jetties (Peters et al. 1998, Gilmore et al. 1983, McMichael et al. 1989). Snook are a large ambush predator feeding primarily smaller fish species and crustaceans. After reaching maturity their habitat utilization becomes more generalized (Stevens et al. 2007, Stevens et al. 2020).

Accelerometer Telemetry

Acoustic telemetry allows for the spatio-temporal monitoring of individual fish. Acoustic tags implanted in fish can provide information on fish position and movement as well as environmental and physiological factors. Acoustic receivers can be utilized to passively track the movement of tagged fish and remotely collect the detailed behavioral data without the need for recapture. Telemetry data can be an extremely useful tool in comparing use of an area between different conditions and times of year (de Almeida et al. 2013).

In order to successfully manage a species, it is essential to understand site use, migration, and behavior, and acoustic telemetry is an important and effective tool to accomplish this (Wright et al. 2014). One of the main advantages of acoustic telemetry is the ability to passively track tagged fish. The addition of miniaturized accelerometers allows for the collection of acceleration data to record fine scale behavior and activity levels over time in individual fish (de Almeida et al. 2013, Getz and Kline 2019).

Acoustic accelerometer tags are outfitted with acceleration transducers that allow for calculation of triaxial overall dynamic body acceleration (ODBA; Gleiss et al., 2011) calculated and summed over three planes for a given period of time (Gleiss et al., 2011; Getz and Kline, 2019). Accelerometer tags can be either externally affixed to or surgically implanted inside fish, and the data they record is one of the only ways to remotely study short-term behavior in fish. ODBA can be utilized to categorize behaviors like prey capture and routine swimming (Getz & Kline 2019). This form of telemetry appears to be well suited for a species such as snook, since they are ambush predators and may remain in area long enough to characterize their behaviors over time.

Study Area

The Bahia Grande is a large lagoon surrounded by the Laguna Atascosa Wildlife Refuge that was cut off from the rest of the Laguna Madre in 1936 as a result of the construction of the Brownsville ship channel (Lichlyter 2006). From the construction of the Brownsville ship channel until the construction of a channel reconnecting Bahia Grande to the tidal flow of the Laguna Madre and the Gulf of Mexico in 2006, the Bahia Grande remained a dry dust bowl. Its only source of water came from ephemeral runoff after heavy rainfall events (Lichlyter 2006). In 2006 a channel passing under Gayman's Bridge was cut, allowing for tidal exchange between the Brownsville ship channel and the Bahia Grande. Several factors, including the limited amount of tidal exchange possible through the new channel, minimal freshwater inflow, and the shallow nature of the lagoon, contribute to hypersaline conditions in the Bahia Grande (Lichlyter 2006).

The Lower Laguna Madre is a vast hypersaline lagoon between the barrier island of South Padre Island to the east and the mainland of Texas to the west. It stretches from the Land Cut south to tidal flats near the Rio Grande. There is only one natural inlet, the Brazos Santiago Pass at the south end of South Padre Island. Another pass was cut in the 1950's called the Port Mansfield shipping channel. The Laguna Madre is a highly productive ecosystem rich with seagrass. Despite only accounting for only 20% of the Texas coastal embayment it is responsible for more than half of its inshore finfish catch (Quammen and Onuf 1993).

The Lower Laguna Madre once supported a commercial and recreational snook fishery. Habitat destruction and commercial over-fishing resulted in a significant decline in snook numbers after the peak in commercial snook harvest of 104,451kg in 1928 (Matlock & Osburn 1987). No commercial landings were reported after 1961 (Matlock & Osburn 1987). Commercial harvest of snook was outlawed in 1987. In Texas Parks and Wildlife surveys occurring from 1975-1983 only 110 snook were captured in over 20,000 collections with gill nets, trawls, seines, rod and reel, and other sampling techniques (Matlock & Osburn 1987). Texas Parks and Wildlife only observed 14 recreational snook captures by anglers in 100,000 angler interviews in a period lasting from 1974-1985 (Matlock & Osburn 1987).

Despite the lack of reported commercial harvest of snook after 1961 there was a significant decrease in recreational snook catches suggesting a lack of significant recovery, if not a continued decrease in population numbers after the overfishing of the late 1920s to 1940s (Matlock & Osburn 1987). This continued decrease could have been the result of multiple hard freezes in the 1940s that resulted in several large snook mortality events. A study of the snook population from 1975 through 2004 reported a small population with inconsistent recruitment (Pope et al. 2006). Another major obstacle facing the Lower Laguna Madre's snook population is poaching. Numerous instances of snook poaching of both oversized and undersized fish were observed during this study in popular fishing areas.

Study Objectives

In order to effectively manage the Texas snook population it is essential that we understand the habitat utilization, distribution, seasonal patterns, movement and the behavior types and activity levels occurring in these locations, especially the lower Laguna Madre. Beyond simple capture surveys there has been minimal study of the Texas snook population and there has been no published telemetry study of snook in Texas. Some important questions that need to be addressed are:

1) What areas and habitat types are snook using on the Lower Laguna Madre? Are there behavioral and activity level differences in different habitat areas?
2) How do behavioral and activity level differences change in these locations and habitat types based on season and environmental conditions? (Water temp, time of year, tidal activity, diel period)
3) Are snook using the Bahia Grande as a refuge or as a feeding habitat? (For example, if snook are using it for primarily feeding, ODBA levels will be higher in areas of the Bahia Grande than other areas such as the Brownsville ship channel.)

This study addresses the following hypotheses:

- Environmental variables: diel period, water temperature, and tidal phase will be predictors of ODBA levels in Common Snook.

- Water temperature and diel period will be significant predictors of snook presence in the Bahia Grande.

- ODBA levels for Common Snook detected in channels of the Bahia Grande will be higher than those detected at receivers in other parts of the Laguna Madre.

CHAPTER II

METHODS

Common Snook (*Centropomus undecimalis*) were opportunistically captured in multiple locations around the Lower Laguna Madre including South Bay, the Bahia Grande and the Brownsville Ship Channel with hook and line equipment. Captured snook were anesthetized in a tank with 38 l of saltwater chilled with ice packs, 100 g sodium chloride, and 60 ml acetic acid (Oberg et al., 2015). Once fish were sufficiently anesthetized a small incision was made halfway between the anus and the pelvic girdle deep enough to insert the tag into the peritoneal cavity. After the tag was placed in the peritoneal cavity the incision was sutured shut with 4-0 Vicryl absorbable material and a curved needle (Ethicon Inc., USA). Once fish were implanted with a transmitter, they were placed in a recovery tank with an air stone positioned in their mouth to expedite fish recovery, at which point they were released. These transmitters are tri-axial accelerometer tags that calculate Overall Dynamic Body Acceleration over a period of time and report data on an 8-bit scale. (MTT- IBT-AT-6-I and MTT-T-2, Sonotronics Ltd., Tuscon, AZ.) These tags used the sum of the range of X, Y, and Z axes every two minutes, reported on a 8-bit scale of 0 to 255.

Thirteen Sonotronics Submersible Ultrasonic Receivers (SUR, Sonotronics Ltd., Tuscon, AZ) were deployed around the Lower Laguna Madre in areas where fish were captured, observed, or expected to utilize during movement from one area to another. (Figure 1&2) Four of these receiver locations were removed from the statistical analysis due to low numbers of detection. Data was collected by SURs (Sonotronics Ltd., Tuscon, AZ) for the approximate 18-month lifespan of the tags. SURs were checked at three-month intervals to ensure proper functioning, data download, removal of fouling organisms, and replacement with new batteries. These areas included ship channels, jetties, mangrove shoreline, grass flats, sand and mud bottoms, and tidal creeks among other types of habitat. In locations less than 1.5 m depth, acoustic receivers were anchored by driving t-posts into the substrate. The receiver was attached to a PVC pipe with stainless steel hose clamps and zip ties, which are then slipped over the anchored t-post. In areas deeper than 1.5 m, receivers were attached to a stainless-steel chain with hose clamps and zip ties just above the bottom with a 22 kg anchor. The other end of the chain was shackled to mangroves or another anchor point on the shoreline.

In order to monitor the number of tagged fish at large, the number of fish captured by anglers, and to determine their ultimate fate, tags were labeled with contact information as well as an offer of reward for their return. This was done to maximize the possibility that anglers would report their capture of tagged fish. Fish that were detected in the last month of the study were considered present. Fish that left the array prior to that were considered to have emigrated unless reported captured by anglers or exhibiting mortality tag behavior.

Receiver range was found to be highly variable with the SURs based on environmental conditions, particularly wind and tide. High winds created noise, making it more difficult for receivers to detect tags pinging from fish. Areas like the channels between different water bodies like the Gayman’s Bridge Channel at the mouth of the Bahia Grande, and the channels between the different Bahia lagoons move a large amount of tidal water through a constricted area that creates noise and decreases SURs ability to detect tagged fish. A study done with very similar SURs and accelerometer tags, Getz and Kline (2019), estimated receiver range at 200 m. This study occurred offshore, 40 km northeast of South Padre Island in the Gulf of Mexico at a depth of 33m. The Bahia Grande and the other habitats monitored for this study within the receiver array were typically less than 0.7 m depth, which also decreases receiver range. Through multiple range tests with the equipment and under varying conditions at study sites, the receiver range was estimated to be roughly 100 m under ideal conditions. On multiple days with varying turbidity, wind speeds, water depths, and tidal conditions, range tests were conducted in which a timer was utilized to ensure two minutes were spent at 10 m intervals moving away from a receiver location with a test tag pinging a signal every 5 sec in order to determine the range at which detection no longer occurred consistently.

Environmental data was collected from the NOAA Port Isabel turning basin weather station PTIT2 (https://www.ndbc.noaa.gov/station_realtime.php?station=ptit2) for the duration of the study period. This weather station was the one positioned closest to the middle of the study area. The turning basin was the most centrally located weather station between the South Bay, the Brownsville Ship Channel, Bahia Grande, and San Martin Lake receiver locations.

Data Analysis

Occurrence Model

Environmental data collected from the NOAA PTIT2 weather station was analyzed for its effect on snook occurrence in the Bahia Grande. Each hour of the study was evaluated to determine whether a snook detection occurred during that hour at one of the receiver locations within the Bahia Grande. Each hour was classified into the presence (1) or absence (0) category based on whether a detection occurred during that hour. As a result, there was a significant number of zeros in the data. Environmental variables included in the analysis included barometric pressure, water temperature, tide height and diel period. These variables were binned by hour to compare their effect on snook occurrence by hour. Due to the binomial distribution of the data and the inflated number of zeros it was then analyzed with a Zero Inflated Poisson with Bernoulli Binomial distribution to determine the effect of environmental data on snook occurrence. The model was run in R (v4.0.1, R Core Team, 2020) in R studio (v1.1.419, RStudio Team, 2020) using the pscl package. The model was then analyzed with the dredge function from the MumIn package in R (v4.0.1, R Core Team, 2020). The dredge function compares many models by interchanging factors in the model until all combinations are tested. The models with the lowest ten ΔAICs are reported. The model with the lowest ΔAIC was then selected. Model fit was assessed utilizing McFadden pseudo-R^2 (McFadden 1977).

Generalized Additive Model of ODBA

A generalized additive model (GAM) similar to Froehlich et al. (2021) was used to examine the relationship between snook activity levels and environmental variables. Environmental data was analyzed for its effect on overall dynamic body acceleration (ODBA) data collected from snook with a generalized additive model (GAM). For this analysis ODBA data was averaged by each hour of the study, by each individual fish tag, and by each individual receiver location. Environmental data was also averaged by each hour of the study. Environmental factors used to analyze ODBA included water temperature, hour of the day (a proxy for diel period), tide height, and date. Individual fish often exhibit unique behaviors to that individual. To account for this variation, tag was included as a random factor in the model. Receiver locations were placed in a variety of habitats, but still could not represent all possible habitat types for snook. To account for this variability, receiver location was included in the model as a random factor. Hourly ODBA was analyzed using GAMMs fitted with Poisson distributions (Figure 4) and identity link functions, date as cyclical smoothing term, hour of the day as a cyclical smoothing term, tag as a random effect smoothing term, receiver location as a random effect smoothing term, as well as detection by hour, tide, and water temperature as covariates. Because the dataset was so large, the bam function within the mgcv package (Wood, 2011) was utilized to analyze it. Variance inflation factor (VIF) was used to test for collinearity between variables. There was no collinearity detected between the variables used in the model. The relative importance for each variable was determined by examining the difference in deviance explained (ΔDE) by removing each variable from the model as described in Rooker et al. (2012) and Wells et al. (2018). All data analyses were completed with R (v4.0.1, R Core Team, 2020) in R studio (v1.1.419, RStudio Team, 2020) with the packages: mgcv (Wood, 2011), tidyverse (Wickham et al., 2019), car (Fox and Weisberg, 2019), emmeans (Lenth et al., 2020), and visreg (Breheny and Burchett, 2017).

CHAPTER III

RESULTS

Twenty-three Common Snook were tagged in June of 2019 through October of 2020 using hook and line equipment (Table 1). The study period lasted from July 2019 through October 2020. A total of 92,006 detections were recorded during the study period from July 2019 to October 2020. Eight tagged Common Snook reported over 1,000 detections. Mean total length of tagged snook was 658±24.4 mm, ranging from 438 to 833 mm in total length. Mean weight of tagged snook was 2103±220.9 g ranging from 530 to 3750 g. The mean number of days from the first detection to the last detection of a tag was 132 ± 33.6 d at liberty. One fish was released and never detected again. This fish was not included in the statistical analysis. The fish with the highest number of days at liberty was 472. In August of 2020 a fish tagged in the Bahia Grande, Tag 13, was reported captured by a commercial fisherman in Tampico, Mexico in a gill net.

A total of 91,669 out of 92,006 (99.6%) of the detections occurred in the Bahia Grande. Snook displayed different behaviors in different habitat types throughout the Bahia Grande. These differences were observed by SURs at receiver locations throughout the Bahia Grande. At sites Bridge 13, Mouth of Bridge 13, Bridge 15, and Mouth of Bridge 15, receivers were placed inside tidal creeks and at the mouths of tidal creeks that allowed for tidal flow between the main body of the Bahia Grande and the smaller back lagoons. These sites are where the most Common Snook detections occurred, with fish spending more time at these locations than any other locations monitored in this study. Many of the high ODBA detections occurred at these sites, indicating much of the observed feeding behavior in this study occurred in these tidal creek locations. Locations in different habitat types like East Cove, and the receivers at the Mouth of the Bahia Grande accounted for fewer detections overall and fewer high ODBA detections. This indicates less of the observed feeding activity for this study occurred outside of tidal creek habitat. Four of the thirteen receivers were removed from the analysis due to low detection numbers. Seventy-Eight percent of fish tagged in this study were detected within in the Bahia Grande, eighteen of twenty-three tagged fish. One fish tagged in South Bay, tag #18, was detected in the Bahia Grande (Table 3). Seventeen of twenty-three fish were tagged in the Bahia Grande.

Occurrence Model

The environmental variables included in the final occurrence model showed a significant relationship in predicting Common Snook occurrence at telemetry receiver locations within the Bahia Grande. The GLM for occurrence reported a McFadden pseudo-R^2 of 0.186 with four of eight variables included in the final model (Table 2). Barometric pressure ($p<0.001$) had a negative relationship to snook occurrence. As barometric pressure increased, the likelihood of Common Snook presence decreased at the receiver sites. Tide height ($p<0.001$), water temperature ($p<0.001$), and daylight ($p=0.0123$) all exhibited a positive relationship to snook occurrence. As tide height and water temperature increased, the likelihood of a snook presence increased at the receiver locations. The likelihood of Common Snook presence increased during daylight hours and decreased during dark hours.

Water Temperature

Through two winters of data collection, it was observed that in the fall around November the fish leave the Bahia when the water temperature reached 23° C. They did not return until March when the water temperature was above 23° C. The model showed a positive relationship between snook presence and higher water temperature. The number of detections at receivers greatly decreased from November through March (Fig. 5) and the only detections during these months occurred in San Martin Lake and the Brownsville Ship Channel.

Generalized Additive Model of ODBA

The final GAM for environmental effect on ODBA had a deviance explained of 20.5% with seven out of ten variables retained for the final model. The most important variables in descending order of importance were the random factor of individual tag ($p<0.001$), hour of the day ($p<0.001$), detections by hour ($p<0.001$), date ($p<0.001$), random factor of location ($p<0.001$), water temperature ($p<0.001$), and tide height ($p<0.001$). Response plots indicated ODBA was highest for Common Snook from the hours of 600 to 1800, this trend showed a relationship between time of day and activity levels, where ODBA was higher for snook during the daylight hours (Figure 7). Detections by hour showed a negative relationship with ODBA in Common Snook. If more detections occurred in an hour, the average ODBA for that hour decreased (Figure 9). If ODBA increased as tide height increased, the response plots showed this relationship peaking around 0.8 m (Figure 8). ODBA was highest in Common Snook in water temperatures between 22 and 30° C (Figure 10). Date helped explain some of the deviance in the model by accounting for the cyclical changes in snook behavior throughout the year. Individual tag ($p<0.001$) was retained as a random effect that explained deviance by accounting for individual differences in fish behavior. Location ($p<0.001$) was also retained in the model as a random factor that accounted for differences in behavior by fish at receiver locations.

CHAPTER IV

DISCUSSION

This was the first study to use accelerometer tags to study the effects of environmental factors on overall dynamic body acceleration (ODBA) in Common Snook in Texas. ODBA data collected by this study was utilized to analyze behavior in response to environmental variables. ODBA and occurrence data revealed differences in snook behavior over the course of a year and a half in relation to changes in environmental variables. Similar studies have been conducted in Florida utilizing standard acoustic telemetry to examine the responses of snook to environmental changes. Stevens et al. (2016) observed snook utilizing different habitat for cold temperature avoidance in south Florida. While Eggenberger et al. (2019) found a relationship between snook movement and whether habitats where eutrophic and mesotrophic in Florida. Understanding the effect of environmental variables on the behavior and occurrence of snook can help with their management by increasing understanding of their habitat use and requirements as well as their movements seasonally and connectivity with populations in other ecosystems (Eggenberger et al 2019) (Stevens et al 2016).

More high ODBA detections occurred in the Bahia Grande during this study than in other locations, but 99.6% of all detections collected during this study occurred within the Bahia Grande. For this reason, all that can be concluded is that snook display high ODBA behavior in the Bahia Grande as well as the rest of the Lower Laguna Madre. Further study will be required to examine the hypothesis that ODBA levels would be higher in the Bahia Grande than the rest of the Lower Laguna Madre. However, the data did show that snook stay in channels within the Bahia Grande for long periods of time and exhibited a wide range of behaviors ranging from high ODBA feeding behavior to low ODBA energy conserving behavior. As ambush predators the vast majority of detections were low ODBA value behavior (Figure 4). The data show that some individuals will spend months at a time in the Bahia Grande. There was also a marked difference in the behavior from November through March when all tagged snook left the Bahia completely. These same fish were only detected in San Martin Lake or the Brownsville Ship Channel during these colder months. These locations include deep, man-made channels, and freshwater inflows that could be used as thermal refuges to avoid lower lethal temperatures. Blewett et al. (2009) also found snook abundance to be lowest in the winter months in the Charlotte Harbor of Florida where one cold front resulted in water temperatures of 15.1° C in the Peace River and 16.7° C in an adjacent man-made canal.

Barometric pressure showed a negative relationship with snook occurrence. As the barometric pressure increased, the likelihood of snook presence decreased. For ODBA however, barometric pressure did not have a significant effect on activity levels in snook. This could be because increased barometric pressure often occurs in tandem with cold fronts decreasing water temperatures causing snook to leave the Bahia Grande and the shallower locations where our receiver array is located, in order to reach deeper thermal refuges as was observed in Common Snook in Florida (Stevens et al 2016). Massie et al. (2020) also found a relationship between large scale snook movement and lower barometric pressure in a study investigating snook response to major climactic events like a hurricane.

Water Temperature had a positive relationship with Common Snook occurrence. As the water temperature increased, so did the likelihood of snook presence at our receiver locations. This supports the hypothesis that water temperature would be significant predictor of snook presence. Looking at the response plots the highest ODBA activity for snook occurred between the water temperatures of 23 to 30° C. Below the water temperature of 22° C Common Snook behavior changes and they no longer display high ODBA feeding activity (Figure 6, Figure 10). This supported the hypothesis that water temperature would be a significant predictor of ODBA levels in snook. The lower lethal temperature limit for the snook is 10° C (Howells et al. 1990). This follows the seasonal behavioral change snook exhibited when fall temperatures decrease below the temperature threshold of 23° C in early November, detections in the Bahia Grande ceased until March. McMichael et al. (1989) also observed snook moving out of sampling areas during cold fronts and lower water temperatures in Florida. Snook presence was also most consistent in the Bahia Grande during months with consistently warmer water temperatures between 23 and 30° C. This period typically occurs from March through October. In a laboratory study on juvenile snook collected from South Padre Island, Howells et al. (1990) found a marked decrease in feeding activity by fish in the range of 18-20° C, showing a change in snook behavior at a close temperature range to the change observed in our study. Fish were still observed in San Martin Lake and the Brownsville Ship Channel during colder months, but with less frequency and with no high ODBA feeding activity values recorded during these colder winter months.

Snook occurrence showed a positive relationship to light period. The likelihood of snook presence increased during light period at the receiver locations. This supports the hypothesis that diel period would be a significant predictor of snook presence. This could be a result of dawn and dusk being included in the daylight category for the binary factor diel period, where every hour was classified as either daylight or dark. The GAM also showed ODBA levels being highest from the daylight hours of 600 to 1800 indicating that snook presence and activity levels are both positively associated with light period. The response curve shows higher ODBA behavior increasing at 600 hours and staying high through 1800 hours in the Bahia Grande. Indicating an increase in feeding behavior that is sustained throughout the daylight hours. This data supports the hypothesis that diel period would be a significant predictor of ODBA in snook. Other studies conducted in Florida have found snook feeding during the day including McMichael et al. (1989) who examined juvenile snook stomachs for their dietary study sampling for the from 900 to 1500 hours. Rock (2009) found that 70% of snook sampled during the day had prey in their stomach, however the periods with the greatest number of fish with prey in their stomach were dawn and the nocturnal period.

Snook displayed different behaviors in different habitat types throughout the Bahia Grande. These differences were observed at receiver locations throughout the Bahia Grande. At sites Bridge 13, mouth of Bridge 13, Bridge 15, and mouth of Bridge 15, receivers were placed inside tidal creeks and at the mouths of tidal creeks that allowed for tidal flow between the main body of the Bahia Grande and the smaller back lagoons. These were sites where the most Common Snook detections occurred with fish spending more time at these locations than any other locations monitored in this study. Stevens et al. (2007) found that snook, especially juveniles, heavily occupied creeks, creek mouths, and pond networks in the estuary in Florida. Many of the high ODBA activity detections occurred at this site, indicating a significant amount of feeding behavior occurred at these sites. The East Cove and the mouth of the Bahia Grande accounted for fewer detections overall, and less of the high ODBA activity detections as well. Stevens et al. (2007) also found their greatest concentrations of snook in creeks and creek mouths. This difference in the number of detections and time spent at these different receiver locations could be a function of the constricting nature of the tidal creeks. As the tide flows through these creeks, they carry prey items through a constricted area. Ambush predators, like snook, can remain stationary in these tidal creeks and feed efficiently. This phenomenon was observed at receiver locations during sampling and receiver maintenance. It is possible this concentrates the number of snook in one small area near an acoustic receiver, leading to more detections. It is possible that Common Snook also feed in more open areas of the Bahia Grande, but other receivers placed within the Bahia Grande during the present study did not record this. Blewett et al. (2006) conducted a feeding study examining stomach contents and found evidence of snook feeding in many diverse habitat types, including mangrove shorelines, seagrass beds, as well as open sand and mud bottoms.

The south Texas snook fishery historically, has fewer fish than the Florida fishery, and there are also fewer angler days per year spent targeting snook in Texas. (Matlock & Osburn 1987) Many of the fish tagged in this study were outside of the relatively restricted Texas snook slot limit of 24-28 inches, or 610 mm to 711 mm, and only one fish is allowed per angler per day (TPWD, 2021). As a result, it is likely that many of the fish tagged could have been caught and released, without the anglers knowing these fish were tagged. It is also possible that if these fish were poached, anglers would be unlikely to report a tag recovery. In the spring of 2020 tag #13 was reported captured in a commercial gill net in an inlet in Tampico, Mexico by a Mexican fisherman. This is an important data point that illustrates connectivity between the Mexican and Texas populations of Common Snook. This fish was captured around 480 km south of the location it was tagged, indicating significant migration southward by the snook residing in Texas bays. This also demonstrates the direct effect commercial harvest of snook in Mexico has on the adult snook population along the Texas coast. It is feasible that more mature fish have adapted to use migration to avoid mortality related to water temperature in the winter. Migration has been observed in relationship to cold temperature avoidance as noted by Trotter et al. (2012) as well as Blewett et al (2009) in Florida snook populations. It is also very likely this migration occurs for the purposes of spawning. Several Florida studies have looked at the migration behavior in snook populations as a result of their catadromous spawning behavior, including Trotter et al. (2012) and Lowerre-Barbieri et al. (2014), who noted a high level of spawning site fidelity over multiple years in some individuals. While some tagged fish were still observed in San Martin Lake and the Brownsville Ship Channel from November through March, the number of detections and the number of tags observed decreased precipitously, and no detections occurred in the Bahia Grande during these months.

The majority of tagged fish in the present study were considered to have emigrated. Two fish were reported caught by anglers. Some fish left the Bahia Grande and were not detected again just days after tagging. It is common in telemetry studies to have fish leave the study area or cease to be detected without having a definite fate determined (Trotter et al. 2012, Getz and Kline 2019). To determine the fate of tags with absolute confidence there would need to be an array with full coverage that eliminates the possibility of missing a passing fish as noted by Villegas-Rios et al. (2020). Fish could have migrated out of the array area, the tag could have stopped pinging at the end of its battery life, or some fish may have been captured by anglers who did not report the capture. Due to the limiting factors of receiver coverage over a large area, a limited number of receivers, and variability in receiver reception range, it is possible that snook exited the Bahia Grande under certain conditions without being detected as they left the bay system.

Very little work on the Texas coast has focused on snook movement, habitat utilization, and behavior. This study is a first attempt at characterizing these important ecological factors. Matlock & Osburn (1987) describe the potential reasons behind the apparent lack of recovery of the Texas snook population to habitat loss or degradation, freeze events, and overfishing. Characterizing snook current habitat utilization, behavior, movement could hold the keys to understanding how best to manage this fish. This data demonstrates that since the restoration of the Bahia Grande, it has become an important habitat for a resident population of snook. Many of the fish tagged in this study are spending the majority of the year residing in the Bahia Grande. In order to protect this resident population of adult Common Snook, it could be important to keep the Bahia Grande an ecosystem protected from harvest. It may be beneficial to eliminate harvest from the Gayman's Bridge Channel, the only source of tidal flow for the Bahia Grande and the only path in or out for fish leaving to spawn, find thermal refuge, or migrate. Due to the major behavioral changes observed in snook in this study, a valuable management tool might include closing the snook harvest on a seasonal basis. Snook are leaving protected backwater lagoons in search of thermal refuges in colder months. When they concentrate in these thermal refuges to utilize areas with more consistent water temperatures, they are more vulnerable to harvest. Reducing the pressure and harvest of this important population of fish as they migrate to spawn and avoid temperature mortality may help to grow the snook population in the Lower Laguna Madre.

CHAPTER V

CONCLUSION

This study demonstrates the potential of accelerometer telemetry to examine the relationship between fish behavior and environmental variables in Common Snook in an estuarine environment. Snook behavior was shown to undergo changes in response to shifts in environmental variables. Snook were observed to utilize different habitats in response to changing environmental cues. Common Snook displayed different behavior during the colder months, November through March, in which fish left the Bahia Grande and began to utilize different habitats like the Brownsville Ship Channel and San Martin Lake. These locations included habitats like man-made channels, man-made structures, deeper waters and fresh-water inflows. Snook were shown to heavily occupy tidal creeks and the mouths of tidal creeks within the Bahia Grande. Migration of over 450 kilometers was observed for snook between Texas and Mexico, potentially indicating a high level of connectivity between snook populations along the western Gulf coast.

Table 1. Meristics and detection information for tagged Common Snook (*Centropomus undecimalis*).

Tag Number	Fish Number	Date samples retrieved	Length (mm)	Weight (g)	Last date detected
			Total	Total	
3	CS 155	10/23/2020	797	3750	10/24/2020
7	CS 154	10/8/2020	438	530	10/27/2020
9	CS 140	12/5/2019	558	1133	12/27/2019
10	CS139	11/24/2019	704	2235	2/5/2020
11	CS137	9/18/2019	600	1405	10/4/2020
12	CS136	9/18/2019	657	1930	9/18/2019
13	CS135	9/6/2019	675	1990	6/2/2020
14	CS134	9/6/2019	682	2070	7/25/2020
15	CS133	9/6/2019	825	3720	9/6/2019
16	CS121	7/19/2019	765	3225	8/15/2019
17	CS 114	7/5/2019	494	775	8/7/2020
18	CS 101	6/3/2019	540	907	4/23/2020
19	CS 124	7/31/2019	593	1590	7/31/2019
20	CS 127	8/7/2019	500	875	8/7/2019
21	CS131	9/5/2019	833	3550	9/12/2019
22	CS 128	8/28/2019	750	2720	8/28/2019
23	CS 130	9/5/2019	494	775	6/21/2020
24	CS129	8/28/2019	767	3325	8/29/2019
25	CS132	9/5/2019	771	3055	4/19/2020
26	CS 118	7/13/2019	760	3400	10/27/2020
28	CS 102	6/3/2019	580	1729	N/A
29	CS 122	7/25/2019	680	2365	10/11/2019
30	CS 103	6/3/2019	670	1304	10/11/2019

Table 2. Coefficients and significance values from the results of the Generalized Linear Model for Common Snook (*Centropomus undecimalis*) occurrence binned by hour from 7/31/2019 to 10/31/2020. Model yielded a McFadden pseudo-R^2 of 0.186.

<table>
<tr><th></th><th colspan="4">GLM Coefficients:</th></tr>
<tr><th></th><th>Estimate</th><th>Std. Error</th><th>z value</th><th>Pr(>|z|)</th></tr>
<tr><td>Intercept</td><td>37.636678</td><td>3.654859</td><td>10.298</td><td><2e-16 ***</td></tr>
<tr><td>Barometric</td><td>-0.042233</td><td>0.003582</td><td>-11.792</td><td><2e-16 ***</td></tr>
<tr><td>Tide Height</td><td>1.442346</td><td>0.068698</td><td>20.995</td><td><2e-16 ***</td></tr>
<tr><td>Water Temp</td><td>0.155576</td><td>0.004175</td><td>37.26</td><td><2e-16 ***</td></tr>
<tr><td>Light</td><td>0.06821</td><td>0.027241</td><td>2.504</td><td>0.0123 *</td></tr>
</table>

Table 3. Receiver locations where tagged Common Snook (*Centropomus undecimalis*) were detected over the course of the study as well as fates of fish at the end of the study period (July 2019 through October 2020). The Ship Channel receiver was not included in statistical analysis due to its low number of detections. Tag 15 was detected during receiver testing and did not report swimming ODBA and was presumed dead.

Tag Number	Fish Number	UTRGV Dock	San Martin	East Cove	Bahia Mouth NE	Bahia Mouth SW	Bridge 13	Bridge 13 Mouth	Bridge 15	Bridge 15 Mouth	Ship Channel	Fate
3	CS 155						x					Present
7	CS 154						x	x		x		Present
9	CS 140										x	Emigrated
10	CS139		x									Emigrated
11	CS137		x	x	x	x	x	x	x	x		Present
12	CS136							x	x	x		Emigrated
13	CS135		x	x	x	x	x	x	x	x		Captured by gill net in Mexico
14	CS134	x	x	x	x	x	x	x	x	x		Emigrated
15	CS133						x					Presumed dead
16	CS121			x			x	x				Emigrated
17	CS 114	x										Emigrated
18	CS 101	x			x	x						Emigrated
19	CS 124								x			Emigrated
20	CS 127								x	x		Emigrated
21	CS131			x			x	x				Emigrated
22	CS 128								x			Emigrated
23	CS 130		x	x	x	x		x	x	x		Emigrated
24	CS129								x	x		Emigrated
25	CS132			x		x	x	x				Emigrated
26	CS 118		x	x	x	x	x	x	x			Present
28	CS 102											Emigrated
29	CS 122			x	x			x	x	x		Emigrated
30	CS 103	x										Emigrated

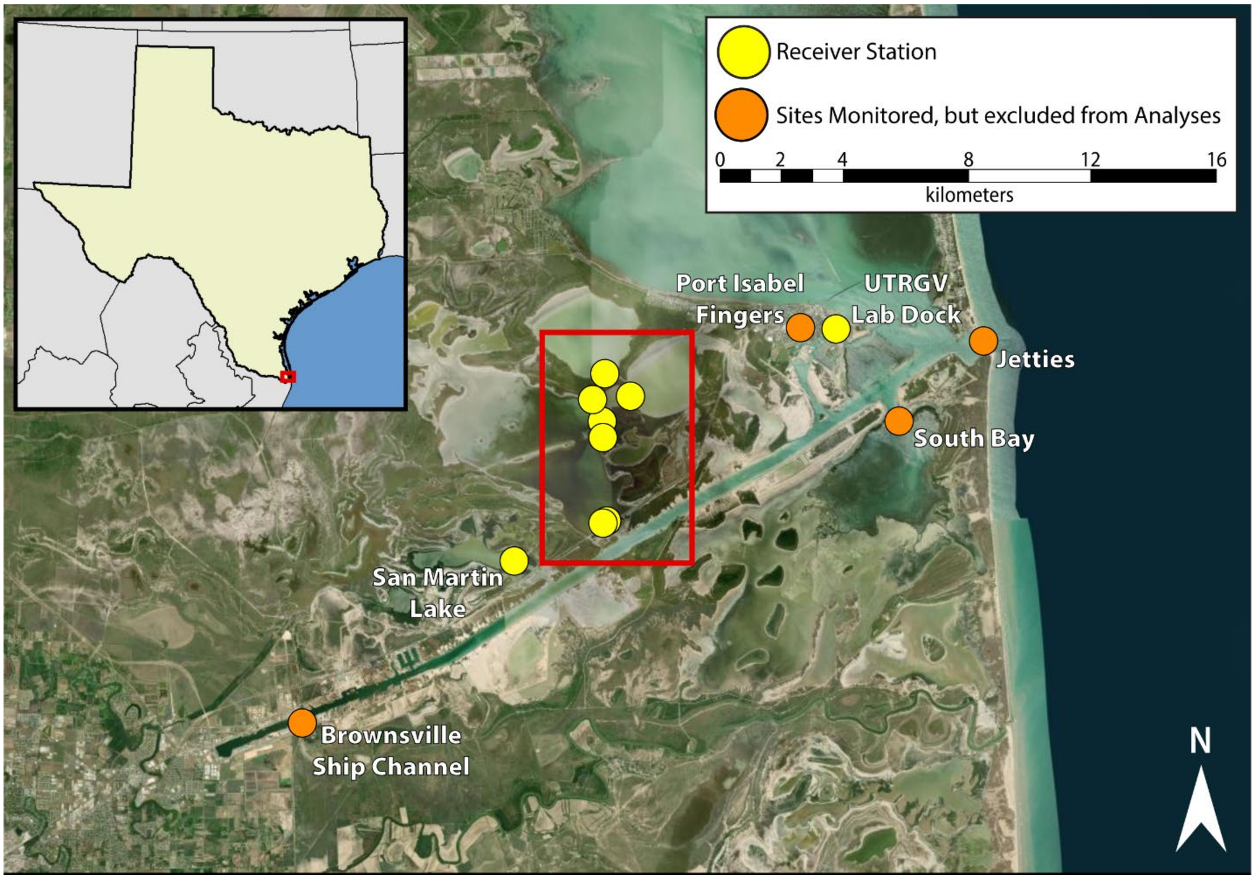

Figure 1. Map of receiver locations monitored in this study around the southern Lower Laguna Madre. Sites in orange were excluded from the analyses due to low detection levels.

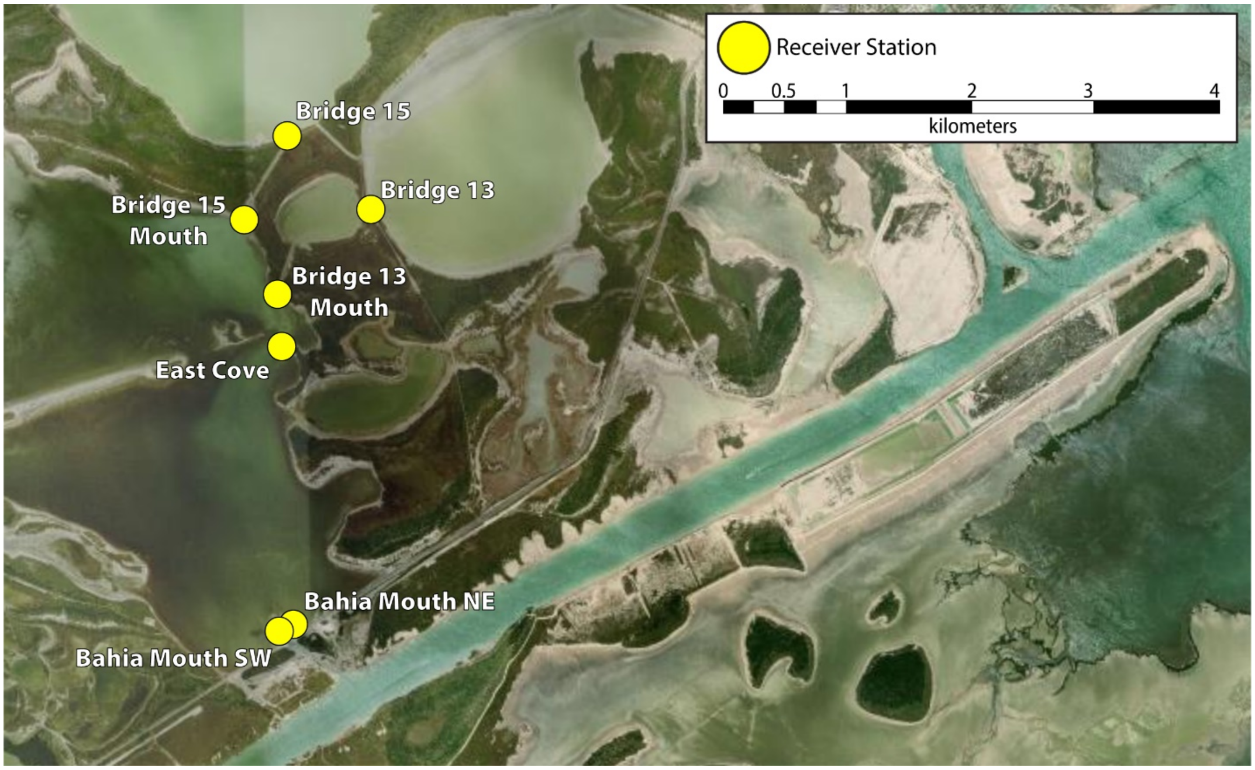

Figure 2. Map of receiver locations monitored in the Bahia Grande.

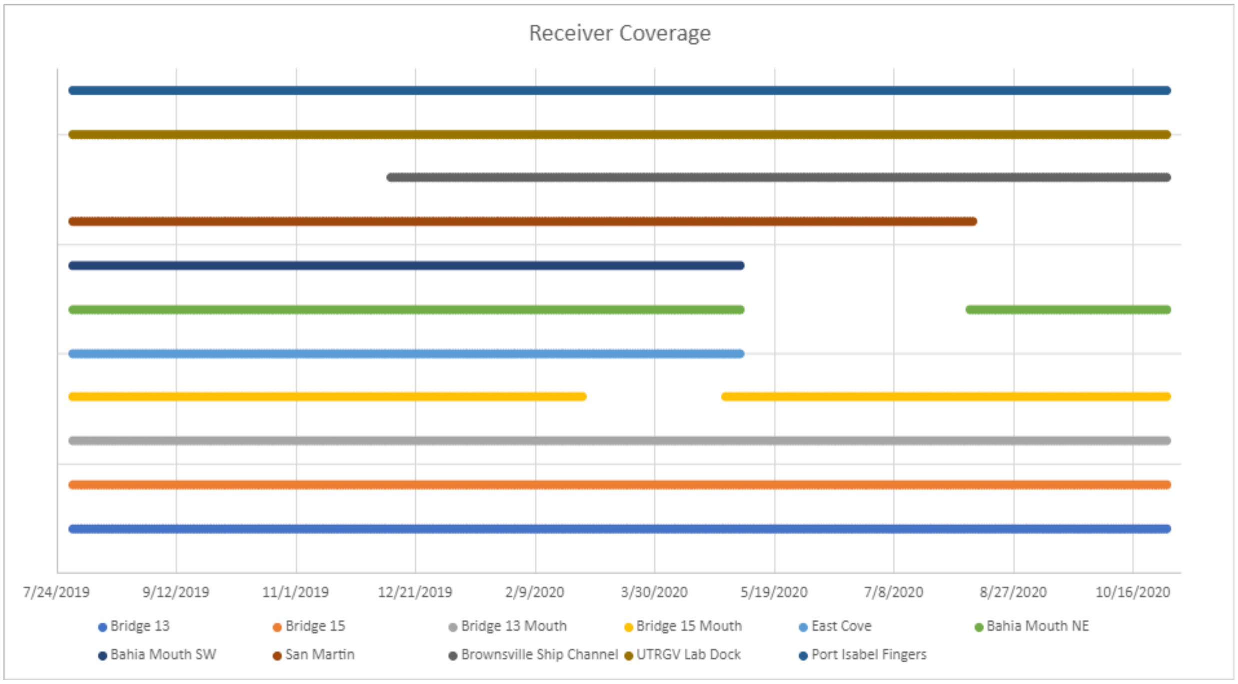

Figure 3. Coverage of acoustic receiver locations over the course of study showing dates where the receiver was actively monitoring from July 2019 through October 2020.

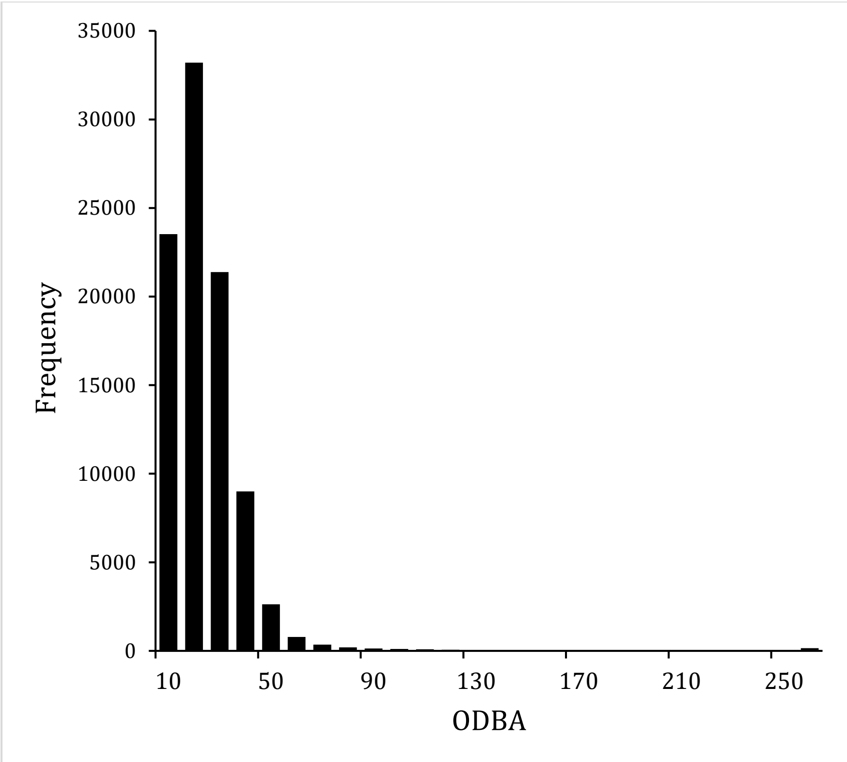

Figure 4. Histogram of accelerations recorded for Common Snook (*Centropomus undecimalis*) at all receiver locations occurring between July 2019 and October 2020.

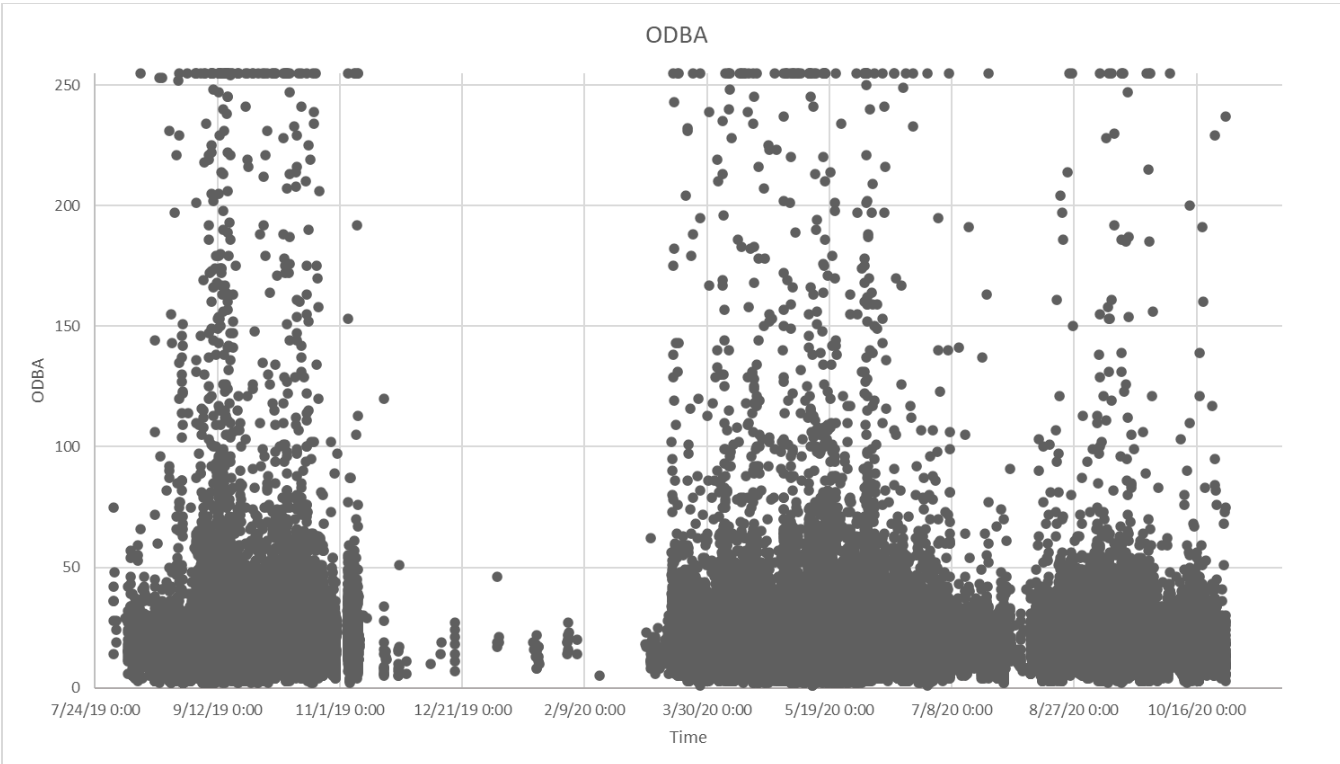

Figure 5. Scatter plot of Overall Dynamic Body Acceleration (ODBA) values collected from tagged Common Snook (*Centropomus undecimalis*) over the course of the study July 2019 through October 2020 at all nine receiver locations.

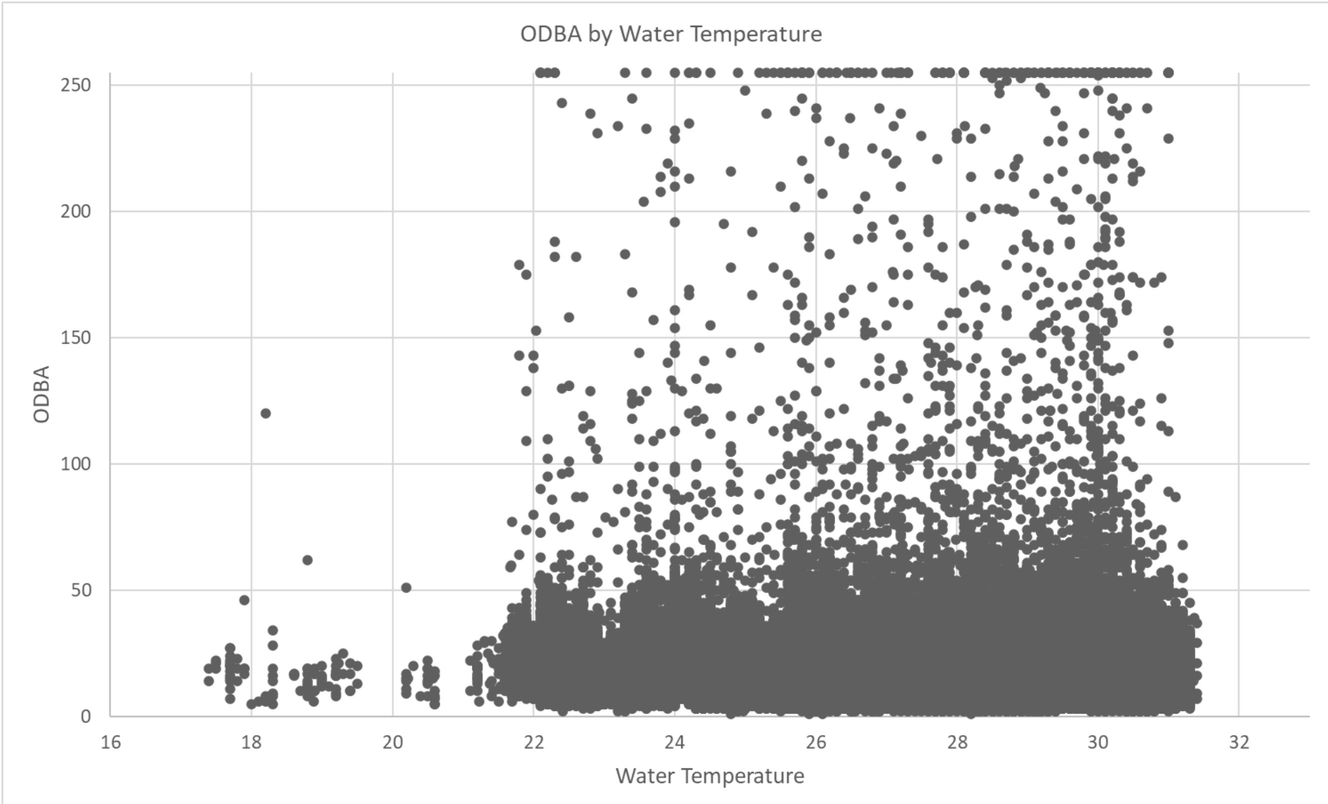

Figure 6. Scatter plot of Overall Dynamic Body Acceleration (ODBA) values collected from tagged Common Snook (*Centropomus undecimalis*) over the course of the study July 2019 through October 2020 at all nine receiver locations plotted against water temperature (C).

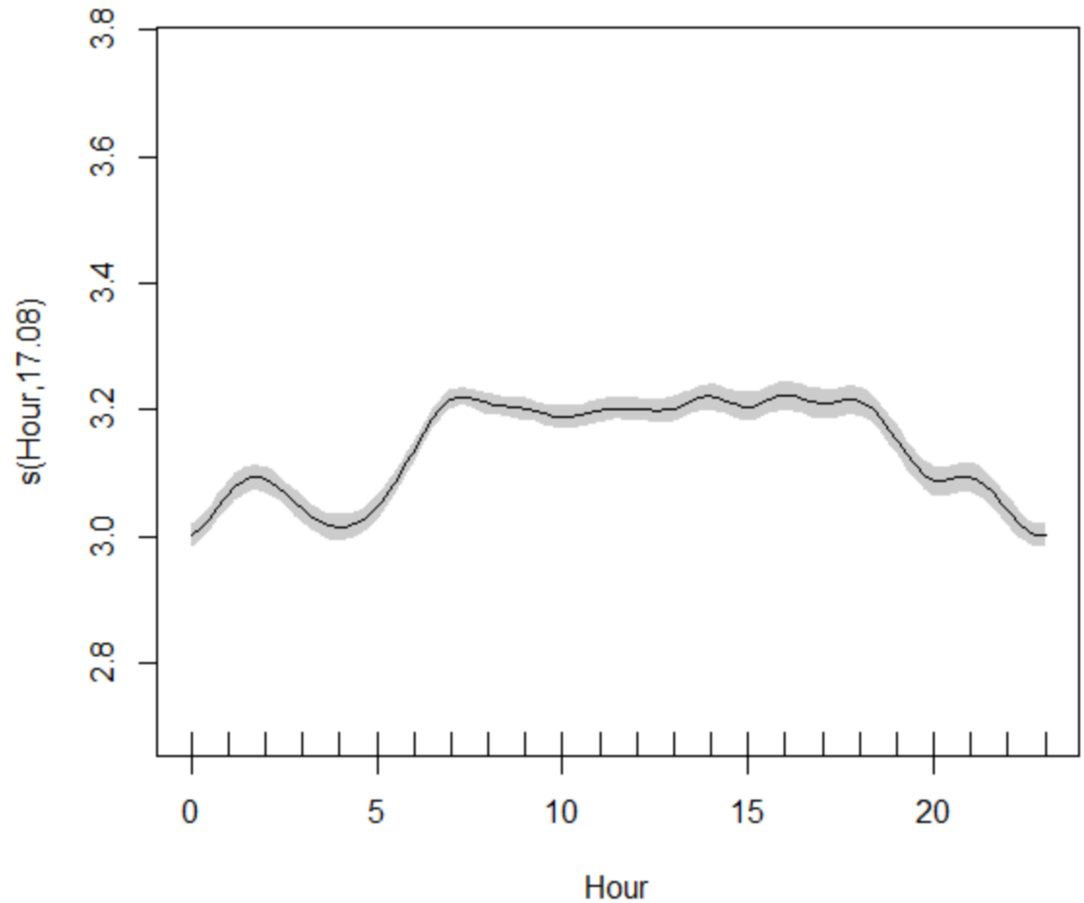

Figure 7. Response plot from the generalized additive model (GAM) of hour of the day relative to the overall dynamic body acceleration (ODBA) of Common Snook (*Centropomus undecimalis*). The y-axis represents the spline function. The x-axis represents the variable value. The gray area represents the 95% confidence interval.

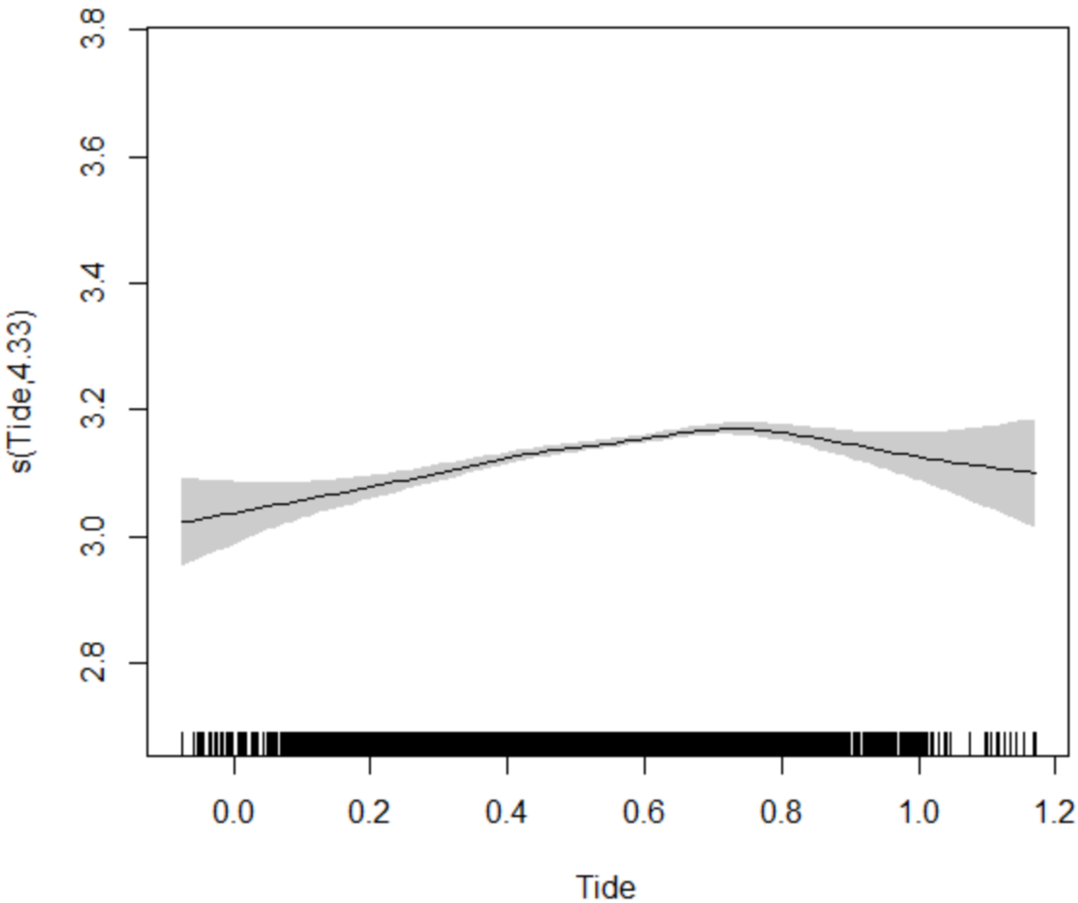

Figure 8. Response plot from the generalized additive model (GAM) of tide height relative to the overall dynamic body acceleration (ODBA) of Common Snook (*Centropomus undecimalis*). The y-axis represents the spline function. The x-axis represents the variable value. The gray area represents the 95% confidence interval.

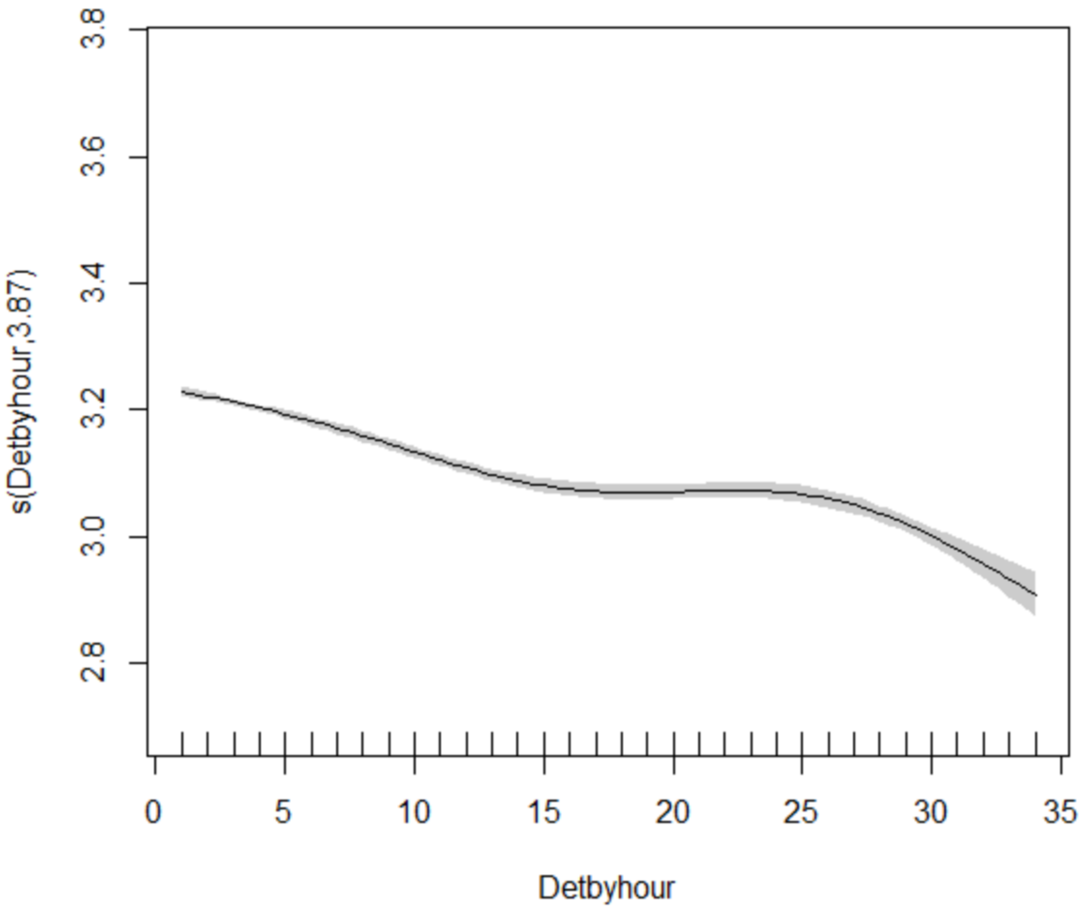

Figure 9. Response plot from the generalized additive model (GAM) of detections by hour relative to the overall dynamic body acceleration (ODBA) of Common Snook (*Centropomus undecimalis*). The y-axis represents the spline function. The x-axis represents the variable value. The gray area represents the 95% confidence interval.

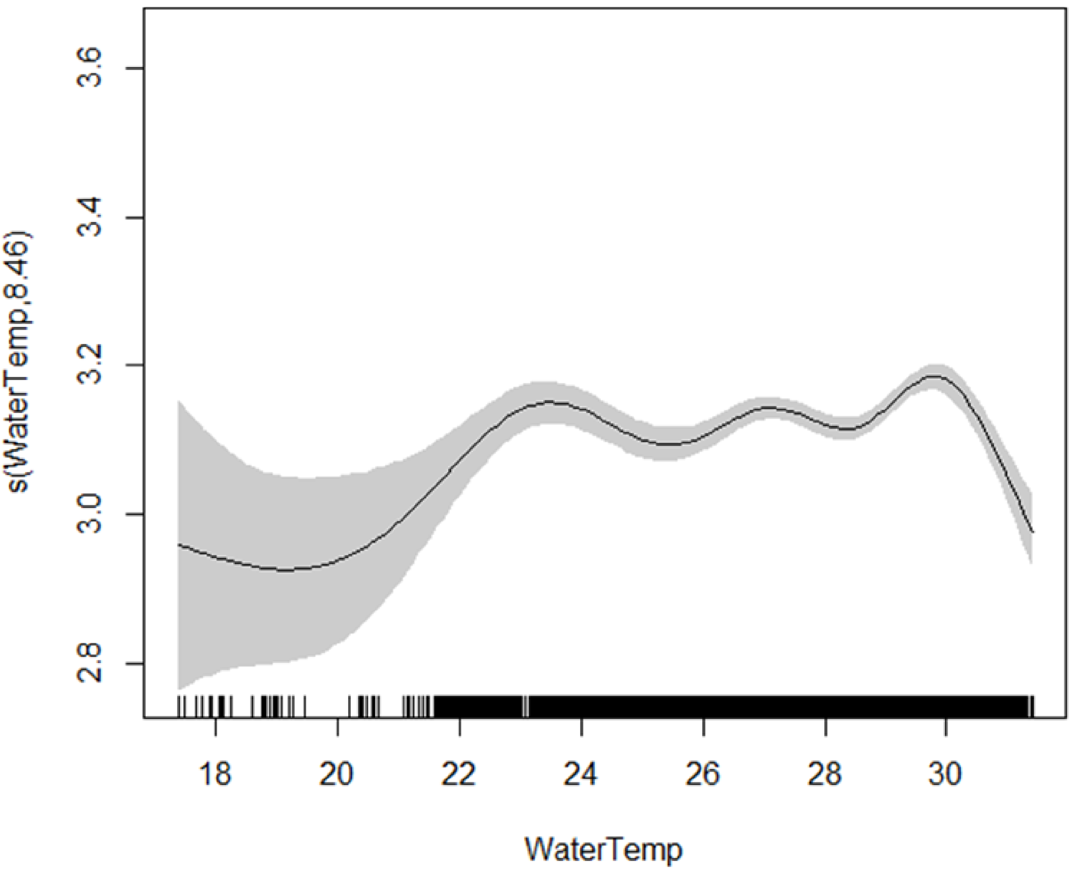

Figure 10. Response plot from the generalized additive model (GAM) of water temperature relative to the overall dynamic body acceleration (ODBA) of Common Snook (*Centropomus undecimalis*). The y-axis represents the spline function. The x-axis represents the variable value. The gray area represents the 95% confidence interval.

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BIOGRAPHICAL SKETCH

Jonathan Truett Cawlfield attended Texas Tech University and earned his Bachelor of Science in Natural Resource Management with a specialization in Wildlife Biology in May 2016. While at Texas Tech, Truett assisted with quail research through the Quail-tech research program across northern and western Texas, trapping, tracking, sampling, and monitoring birds on cooperating ranches. After graduating, Truett worked as a fly fishing guide on the Lower Laguna Madre. In the fall of 2018 Truett began his Master of Science at the University of Texas Rio Grande Valley which was completed in December of 2021.

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