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Evaluating Elasmobranch Bycatch and Shark Depredation in the Georgia Shrimp Fishery

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EVALUATING ELASMOBRANCH BYCATCH AND SHARK DEPREDATION IN THE GEORGIA SHRIMP FISHERY

by

MATTHEW M. SCANLON

Under the Direction of Christine Bedore

ABSTRACT

The Georgia shrimp fishery has seen a dramatic decrease in profit and productivity since the 1980’s due to a number of economic factors. Additional, yet undocumented, pressures on this fishery include interactions between foraging sharks with trawl gear. Fishermen report that sharks frequently bite nets in an attempt to prey on netted fish, resulting in large holes in the gear. Further elasmobranch interactions with trawl gear occur as bycatch; shrimp trawls represent nearly 100% of elasmobranch commercial bycatch in Georgia state waters, the species composition of which is largely unstudied. Shark interactions with nets were detailed through fishery-dependent observations on commercial shrimp boats in Georgia (n= 6 vessels). Number of damaged sites, location of damage on the net, estimated repair time, and many fishing/environmental variables were recorded for 96 trawling events May 2016 - November 2017. Sharks bit on average 1.51 holes (± 0.2 SE) in the nets for every trawl. Shark depredation was correlated negatively with vessel speed (\(\rho=-0.2814, p=0.005\)), and positively with the duration and number of nets (\(\rho=0.2799, p=0.006\)). As a result, fishermen spent an average estimated time of 27 minutes repairing equipment for every trawl they make in a day of fishing. Fishermen were also asked questions related to their perceptions towards this issue for qualitative analysis. Elasmobranch bycatch was also identified and measured for each trawl. Of fifteen total species caught, three species in particular accounted for 76.7% of all elasmobranch bycatch (n=84 trawls, 2247 individuals): *Rhizoprionodon terraenovae* (CPUE = 4.2 individuals/hm² area trawled ± 0.83 SE), *Hypanus sabinus* (CPUE =1.736 ± 0.29), and *Gymnura micrura* (CPUE =1.6 ± 0.22). Because the fishery has decreased in size and effort over the last two decades, further analysis and monitoring is needed to determine if bycatch in shrimp trawls are drastically decreasing stock sizes in elasmobranch species.

INDEX WORDS: Shark, Elasmobranch, Fisheries, Depredation, Bycatch, Conservation
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by

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I. INTRODUCTION

The Georgia shrimp fishery is an integral part of the socioeconomic culture of southeastern and coastal Georgia (Scott-Denton et al. 2012). Shrimp fishermen are often part of families that pass on their vessels, equipment, and advice from generation to generation (Blount 2007; Griffith et al. 2015). Small towns in the coastal south Atlantic region have built entire communities around fishing industries and depend on fisheries for economic survival (Coburn et al. 2006; Blount 2007).

The Georgia fishery targets both white shrimp (*Litopenaeus setiferus*) and brown shrimp (*Farfantepenaeus aztecus*). Both have short life-cycles and therefore stocks are generally replenished annually (Garcia et al. 2007). Fishermen capture the shrimp as they migrate from in-shore regions within the estuaries where the shrimp grow, towards the open ocean where they spawn (Wenner et al. 2005). Adult white shrimp migrate in the late spring and fall months while brown shrimp migrate in summer, therefore fishing effort is highest May - November (Belcher and Jennings 2011; Scott-Denton et al. 2012; Kovacs and Cox 2014). The Georgia Department of Natural Resources (DNR) regulates the shrimp fishery and is responsible for state-wide management decisions. The fishery in state waters is typically open from mid-June through mid-January, however the DNR commissioner has the authority to open it as early as May and close it as late as February depending on shrimp stock assessments (Georgia Department of Natural Resources 2018). Federal waters are only closed in early spring and effort is usually highest in these areas April-June (Belcher and Jennings 2009, 2011).

Shrimp migration routes throughout their life cycle overlap spatially with documented nursery habitat for coastal elasmobranchs (shark, rays, and skates) such as the Atlantic sharpnose shark (*Rhizoprodon terraenovae*) (Wenner et al. 2005; Belcher and Jennings 2009, 2011). This is an example of a small coastal species that has been found to pup May-July, which is during heavy shrimp trawling season (Belcher and Jennings 2009, 2011). Early shrimp fishing season
also overlaps with the time of year that blacktip sharks (*Carcharhinus limbatus*) are migrating north following baitfish (Keeney et al 2005; Kajiura and Tellman 2016).

Georgia coastal ecosystems are an ideal place for many elasmobranch species, whether year-round or seasonally, due to a warm climate and relatively undeveloped coastline. Because of this overlap spatially with the fishery there are conflicting interactions that occur between vessels and elasmobranchs. The non-selective nature of trawling, even with the use of Turtle Excluding Devices (TEDs), means juvenile sharks and batoid elasmobranchs may be incidentally caught in the gear with a high mortality rate (Diamond 2002; Stobutzki et al. 2002; Clarke et al. 2015). Another way elasmobranchs reportedly interact with the shrimp fishery is through depredation by large coastal sharks, such as migrating or resident blacktips (Kovacs and Cox 2014).

Conversations with fishermen and the Georgia SeaGrant Marine Extension have revealed that these sharks are frequently observed attacking the shrimp nets while the catch is being hauled on board, and associated gear damage is an increasingly frustrating economic cost (B. Fluech and L. Parker, *pers comm*).

This study aims to characterize and quantify these interactions between the Georgia shrimp fishery and elasmobranch species. Shark depredation of trawl gear is described and quantified for the first time, and the results offer suggestions for fishermen to reduce the frequency and severity of damage. Bycatch rates of shark species on a subsample of commercial vessels are reported for the first time in a decade, and overlooked ray species are included to get a baseline measurement of how frequently they are caught and what environmental variables are associated with the assemblage of elasmobranchs affected by the fishery.
II. CHAPTER 1: CHARACTERIZING THE FREQUENCY AND POTENTIAL IMPACTS OF SHARK DEPREDATION IN THE GEORGIA SHRIMP FISHERY

BACKGROUND

Fisheries of all types report struggles with depredation of catch and gear (Weise and Harvey 2005; Gillman et al. 2008; Peterson and Carothers 2013). In fisheries, depredation is defined as the attacking and subsequent damage of target catch or fishing gear, usually by non-target predatory species. Marine fish and invertebrates are usually caught commercially in two main ways: aggregation of schools with trawls or large nets or by baiting targets to gear such as hooks. Both of these methods potentially draw the attention of predatory species, which see the aggregation of catch or hooked individuals and bait as a foraging opportunity. When predatory species (usually marine mammals, sharks, or birds) are attracted to the fishing gear, their predatory behavior can result in damage to the catch or to gear. The resulting loss of catch, functional gear, and reduced quality of catch from depredation has the potential to be an economic hardship for the fishery and a source of frustration for stakeholders.

Studies have quantified marine mammal depredation and associated mitigation techniques in a number of fisheries (Hernandez-Milian et al. 2008; Hamer et al. 2012; Peterson and Carothers 2013; Rabearisoa et al. 2015; Tixier et al. 2015; Werner et al. 2015). Examples of economic damage via predator depredation of catch or gear in fisheries are common. Central California salmon fisheries have suffered substantial gear and product losses due to depredation from California sea lions (*Zalophus californianus*). Commercial fishermen lost an estimated $22,333–$60,570 of cumulative gear damage annually in a 1997-1999 study, and up to $504,548 due to take of their catch (Weise and Harvey 2005). In Brazil, longline tuna and swordfish fisheries experience depredation from both sharks and killer whales (*Orcinus orca*). Sharks are the source of year-round, frequent depredation, whereas killer whales are responsible for seasonal and more severe instances of depredation (Dalla Rossa and Secchi 2007). A similar conflict between spotted-necked otters (*Lutra maculicollis*) and artisanal long-line fishermen in the Hlan
River, West Africa, has been studied via fishermen interviews and observation (Akpona et al. 2015). Fishermen report otter depredation to be frequent and severe, illustrated by the researchers’ observation that they lose 9% of their monthly income to fish loss or gear damage from otters.

Most shark-focused studies have centered on depredation in longline fisheries (Gilman et al. 2008; Brill et al. 2009; Jordan et al. 2013). Longline fishers worldwide experience depredation of their catch, with pelagic species such as tuna removed from hooks or captured with severe damage and bite marks that make them substantially less valuable. Fishermen have developed avoidance strategies to help mitigate these interactions that are different from fishery to fishery (Gilman et al. 2008; Peterson and Carothers 2013; Tixier et al. 2015). Some avoidance strategies are logistical, such as the use of specialized equipment, while others are behavioral such as avoiding chumming or changing fishing location (Neis et al. 1999; Gilman et al. 2008; Brill et al. 2009; Jenkins and Garrison 2012; Jordan et al. 2013; Peterson and Carothers 2013).

For a number of reasons, American shrimp fisheries are decreasing in size, effort, and profits and therefore any additional cost is increasingly burdensome for fishermen (Coburn et al. 2006; Blount 2007). In Georgia, a potentially significant burden to fisheries is gear damage via shark depredation. Shark depredation in trawl fisheries occurs worldwide, yet it remains vastly understudied, possibly because it is considered an occupational regularity (Fertl and Letherwood 1997). This is particularly true in trawl fisheries where the damage is done primarily to gear as opposed to reduction in quantity or quality of target catch. Long-line fisheries inherently have a different outlook on shark depredation compared to trawl fisheries because the presence of large sharks attracted to their hooks can offset the depredation costs with the capture and sale of the sharks (ex. Thresher sharks, *Alopias spp*; Gilman et al. 2008). Shrimp fishermen in the United States incidentally catch small sharks of no regional economic value, whereas large sharks attracted to their gear are not captured because of size selectivity of the catch by mandated turtle
excluding devices, or TEDs (Belcher and Jennings 2011; Hataway et al. 2017; Garst and Oxenford 2018).

Georgia shrimp fishermen frequently express frustration as sharks interfere with gear and fishing efforts during these depredation events. Sharks bite nets in an attempt to prey on fish that are both collected in the bag and gilled in the netting, resulting in large holes in the mesh or entanglement of the animal in the gear (B. Fluech and L. Parker, pers comm). These external attacks from sharks can cause substantial damage to nets and have the potential to completely halt fishing efforts. Georgia shrimp fishermen report that they are forced to spend many hours repairing equipment by sewing the nets at the end of the day after fishing. With target catches and profits harder to come by, regular inconveniences such as repairing and replacing fishing equipment can become a more significant economic hardship when they take away from time that could be spent fishing and can diminish morale among captains and crew (Fertl and Leatherwood 1997; Gilman et al. 2008; Peterson and Carothers 2013; Tixier et al. 2015). Shark depredation in shrimp fisheries has only been referred to briefly in studies that are primarily focused on dolphin behavior associated with shrimp trawls (Fertl and Leatherwood 1997; Kovacs and Cox 2014). The frequency and severity of shark depredation on shrimp fishing gear was not quantified or characterized in these studies.

The eventual limiting of gear depredation by organisms such as shark species in fisheries first requires a understanding of specifically what organisms are responsible for the depredation and the set of ecological variables that facilitate that organism’s presence in the system with the fishery. In oceanic systems, environmental variables such as temperature, dissolved oxygen, salinity, and tide can drive large differences in fish behavior, reproduction, and community structure. Temperature is a significant factor in many large aggregative migrations seen in elasmobranch species such as the blacktip shark (Bizzarro et al. 2009; Kajiura and Tellman 2016). Much of this stems from associated biological changes in the environment at lower trophic levels that influence higher trophic levels to change their behavior respectively, such as blacktip
migration correlating to menhaden migration in the western Atlantic. It is likely that because variables such as these correlate to fluctuations in local population sizes, that variables of shark depredation would also have similar relationships and identifying them can help to inform stakeholders on how to avoid these conditions. Determining environmental covariates that can indicate a larger fishery impact under specific conditions is an important aspect of fisheries biology.

This issue of shark depredation has been a problem within the fishery for a number of years, and fishermen are growing increasingly frustrated with the lack of study and options to alleviate this financial concern. While a fishery-independent approach to studying this issue would offer the ability to make clear conclusions through experimental controls, a fishery-dependent and interdisciplinary approach was also a valid option due to the human dimension of this issue and how it is experienced by stakeholders. Observing shark depredation on working shrimp trawlers with the ability to ask fishermen questions via semi-directed interviews allows for a greater understanding of the problem and how it affects them and reduces the likelihood of misunderstandings between stakeholders on what can be a sensitive topic. Achieving a baseline understanding on the frequency, severity, and economic cost of shark depredation through a fishery-dependent approach at the onset of studying this issue can facilitate more controlled, targeted study in the future that addresses solutions that can be offered.

This study documents the presence and severity of shark depredation in a south Atlantic trawl fishery. Through on-board observing of six commercial shrimp vessels in Georgia, the presence of sharks and the resulting damage on nets was quantified during the 2016 and 2017 shrimp trawling seasons. A qualitative pilot study was also conducted using semi-structured interviews with fishermen that were used to give insight on the scale of depredation and perceptions of the cause and severity of the problem for resource users (Mackinson and Nottestad 1998; Weller 1998; Neis et al. 1999). Environmental variables such as water temperature and depth can influence the spatial distribution of both teleost fish and their elasmobranch
predators (Kajiura and Tellman 2016). Because it is likely that shifts in these parameters and subsequent shifts in shark populations would correspond to changes in depredation rates through the shrimping season, many of these variables were quantified and compared to depredation measurements to determine what environmental variables are related to prevalent gear damage. Variation among the fleet’s human-based fishing behaviors such as bycatch disposal, trawl duration, and gear configuration can lead to potential differences in the amount of depredation a vessel experiences; these were observed and quantified as well to determine if some boats exhibit fishing behaviors that increase or decrease shark depredation. The results of this study can potentially be used by fishermen to make informed decisions regarding shark presence that could decrease frequency and severity of depredation that is currently resulting in economic hardship.

METHODS

Fishery-dependent observation of shark depredation and stakeholder perceptions

In order to accurately quantify and characterize the nature of shark depredation in the Georgia shrimp fishery, an interdisciplinary approach that incorporates both biological observation and consideration for fishermen’s perceptions toward the issue was necessary due to how this issue is experienced by stakeholders. I incorporated the anthropological technique of participant observation to record both quantitative and qualitative data relating to patterns and frequency of shark depredation on a sub-sample of vessels in the Georgia shrimp fishery (Bernard 2011). A participant observation approach allowed me to gain access to these boats and learn their patterns and fishing behaviors, while methods associated with fisheries observing, behavioral observation, and semi-structured interviews allowed data collection and opportunities to quantify this peculiar problem (Glaser and Strauss 1967; Weller 1998).

In the spring of 2016, I was introduced to commercial shrimp fishermen in Georgia with vessels 40’-70’ long who allowed me to observe their fishing to document and quantify shark depredation. These vessels were typical of the methods, crew size, and practices of this fishery,
and the average vessel size in the fleet (53 feet) is solidly in the middle of the size range of vessels sampled (Georgia Department of Natural Resources 2017). In 2016 there were 261 commercial shrimp licenses sold in Georgia, including many non-resident trawlers that travel from state to state in addition to inactive vessels that fish infrequently. Participation in this study was completely voluntary (IRB protocol #H17015) and informed consent was obtained from each individual at the start of each session. Introductions to vessel captains were facilitated through collaboration with the University of Georgia Marine Extension Service. Vessel selection and the days that were chosen for observation were primarily based upon weather and the availability of the researcher and boat captains. Fishermen trawling procedures during observations were unaltered from normal commercial practices. Six vessels participated in this study: one from Chatham county, one from Liberty/Bryan county, one from McIntosh county, and three from Glynn county, GA. These vessels represented the geographic range of the fishery in Georgia, as Chatham county is the northernmost port in the state, Glynn the southernmost, and Liberty/Bryan and McIntosh are between them. Observations took place on at least a bi-monthly basis over the course of the 2016 and 2017 commercial shrimping seasons, April through November both years (Table 4).

Fishermen accounts suggested that shark activity is at its highest when a trawl net is hauled (i.e. brought on board and emptied). This was confirmed by observation where sharks were visually observed at the surface during trawls, foraging on and near the shrimp nets when they were brought up to the surface. Therefore, the number, species, and estimated size of sharks present around the nets during hauls was recorded. Photographs and video of sharks during hauls were used to record shark activity and positively identify species to the lowest possible taxonomic level. Any shark bites resulting in damage to the nets were recorded in terms of the number and size of resulting holes following every trawl. The extent of damage via holes was recorded as small, medium, or large categorically defined as having a diameter of <15cm, 15-30cm, and >30cm and given a “Damage Index” value of one, two, or three, respectively. For each hole, the
shrimp fishermen were asked how long they estimated it would take to sew each hole back together to achieve a value for “estimated repair time” in minutes. The location of shark depredation damage on the shrimp nets was documented for each instance of damage on the nets. This allowed us to identify problem areas on the nets that can be the focus for future deterrent work.

A number of variables were recorded and compared to variables associated with depredation to find patterns that might offer suggestions for fishermen to reduce depredation frequency. Temperature, dissolved oxygen, and salinity were recorded during each trawl using a YSI device. Turbidity was estimated to the nearest 0.25m using a secchi disk. Location, tide, and timing (duration, time of day, date) of each trawl was recorded using a handheld GPS unit at the beginning of trawls when nets were lowered into the water (trawl locations in Figure 1). A “distance from shore” value was calculated after uploading trawl coordinates onto ArcGIS 10.2 and using the vector tool. Vessel speeds (Kt) and trawl depth (m) were recorded from the boat’s instrumentation.

During on-board observations and dock-side interviews, I asked captains and crew a series of questions related to shark interactions (Appendix 3). Question responses were recorded verbatim in detailed notes, without identifying information. Written interview notes and information recorded during interviews was stored in a secure location. Consent to observe was given verbally by the captain and crew of each boat.

Semi-structured interview questions address general concerns and offered an opportunity for fisherman to propose their own solutions concerning elasmobranch interactions (Jacobsen et al. 2012). Interviewing in this format enables the interviewer to direct the line of questioning but allows for the subject to elaborate about personal experiences and guide the conversation however they see fit (Weller 1998). The questions were developed based on preliminary conversations with the fishermen and the need for accounts regarding specific variables that have to deal with shark depredation (Bernard and Gravlee 2014). Interviews included questions
designed to gather more information about the fishery’s state, perceptions towards sharks and management, and biological trends that fishermen may notice (Mackinson and Nottestad 1998; Weller 1998; Neis et al. 1999; Bernard and Gravlee 2014). Interviews were conducted with captains and members of the crew individually on vessels that were observed (Weller 1998). Interviews took place during regular fishing operation, in down times such as the sorting of the catch and during the trawls, or at the dock in the afternoon. Questions were asked verbatim to ensure standardization across all interviews, but respondents were able to direct the conversation and elaborate on any topic they felt was important. I recorded their responses by taking detailed and careful notes, and no identifiable information (name, vessel name, etc) was noted.

Statistical analyses

The following analyses were performed in order to test the hypothesis that certain environmental and fishing variables correlate to higher frequencies of shark depredation on trawling gear. In particular, I hypothesized that temperature, and therefore seasonality, would positively correlate with higher rates of shark depredation. I also hypothesized that fishing behaviors that can lead to a larger or longer sensory signals being released into the water, like the duration of trawls, number of nets, and bycatch disposal during trawls, would result in more frequent depredation in vessels that exhibited them. Rates of depredation, including estimated repair time, damage index, and number of sharks observed biting nets were standardized on a per net basis to minimize bias towards trawls where four nets were used as opposed to the more common two nets. Spearman-rank correlations evaluate continuous environmental (e.g. temp, DO) and fishing variables (e.g. tow speed) on measurements of depredation (e.g. damage index, shark presence, estimated repair time). Nonparametric ANOVA (Kruskal-Wallis) tests compared proportions, presence-absence, and extent of shark damage between categorical variables (vessel, season, etc). Environmental variables and fishing variables such as depth and temperature were compared to depredation response variables using spearman rank correlations (α=0.05;
The proportion of nets that had incurred shark damage was compared among months using Chi-squared test ($\alpha=0.05$; Weise and Harvey 2005; Belcher and Jennings 2011).

To determine how significant variables affecting the frequency of shark depredation perform additively, shark depredation presence or absence was modeled using a binomial generalized linear model with a logit link function. A correlation matrix was made between all environmental and fishing variables, and if two variables were highly correlated ($r>0.6$) only the one more normally distributed (according to Shapiro-Wilk W tests, $\alpha=0.05$) was included in models. Variables were added and removed from the model using backward selection until all combinations of variables had been evaluated. Initially all variables were entered into the model, and from there the least significant variable was dropped one at a time. If the removal of an insignificant variable caused a change in the significance determination of another, it was added back into the model and the next most insignificant variable was removed. This process was orchestrated until all remaining variables in the model were found to be significant. Significance for variables influencing the rate of depredation was established at $\alpha=0.05$. If variables were insignificant statistically with great effect on the significance of other variables, model performance was also evaluated based on Akaike information criterion adjusted for sample-size (AICc). In these cases, the model that had the lowest AICc value was determined to be the best model.

In order to identify fishing behaviors that influence the frequency of shark depredation, behavioral observation techniques were used throughout the day of fishing. I focally followed the crew members as they deployed and hauled the nets, recording every occupational behavior and the time when it occurred. This included entries such as “hauled nets”, “washed deck”, “discarded bycatch”, “cleaned nets”, etc. Behaviors were coded, and the order and timing/duration in which they occur was compared to other vessels and compared to shark depredation frequencies that are recorded via biological monitoring (Bernard and Gravlee 2014). Behaviors that could potentially
attract sharks (e.g., bycatch disposal when nets are in the water) were identified and vessels were categorized into whether they exhibited that behavior or not. Depredation rates and the number of sharks present around the nets at haul time were compared among categorized behaviors using a non-parametric Wilcoxon-Mann-Whitney test \((\alpha=0.05; \text{Belcher and Jennings 2011})\). The depredation rate, both by damage index and estimated repair time, was found to not differ significantly between any pair of vessels observed in the study, mostly due to large within-vessel variation. However, the presence of these potentially difference-making behaviors in addition to uneven sampling among boats warranted the depredation binomial model have a nested structure using random effect variables that could account for these differences. Because individual net was the basis on the response variable, and every trawl has multiple nets with one set of environmental variable measurement on basis of trawl, trawl ID also needed similar treatment. Trawl ID was nested within the date that it took place (maximum of four trawls in a day, the minimum was one) and this together was treated as a random effect variable, along with the identity of the vessel separately.

A preliminary grounded-theory approach (see concept map, Figure 10), in conjunction with biological data collected, was used to identify and link concepts that fishermen state in interviews \((\text{Glaser and Strauss 1967; Jacobsen et al. 2012})\). Peterson and Carothers \((\text{2013})\) used similar and more intricate analysis techniques to evaluate the effects of cetacean depredation in an Alaskan fishery and many of the techniques they used and types of questions asked were adopted in this study because of the similar nature of study objectives. Statements in the interviews were coded for thematic content based on inductive coding methods. Inductive coding allows the codes, which are used to quantify qualitative data, to be derived from the interviewed participants’ answers \((\text{Weller 1998, Peterson and Carothers 2013})\). Each code was analyzed for frequency, repeatability, and co-occurrence with other codes. Statements and perceptions were grouped into the coded categories and the percentages of respondents that make similar statements were compared. For example, question #1, “What is the state of the Georgia shrimp
fishery?” answers were coded as “positive”, “negative”, or “other”. Using these coded answers, I made comparisons and analyzed how fishermen’s perceptions related to shark depredation and associated effects on the fishery. The codes, listed in Appendix 3 with the questions, can also be used to identify recurring concepts regarding depredation and willingness to use shark deterrents that can be linked to develop narratives that accurately describe the scope of the problem (Peterson and Carothers 2013).

RESULTS

Quantitative analysis of shark depredation

A total of 218 nets from 96 trawls on six vessels were observed in Georgia waters over the 2016-2017 commercial shrimping seasons (Table 4). Throughout the study, 38.5% of nets were damaged by sharks. Shark species directly observed in depredation of shrimp trawl gear during this study were primarily blacktip or spinner sharks (Carcharhinus limbatus or C. brevipinna), with bull (C. leucas), lemon (Negaprion brevirostris), sharpnose (Rhizoprionodon terraenovae), and blacknose sharks (C. acronotus) also identified infrequently. There were significant correlations between the number of sharks present and four variables. There was a significant negative relationship between the number of sharks observed during hauls and speed (Figure 2A, Spearman-rank correlation, $\rho$=-0.2814, $p$=0.005) and dissolved oxygen (Spearman rank correlation, $\rho$=-0.2531, $p$=0.0218). A positive correlation was found between number of sharks and the duration of trawl multiplied by the number of nets in the water (i.e. total submergence time; Figure 3, Spearman rank correlation, $\rho$=0.2799, $p$=0.006). Shark presence differed significantly across months (Kruskal-Wallis, $n$=96 trawls, $df$=7, $p$=0.029), with the highest mean number of sharks in April (Mean=4 sharks ±1.5 SE), May (3.5±0.63), and August (3.53 ± 0.5) before quickly declining in October (1.1 ± 0.69) and November (0.71 ± 0.82).
When months were grouped by season (spring=March-May; summer=June-August; fall=September-November), depredation frequency did vary, with summer having the highest incidence of depredation (44% of nets) compared to spring (40%) and fall (26.7%) but these differences were not significant (chi square test; \( n=218 \) nets, \( X^2=5.293, p=0.07 \)). Seasonal groupings were based off differences in how the fishery operates: only federal waters farther than 3 miles offshore are open before June, June-August primary catch is white shrimp, and in the fall the target catch shifts towards brown shrimp. Proportion of nets damaged by month is displayed in Figure 4: the highest frequency of damaged nets was in August (52.1%) before dropping off to the lowest frequency (7%) in November. The proportion of nets where shark damage occurred did not significantly differ by vessel (chi square test, \( n=218 \) nets, \( X^2=8.5, p=0.2 \)).

Nets were classified on the basis of presence-absence of shark depredation. Nets that had incurred net damage from sharks occurred in significantly warmer water (Figure 5, Kruskal-Wallis, \( n=218 \), \( Z=2.31, p=0.02 \)). When shark damage was present in a trawl, the mean temperature of the water was 27.12°C (±0.294°C SE) compared to 26°C (±0.286°C SE) in trawls where nets emerged undamaged.

Data of damage index per net of every trawl was Hellinger-transformed due to a large proportion of zero’s in the data set. This transformation is common in fisheries-related studies with zero-inflated data, as it separates values with zero from values above zero to place emphasis on presence-absence. Damage severity did not differ between seasons, but trawls in November had significantly lower damage index compared to all months aside from July and October. Shark depredation severity was not correlated with a reduction in shrimp CPUE (lbs. head-on shrimp / net / hours trawling; Pearson correlation, \( p=0.35 \)). There was a significant relationship between shark depredation damage index and the approximate number of sharks observed near the surface during the haul (Figure 6, Linear regression, \( r^2=0.229, p<0.001 \)). As was the case with shark presence, Hellinger-transformed depredation index was negatively correlated with vessel speed (Figure 2B, Pearson correlation \( r=0.42, p=0.04 \)). Despite small differences in fishermen
behaviors, there were no significant differences between the mean depredation index in any pair of vessels (Kruskal-Wallis, $n=96$, $p=0.37$).

A binomial model (Table 2), with the presence or absence of shark depredation the response variable, was created to analyze how fishing and environmental variables additively affected the occurrence of shark damage. The model, created using reverse selection, had two variables that were significant: temperature ($p=0.001$) and the depth of the trawl (0.021). Depth and temperature, while they do not correlate with each other in this relatively shallow-water fishery, additively perform well in conjunction in a binomial model predicting presence or absence of depredation. Taking temperature into effect with vessel, trawl, and date entered as random effects, shark depredation of nets was more likely to occur in deeper and warmer water.

Mean shrimp catch was highest in the summer months (37.6 lbs. shrimp per net per hours trawling $\pm 6.6$ SE) compared to spring and fall, which had similar CPUE values (21.37 vs 26.47 CPUE, respectively). By month, September had significantly higher average shrimp CPUE (36.54 $\pm 4.783$) compared to all months aside for July (45.98 $\pm 13.58$; Kruskal-Wallis $X^2=17.97$, $p=0.012$). Predictably, these monthly differences translate to shrimp CPUE being positively correlated with water temperature ($n=96$ trawls Pearson correlation, $r=0.255$, $p=0.015$).

**Qualitative analysis of fishermen perspectives**

Stakeholders, in this case captains and crew members of boats observed in addition to fishermen spoken to at docks, were united in some of their perceptions towards shark depredation and divided in others. The seventeen fishermen and crew interviewed in this study vary widely in age (19-70 years old) and were all male. About half of the subject’s interviewed had a positive outlook on the fishery (Figure 7A) as a whole while the other half thought the fishery was going the wrong direction or that success depended on a multitude of factors (Foster and Vincent 2010). One fishermen explained to me that the fishery is, “Not as good as it used to be. Some of us have
fallen on hard times. If you can learn how to hustle your shrimp you can still make money”. Many of the positive respondents mentioned shrimp fishing to be flexible with their schedules and provide enough monetarily to be worth it. “It’s hard work, but I like being on the water”, one fishermen said which was emblematic of similar positive responses. Some fishermen claimed that establishing connections or that learning by trial and error has led to them being able to get more money for their shrimp, saying statements such as, “I have been doing it so long now that I know how to get good money for the shrimp”.

Twelve of seventeen stated a belief that shark depredation could not be avoided by changing locations, and their perceptions of which environmental variables indicated increased shark populations were more varied. Temperature, water clarity, and time of year were three common answers when stakeholders were asked which variables most influence increased shark depredation (see Concept map, Figure 10). All respondents named spring or summer as the highest depredation time of the season, consistent with observations of sharks and the corresponding damage. All respondents interviewed stated that shark depredation has either increased (65%) or stayed the same (35%) over the last few years, with no stakeholder indicating a decrease (Figure 7B). One McIntosh county fishermen raised a valid point that may explain some of this trend, stating that shark depredation has, “Always been a problem but worse now. Could be that there are less boats out shrimping that spread out the attention of the sharks”. Considering the dramatic decrease in the number of registered vessels since 1979, this could be an important factor to consider when evaluating why shark depredation is perceived to be increasing over the last couple of decades.

Fishermen were consistent in their evaluation of time spent sewing nets due to shark depredation. When asked how long it would take to repair all the holes observed on nets after a trawl, the overall average repair time was 27 minutes per trawl. When asked separately in interviews how much time they repaired nets daily, 65% of respondents believed the boat spent one to three hours sewing daily (Figure 7C). Assuming each day fishing has two or three trawls
(i.e. 87 minute average estimated repair time for a day of three trawls), these estimations are consistent with one another. Fishermen were also internally consistent with evaluating the time that damage took to repair in relation to the extent of the damage (Figure 8; \(n=96\) trawls, \(p<0.01\), \(r^2=0.8595\)).

All respondents indicated that shark depredation reduces target catch of shrimp either consistently or periodically. Most mentioned that monetary loss from sharks occurs primarily when sharks bite through the bag-end of the net, causing a loss of all shrimp. Two respondents said that additional catch can be lost when nets have been damaged and repaired repeatedly, changing the shape of the net and “warping” it. Two McIntosh county fishermen stated that they believe shrimp is being lost to increasing shark populations via predation. One crewmember from Liberty County stated that sharks and rays can clog the TEDs, reducing catch by blocking shrimp’s entry to the bag of the net. However, shark depredation did not appear to be a significant factor in their decision-making process on how and when to fish, with only one stakeholder stating that avoiding shark depredation was the most significant reason why he trawled where he did.

When asked about previously-tried techniques to reduce shark depredation, there was a surprising variety of topics that were brought up. Some respondents mentioned gear changes, such as using different colored nets or nets with smaller mesh size. Some were behavioral or logistical, like trying to fish in shallower and turbid water or limiting bycatch disposal to once a day. One McIntosh county fisherman said, “I try to stay in the mud to avoid the sharks. Catch different stuff every day,” a sentiment that was echoed by other fishermen in interviews. A few respondents recalled fishermen who have tried electrical impulses or magnets, or even more extreme measures such as dynamite or using fermented shark meat as a chemical stimulus to repel sharks. When asked if any of these worked, most stated that these techniques either didn’t work to their knowledge or that evaluation of effects were inconclusive.
Most fishermen did not have a positive perception towards the Georgia Department of Natural Resources. When asked if GA DNR is sympathetic to the concerns of fishermen regarding shark depredation, 53% (n=9 of 17) said “No”, while those remaining simply stated that they deal with the DNR very infrequently. For many fishermen this seems to be because of their own concerns within the fishery being unheard by regulatory agencies such as GA DNR and the South Atlantic Fisheries Management Council. They feel that they have expressed their concerns regarding shark depredation and other issues such as spatial or seasonal regulation and have been met with inaction or laws that only exacerbate problems. Because these problems are directly related to the economic anxiety that the fishermen are increasingly experiencing, many feel very strongly and enthusiastically about sharks and the laws and agencies protecting them. Some fishermen express negative sentiments towards shark conservation and regulation, believing that protections for sharks have led to the aforementioned increases in depredation. Eleven out of seventeen respondents believe that opening up or expanding Georgia shark fishing, whether commercially or recreationally, would be an effective solution to reduce depredation through population control (Figure 7D). One responded that, “*Maybe opening them up to be sold as meat. Not a huge fishery but something to bring down numbers. There used to be longliners and gillnets that caught sharks too*”, and many other interviewed also had similar comments regarding the expansion of shark fishing and how there used to be fisheries targeting them in the past. Three stakeholders mentioned spatial or seasonal deregulation would help offset the cost due to shark depredation. Of those eleven that wanted to expand shark fishing, seven stated a willingness to try a cost-effective (less than $300 per year) shark deterrent array should one be developed and proven to work.
DISCUSSION

Shark depredation and southeast coastal ecosystems

When sharks were observed following trawls, 72% of the sharks were positively identified as either blacktip or spinner sharks (*Carcharhinus limbatus* or *C. brevipinna*). Some male blacktip shark populations are known to follow a migration pattern, residing off the northern Atlantic coast in the summer months and swimming in large scale aggregations towards south Florida in the winter months. Kajiura and Tellman (2016) found that migrating blacktip populations off the coast of Florida spiked January-April most years, spatially and temporally correlating with the movement patterns of many species of abundant baitfish (Leggett and Whitney 1972). Large aggregations of blacktip sharks along the Florida coast are directly related to water temperature, as notable blacktip presence was only discovered in water 20-25°C (Kajiura and Tellman 2016). Shark depredation and observed presence was highest in Georgia May-August, which could correspond to this blacktip migration aggregate on the return north. The late part of this range of time for high depredation typically had water temperatures in the high 20’s, so this could implicate female blacktip residents or spinner sharks that are not participating in the temperature-driven migration.

Many species of coastal Atlantic shark use estuarine systems and channels as nursery areas for their young (Baum et al. 2003, Keeney et al. 2005, NMFS 2007; Belcher and Jennings 2009). Some of these species include blacktip, bonnethead (*Sphyra tiburo*), and sharpnose sharks (*Rhizoprionodon terraenovae*). This can lead to seasonal fluxes in local population sizes when adults move in and out of the estuaries to breed and/or pup (Belcher and Jennings 2009). Shrimp fishermen are not permitted to trawl in estuarine channels, but they do trawl in coastal areas at the mouths of river deltas and along the barrier islands adjacent to the estuary. Because the Georgia coast is relatively undeveloped compared to much of the coastal Atlantic and has such an expansive estuarine system, it can be hypothesized that adult sharks not only use these areas as a stopover on long migrations to breed and pup, and but also as longer-term residents.
who can use the productivity of these systems to forage year-round (Bryan Frazier, SC DNR, personal communication). The combination of nursery, resident, and migratory individuals in spring and summer overlap with the shrimping season. This leads to large populations of adult sharks looking for foraging opportunities in the waters near the estuary, which likely corresponds to high depredation rates on trawl gear.

Data on North Atlantic shark populations through time varies by species, and is somewhat contradictory in commonly cited interpretations. Baum et al. (2003) reported that most highly migratory shark species commonly caught in Atlantic longline fisheries were going through a population collapse. Shepherd and Myers (2005) made similar claims regarding coastal sharks in the Gulf of Mexico. Burgess et al. (2005) points out the extreme variability in sampling effort and validity of these observations and warns against making these conclusions based on limited sampling effort and inconsistent data collection.

_Shark depredation and effects on the Georgia shrimp fishery_

Shark depredation of trawl gear is known to be a problem for shrimp fishermen across the eastern seaboard (Fertl and Leatherwood 1997; Kovacs and Cox 2014). Despite being a clear and persistent issue, there have been no significant studies that quantify this problem as there have been with depredation studies on longline fisheries and marine mammal species. This may be for a number of reasons; chiefly the nature of depredation affecting nets and gear in small shrimp fisheries as opposed to valuable target catch in longlines. Another difficulty in assessing depredation in trawl fisheries is accurately quantifying economic or physical damage. In longline fisheries, each line can have hundreds of hooks, and depredation frequency can be quantified based on the number of damaged fish caught during each set (Gilman et al. 2008). In trawl fisheries there is also a great variation in the size and type of nets and gear used that may cause minute differences in the frequency of shark depredation (Scott-Denton 2012).
Fishermen-influenced variables such as speed, number of nets, and duration of trawl had a more significant correlation with increased shark presence and depredation rates than non-seasonal differences in environmental variables such as distance from shore, turbidity, and location (Figures 2-3). Three environmental variables had a significant relationship with the number of sharks observed and depredation variables: time of year, temperature, and depth (Table 2, Figures 4 and 5). Seasonal variation in water temperature is high in the American southeast (below 15°C in winter, 30+°C degrees in summer). Fishermen often stated that they would try to stay in the “mud”, meaning closer to shore in more shallow and turbid water, to avoid sharks when the shrimp was plentiful inshore. Although damage index did not negatively correlate with turbidity, depth was found to be a significant factor in presence of shark depredation in the binomial multivariate model and this confirms the fishermen perceptions that they can reduce depredation by fishing in shallower water during the summer months.

When reporting observed damage repair time, fishermen estimated the average economic cost of shark depredation was 27 minutes of repair/sewing time for every trawl. Considering that the usual shrimping day consists of two or three trawls, this equates to at least a man-hour per day of net repairs on average across the entire fishing season. This is consistent with most estimates of repair time when asked generally, as 65% of stakeholders believe they spend an average of one to three hours sewing nets per day. Commercial shrimp fishing is physically and mentally exhausting work. Many crews meet at the vessel at 4:00-5:00am and do not return until 3:00-4:00pm, with varying returns in regards to shrimp catch and profits. For these reasons, it is apparent that the addition of this much work time sewing nets at the end of the long day is burdensome both financially for the boat captains and physically for the crew member tasked with sewing, and can result in decreased morale as the season progresses. This lost time could also be allocated for an additional trawl while out fishing, which could potentially be valued at hundreds of dollars daily depending on shrimp abundance. Most vessels in this fishery either sell
their shrimp to their dock which acts as a distributor or they have established relationships with local restaurants that they sell to.

Fishermen were unified in their exclamation of frustration dealing with shark depredation. They all agreed that shark depredation was at the least an annoyance, and most (71%, n=12 of 17) described depredation as causing a significant economic hardship. While there was variation in their perceptions of the how to avoid depredation and what factors were correlated with shark damage, they unanimously agreed that depredation has the potential to reduce shrimp catch, especially if repeated repairs alter the shape of the net or if the sharks are able to get through the end of the bag. Observation of trawls did not include an instance where all shrimp catch was lost due to depredation damage at the end of the bag, but this is rare, as this part of the net is typically reinforced with chaffing gear that present an additional barrier that is harder for sharks to pierce through. Fishermen stated that this usually happens once or twice a year. The bulk of the shark-induced damage occurred on the five meters of net preceding the TED (Figure 9). This area is where catch is funneled towards the end of the bag, and fish are frequently stuck or gilled in this area, potentially attracting the sharks. It is likely that this area and the chaffing-covered bag are attacked with the same frequency, but the affected area has more instances of damage due to a lack of protection.

Boat captains engage in a complex decision-making process on where, when, and how to fish (Dichmont et al. 2013; Peterson and Carothers 2013). Decisions on whether or not to trawl for shrimp on a given day are made on the basis of crew availability, weather, time of year, and catch of shrimp in the area in recent time periods. Decisions on where to trawl are usually made on the basis of tradition, convenience, and seasonal trends of shrimp catch. The results of this study can further add to this equation and knowledge-base to help inform how avoid shark depredation. Lower speed and longer net submergence time all correlated with increased shark presence which resulted in more depredation of nets. One explanation for this is that the more nets of catch the fishermen have, or longer and slower the nets are in the water, the more time
sharks have to follow and locate the source of the olfactory stimulus. Following the nets at higher trawl speeds may also be energetically costly for the sharks. Captains that have the ability to use fewer nets or trawl faster in shorter intervals can use this information to potentially lower the amount of shark depredation.

Fishery troubles and need for additional study

The Georgia shrimp fishery and other similar penaeid shrimp fisheries in the South Atlantic have seen a large decline in effort and productivity since the late 1970’s. In 1979, there were 1471 commercial shrimping licenses sold for use in Georgia waters (Georgia Department of Natural Resources 2017). In 2016, the first year of this study, that number had been reduced to 261 (82.3% decline over 37 years). These numbers include all shrimp licenses for vessels of all sizes, from less than 20 feet to more than 100 feet in length, and those that are used infrequently or are from out of state. This sharp decline has been attributed to a number of causes. Some fishermen believe that the closure of the sounds for environmental protection in the 1980’s has decreased opportunities for large and valuable hauls (Blount 2007). Most agree that the devaluing of the shrimp due to foreign imports of farmed shrimp is a significant reason for the economic problems of the fishery (Blount 2007). Shrimp makes up almost 30% of all United States Seafood consumption. Almost 90% of this shrimp is imported from Asian and Latin American countries that have the ability through infrastructure and lax environmental laws to use aquaculture to farm shrimp in bulk (Blount 2007; Wirth and Davis 2017).

Despite hardships, the shrimp fishery is still the largest commercial fishery in the state of Georgia in terms of profit, with catch valued at an average of $8,843,060 annually, more than $5,000,000 more than any other state-wide fishery (Georgia Department of Natural Resources 2017). Commercial shrimp fishing is viewed as a way of life and is a significant part of the culture in small coastal Georgia cities such as Darien and Brunswick, and this sense of culture has not changed despite the decrease in fleet size (Blount 2007). Fishermen generally enjoy what they
do and their way of life, valuing the tradition and history behind it all. Every fisherman interviewed in this study either had shrimp fishing as a significant aspect of their family history or stated that they have been shrimping since they were young due to proximity and close relationships within the fishery.

Based on semi directed interviews and participant observation with these stakeholders, a recurring theme of contention between fishermen, management, and scientists was observed. Fishermen hear through various media outlets that shark populations are in the middle of a large decline. They have also observed the atrophy of local shark fisheries via regulation and economic decline. While global shark populations are indeed in the middle of long decline, much of the overfishing for these K-selected species are focused in countries that value sharks for their fins and have few protections for them (Bonfil 1994, Dulvy et al. 2014). While the population dynamics of northwest Atlantic shark species are unknown and vary yearly among species, for the most part these large declines in populations are not present in this area (Burgess et al. 2009). Fishermen, frustrated with seemingly-increasing shark depredation rates, do not personally observe these population decreases and therefore the distrust for regulatory agencies and the science behind them grows. One fisherman told me that shark depredation has, “Gotten real bad last few years. They sayin' the sharks are going extinct is a bunch of bull,” which is emblematic of this contention between these stakeholders. A Brunswick fisherman explained to me, “When the sharks start biting the tourists, maybe they [Management] will begin to care about the shark problems we see all the time.” Biologists should be more nuanced in their claims regarding shark populations so to not alienate the perceptions of fishery stakeholders, who spend the most time on the water and have a unique familiarity with coastal resources (Mackinson and Nottestad 1998; Neis et al. 1999; Coburn et al. 2006).

Further study of shark depredation is needed in trawl fisheries as fishermen grow more frustrated with the lack of solutions offered. While the opening of shark fisheries is ill-advised and unlikely, it is imperative for fisheries management to focus on all aspects and issues within
fisheries and not just those pertaining to resource availability and catch rates (Mackinson and Nottestad 1998; Neis et al. 1999; Dulvy et al. 2014). Studying shark depredation and avoidance strategies in Gulf of Mexico shrimp trawl fisheries would offer an interesting comparison, and analysis in other coastal Atlantic states such as North and South Carolina would also add to this knowledge-base. Fishermen are also willing to experiment with potentially effective shark deterrents such as Neodymium and galvanic reactions to equip on their nets in order to reduce depredation rates, and would welcome any new science that could help them out on this issue (Jordan et al. 2013).
III. CHAPTER 2: CHARACTERIZING ELASMORBANCH BYCATCH IN THE GEORGIA SHRIMP FISHERY

BACKGROUND

Elasmobranch populations worldwide are in decline, including many species in the North Atlantic (Baum et al. 2003; Burgess et al. 2005; Dulvy et al. 2014). A significant source of elasmobranch mortality is through incidental catch in fisheries targeting teleost or invertebrate species (Diamond 2002; Stobutzki et al. 2002; Molina and Cooke 2012). It is estimated that 7-38.5 million tons of non-target species are captured and discarded annually, making up 40% of all landings. Current estimates indicate that many pelagic shark species populations have declined by more than 50% in the past three decades as a result (Baum et al. 2003, Jordan et al. 2013).

Longline fisheries that target pelagic species, such as bluefin tuna (Thunnus thynnus), are heavily scrutinized for the incidental catch of sharks, sea turtles, and marine mammals (Smith 2013; Gallagher et al. 2014). These fisheries use non-selective methods that can hook many different species that exhibit similar feeding strategies. Trawl fisheries for benthic fish and invertebrates such as shrimp are more non-selective than longlines in nature, essentially capturing any organism that comes into contact with the nets being towed along the bottom of the ocean (Dell et al. 2009; Clarke et al. 2015). For example, trawl fisheries in the Gulf of Mexico contribute to 45% of blacknose shark (Carcharhinus acronotus) mortality as bycatch in shrimp fisheries (NMFS 2007b). Commercial shrimp trawls are a large global source of bycatch for elasmobranchs and these fisheries typically have higher effort in southeastern US systems compared to longlines (Trent et al. 1997; Diamond 2002; Stobutzki et al. 2002; Scott-Denton et al. 2012; Clarke et al. 2015).

Most fisheries, including the Georgia shrimp fishery, are regulated such that management decisions are based upon abundance of the target species (Scott-Denton et al. 2012; Georgia Department of Natural Resources 2018). In the case of shrimp fisheries, shrimp stocks are replenished each year and quotas are capped so that sufficient numbers persist year to year to
sustain the fishery. Therefore, incidental catch of non-target species, like elasmobranchs, is not a significant factor in the decision-making process by management. However, bottom trawls are known for high rates of bycatch, which can include more than 30 species of elasmobranchs in the southeastern United States, all of which exhibit more sensitive population dynamics than shrimp species (Bonfil 1994; Scott-Denton et al. 2012). Sharks and rays are slow-growing with late-onset sexual maturity that results in low fecundity compared to most target species. Theses life history characteristics make them more vulnerable to overfishing and stock depletion than teleost and invertebrate species of most targeted fisheries (Stevens et al. 2000; Shepherd and Myers 2005). For example, scalloped hammerhead sharks (Sphyrna lewini) have a population doubling time of 25.1 years, meaning that overexploitation is more likely in this K-selected species than shrimp populations that typically recruit in large numbers every year (Swimmer et al. 2008; Belcher and Jennings 2011). Other species, such as smooth butterfly ray (Gymnura micrura), are considered “data deficient” and their vulnerability to overfishing is unknown despite common occurrences as incidental catch. Information about elasmobranch bycatch in southeastern trawls is limited, even though shrimp fisheries are known to be the largest in many states.

Although incidental catch remains a contributor to elasmobranch mortality, gear modification has opened opportunities for increasing selectivity of fisheries; thereby limiting shark and ray capture (Jordan et al. 2013; Hart and Colin 2015). Most bycatch reduction technologies thus far have targeted sea turtles, sea birds, and marine mammals; however some are also effective at reducing catch of elasmobranchs. For example, the United States government has mandated that all commercial shrimp trawl vessels use Turtle Excluder Devices (TEDs) and many states also require Bycatch Reduction Devices (BRDs). TEDs are metal devices placed in the opening of the net that have spaced parallel bars that funnel large animals through a secondary opening in the net. As a result, sea turtles and large elasmobranchs are caught less frequently in these fisheries without serious loss of target catch (Hataway et al. 2017; Garstin and Oxenford 2018). Bycatch Reduction Devices, commonly referred to as “fish-eyes”, are triangular openings
in the net that reduce water flow and allow for fast-swimming teleost species to exit the net.

Through development of these methods, gear selectivity has improved without sacrificing the amount of target catch (Belcher and Jennings 2011; Hataway et al 2017; Gartin and Oxenford 2018). Identifying the species and magnitude of elasmobranch mortality in fisheries via bycatch is critical to address conservation concerns, especially for IUCN listed and data-deficient species (Diamond 2002; Patrick and Benaka 2013) Due to long tow times and trauma from the nets, most elasmobranchs not excluded from catch by the TED perish before nets are even hauled and many of the individuals that survive through the haul perish on the deck while the catch is being sorted (Stobutzki et al. 2002).

Georgia is an ideal location for improving understanding of elasmobranch bycatch in trawls for several reasons. As the primary commercial fishery in the state of Georgia, shrimp trawls represent nearly 100% of elasmobranch commercial bycatch in state waters (Belcher and Jennings 2011). Nearly 30 elasmobranch species are potentially caught as bycatch in this fishery, including two endangered species, scalloped hammerhead (*Sphyrna lewini*) and smalltooth sawfish (*Pristis pectinata*; Belcher & Jennings 2011; Page 2015; IUCN Red List). Regulation of shrimp fisheries in Georgia prohibits trawling in some areas, primarily small estuarine waterways, due to safety and environmental concerns. South Carolina and Georgia coastal ecosystems are productive and relatively pristine compared to other areas along the Atlantic coast (Schelske and Odum 1962; Wenner et al. 2005; Garcia et al. 2007). Geology, climate, and currents have created an intricate estuarine system with large tidal fluxes and barrier islands that create rich nursery habitats for juvenile elasmobranch species (Keeney et al. 2005; Belcher and Jennings 2009). Many coastal elasmobranchs pup in habitat associated with high productivity, warm temperature, and calm water (Belcher and Jennings 2009). Georgia’s coast is also largely undeveloped, allowing the near-continuous estuarine system to supply food sources for adult sharks along migration routes to and from Florida (Keeney et al. 2005; Belcher and Jennings 2009; Kajiura and Tellman 2016). These factors culminate in a sustained shark presence in Georgia waters,
which often overlap with shrimping areas. However, there remains a considerable gap in our understanding of the abundance and species composition of bycatch in shrimp trawls due to a lack of monitoring and scientific study. One fishery-dependent study in this system found that sharks were present in 34% of 127 observed trawls, and 82% of shark catch was one species, *Rhizoprionodon terraenovae* (Belcher and Jennings 2011). This study reported data limited to shark species, excluding skates and rays that may be more numerous and diverse than sharks in shrimp trawls while serving an equally important ecological role as mesopredators (Belcher and Jennings 2011).

In recent decades, fisheries landings and bycatch rates have been increasingly used as a means to estimate local population sizes (Baum et al. 2003). With appropriate controls to account for large variability and inconsistencies, this approach allows fisheries biologists to get as much information out of monitored fishery data sets that is possible. In oceanic systems, environmental variables such as temperature, dissolved oxygen, salinity, and tide can drive large differences in fish behavior, reproduction, and community structure (Bizzarro et al. 2009; Kajiura and Tellman 2016). Whether variables influence populations directly through physiological constraints within specific preference ranges or indirectly through competition and predation pressures depends largely on the populations in question. It is likely that because variables such as these correlate to fluctuations in local population sizes, that variables of overall elasmobranch assemblage would also have similar relationships and identifying them can help to inform stakeholders on how to avoid the capture of sensitive species.

The lack of fishery-dependent monitoring and studies that include ray species warrants a new look at the composition of elasmobranch incidental catch in the Georgia shrimp fishery. Many elasmobranchs follow prey species on temperature-driven migration through Georgia waters, and other species use the estuarine areas as breeding and nursery habitat (Keeney et al. 2005; Belcher and Jennings 2009; Kajiura and Tellman 2016). Characterizing the assemblage of elasmobranchs affected by the fishery is needed to not only identify which species may be
affected the most, but to also get a more complete picture of how environmental, fishing, and temporal variables drive shifts in the assemblage that can better inform management. Therefore, the goals of the project were to: 1) Use a fishery-dependent approach to quantify elasmobranch catch rates in the Georgia shrimp fishery, 2) model selected species catch to determine what variables affect local population dynamics, and 3) analyze how environmental and fishing variables relate to the overall elasmobranch assemblage affected by the fishery.

METHODS

Fishery-dependent observation of elasmobranch catch

Elasmobranch bycatch was sampled from commercial shrimp vessels \( (n=6) \) 40’-70’ long along the coast of Georgia (Figure 1) during the state shrimp seasons in 2016-2017. Vessels sampled contained either two or four nets in every trawl \( (n=89) \), and vessels would make between one and four trawls per day of observation. In total, 89 trawls containing either two or four nets were sampled for elasmobranchs in this study; Broken down by season, the heaviest sampling effort was in the summer months when the fishery is most active: 14 trawls in spring (April-May, before opening of state-wide fishery), 51 in summer (June-August, primarily brown shrimp season), and 23 in fall (September-November, white shrimp season). Vessel selection and observation day were chosen based upon the availability of the researcher and boat captains. Fishermen were instructed to trawl as they normally would on any typical day of fishing. Depth of trawls was between 1.58-10.97m, ranging from 0.58-4.86h in duration, at speeds from 1.65-3.8 knots.

Environmental and fishing variables were recorded at the beginning of every trawl (Table 1). Temperature \((^\circ C)\), dissolved oxygen \((mg/L)\), and salinity \((ppt)\) were recorded during each trawl using a YSI device (model Pro 2030; Yellow Springs, OH). Turbidity was estimated to the nearest 0.25m using a secchi disk. Location, tide, and timing (duration, time of day, date) of each trawl were recorded using a handheld GPS unit (Garmin GPSMAP 78SC; Olathe, KS) at the
beginning of trawls when nets were lowered into the water (Figure 1). A “distance from shore (m)” value was calculated after uploading trawl coordinates onto ArcGIS 10.2 and using the vector tool. Vessel speed (knots) and trawl depth (ft converted to m) were recorded from the commercial vessel’s instrumentation. Additional fishing variables included TED configuration (3” bar spacing with squared framing or 4” bar spacing with round framing), net configuration for each boat (two nets or four), and the number of trawls per day.

After observation of shark depredation during hauls, all elasmobranchs collected by shrimp nets were identified and measured either on board the vessel or in the laboratory. All specimens were identified to the species level. Length (cm; sharks=fork and total length, rays=and disk width and disk length), mass (g), sex, and estimated age class (neonate, young of year, juvenile, adult) were recorded for each individual. All live elasmobranchs were released alive, whereas mortalities were either discarded on board or frozen at Georgia Southern University for identification and measurements.

Sample selection based on species richness and biodiversity

Sample size adequacy was evaluated based on the number and diversity of elasmobranch species in each trawl and how these measures related to the size of individual samples. Species richness is defined as the number of elasmobranch species caught in each sample, and in this case each sample is one trawl. Because samples were uneven in terms of the length of time spent trawling and different sized nets, ensuring that longer trawls that covered greater area did not affect the rate in which species were caught was important for CPUE calculations and sample size selection. EstimateS software was used to run permutations on rarefaction curves of species richness values to determine that sampling was robust enough to characterize bycatch in this fishery without bias against rarer species. EstimateS also created Chao1 and Coleman simulated accumulation curves based off of observed samples. Chao1 species estimation curves use the given data, randomness of richness, number of samples, and number of infrequent species to
determine the likelihood that sampling is missing rare species (Cayuela et. al 2015). The Coleman
curve estimates species richness under the assumption that different areas or groups of samples
accumulates richness in different rates, and runs simulations to get an average curve under this
assumption. If randomly generated or reordered richness curves are similar to observed, Chao1,
and Coleman curves it indicates that sample size was large enough to characterize elasmobranch
species richness in this fishery.

Species accumulation curves based on the species richness accumulated over total area
sampled during the study were created to ensure an asymptote of maximum elasmobranch species
richness was achieved (Gotelli and Colwell 2010). This was also done for accumulating richness
versus accumulated area sampled when samples are ordered from smallest to largest area.
Shannon biodiversity index was calculated for elasmobranch species in each trawl. Shannon
biodiversity index is a way of the number of different species that a sample collects in addition to
how even they are in abundance with the other species. The number of species and Shannon
biodiversity index in each trawl as a function of individual trawl’s area swept was also charted to
ensure heterogeneity of variance in richness as the study progressed. These comparisons can
confirm or deny sample size valuation and if it is clear that richness or biodiversity is heavily
influenced by the size of individual samples. If I were to see that species richness or Shannon
biodiversity index was correlated (r>0.3) with increasing sample area, then I would conclude that
CPUE measurements (which are a type of rate value – Individuals per area) need an adjustment to
take differences in total sample area values into account.

*Catch-per-unit-effort*

To quantify catch rates for each species, catch-per-unit effort was calculated for each
species for every trawl observed. At the completion of every trawl, the catch was lowered onto
the deck and mixed together regardless of the number or size of nets used on that vessel.
Therefore, every elasmobranch caught in that trawl was counted and catch-per-unit-effort
calculations were quantified by taking into account the differences in net deployment and size that could be a factor in catch measurement. Catch-per-unit-effort (CPUE) for each trawl was quantified both for total elasmobranchs and species-level bycatch as follows:

\[
CPUE = \frac{\text{Number of Individuals}}{\left(\text{Speed} \left(\frac{hm}{h}\right) \times \text{Duration}(h)\right) \times \text{Total net width} \ (hm)}
\]

Each trawl was considered an independent sample, as trawls did not overlap or re-sample area that had already been trawled through that day, reducing chance of a depletion effect. The size range and behavior of the vessels sampled was assumed to be typical of the average commercial shrimping vessel in this fishery, as the middle 44% of trawling licenses granted in 2016 were to vessels within this 40-70’ size rage.

Statistical analyses

We statistically analyzed the additive effects of environmental and fishing variables on elasmobranch abundance using delta-lognormal generalized linear models (delta-GLM; Clarke et al. 2015). This model type is commonly used in multivariate fisheries analysis where CPUE values can be zero-inflated. A correlation matrix was made with all environmental and fishing variables, and if two significantly correlated only the more normally-distributed variable was included in future analysis. Variables were transformed, if necessary, to achieve a normal distribution according to Shapiro-Wilk W Goodness of Fit tests with \(\alpha=0.05\) (Table 1) and added to the GLM with an identity link function. Variables were added and removed from the model using backward-selection until all combinations of variables had been evaluated. Initially all variables were entered into the model, and from there the least significant variable is dropped one at a time. If the removal of an insignificant variable caused a change in the significance determination of another, it was added back into the model and the next most insignificant variable was removed. This process was orchestrated until all remaining variables in the model
were found to be significant. Significance for variables influencing the catch rates of elasmobranchs was established at $\alpha=0.05$. If variables were insignificant statistically with great effect on the significance of other variables, model performance was also evaluated based on Akaike information criterion adjusted for sample-size (AICc). In these cases, the model that had the lowest AICc value with all significant variables was determined to be the best model. Effect size as partial ETA squared ($\eta^2_p$) was calculated for each significant variable to determine the amount of variation that each variable contributed to the overall model. Separate models were created for CPUE of all sharks, all batoids, and for *Rhizoprionodon terraenovae*, and *Gymnura micrura* individually. These species were selected to model because they were two of the more prevalent species that were observed throughout the study and are likely to be the most ecologically relevant in this system. To account for small differences in vessel fishing behavior and gear that may not have been apparent or unobserved differences in habitat, vessel ID was included in all generalized linear models as random effects. The date of the trawl was also entered as a random effect variable to account for potential sampling of similar habitat area and environmental conditions on multiple trawls within the same day.

A model of *Sphyrna lewini* was created because it was the only species caught in multiple trawls that is also considered endangered by IUCN. Based on presence/absence of *S. lewini* in each trawl, a binomial generalized linear model was the logical choice (Table 2). The aforementioned variables and selection process was also used for this model, although variables were added using a logit link function. This different modeling approach compared to those of *R. terraenovae* and *G. micrura* was justified because relatively few individuals (n=59) were incidentally caught over the course of the project and CPUE data was largely zero-inflated.

A multivariate approach was used to examine how the overall elasmobranch assemblage affected by the fishery differs according to variations in the aforementioned environmental and fishing variables (Paliy and Shankar 2016). Non-metric multidimensional scaling (NMDS) was used on Log$_{10}(x+1)$ transformed CPUE data of all species and Log$_{10}(x+1)$ environmental and
fishing variables. Categorical variables were separated into multiple categories and included as binary numbers (0-1). For example, seasonality (spring, summer, fall) was separated into three variables, and trawls were only given a value of one for the variable that indicated when it took place seasonally. NMDS plots were created in R using the ENVFIT package to allow visualization of significant predictor variables on the overall elasmobranch assemblage (Clarke and Ainsworth 1993). The points on NMDS plots represent the composition of species in a given sample plotted on a Bray-Curtis dissimilarity matrix, based on transformed CPUE. The matrix was compared to a Euclidean matrix of environmental predictor variables to determine Spearman’s correlation coefficients. The correlation coefficients were analyzed in multiple iterations of simulations using different combinations of environmental variables to determine those that maximize the coefficient (Clarke and Warwick 2001). Permutation tests were performed on each variable to determine the extent to which they effect assemblage dissimilarities. Significant variables (α<0.05) that correlate to these dissimilarities are plotted on the NMDS plot as vectors (Clarke and Warwick 2001). ENVFIT allowed for visualization of species vectors, as samples in the area around a particular species vector were more likely to have a higher abundance of that species in the trawl’s assemblage. A longer arrow denoting a variable indicated that variables had a stronger correlation with a particular assemblage of species near that vector, and the correlation coefficients and p-values of all environmental/fishing predictor variables included in NMDS plots are listed in Appendix 1.

Two types of TEDs were equipped on vessels observed in this study: square with 3-inch bar spacing and round with 4-inch bar spacing. It is important to evaluate these devices for their effectiveness at excluding individuals and to determine the size in which most animals are excluded for all gear configurations. This is because these differences in gear type can lead to changes in catch rates that need to be taken into account as well as being a important evaluation for conservation concerns. Therefore, Kolmogorov-Smirnov Goodness-of-fit statistical tests were used to determine whether the size composition (mass of individuals) of shark and ray catch
differed significantly by TED type (α=0.05). Because of the hypothesized differences in CPUE and size distribution of catch based on TED, this was included as a variable in generalized models and NMDS analysis in addition to the direct comparisons.

RESULTS

General catch characteristics

Four species dominated the elasmobranch assemblage affected by shrimp trawls (91.1% of individuals): Atlantic sharpnose shark (39.2%, *Rhizoprionodon terraenovae*), Atlantic stingray (21.3%, *Hypanus sabinus*), smooth butterfly ray (16.5%, *Gymnura micrura*), and southern stingray (14.1%, *Hypanus americanus*). Adequacy of sample size was determined by EstimateS software, which determined the projected accumulation of species encountered throughout the study. The chao1, Coleman, and observed curves all fit within the projection’s 95% confidence interval, suggesting that it is unlikely that there were rare species unaccounted for due to small sample size.

Based on sample-based species accumulation displaying the number of total species as area sampled and effort increased through the study, an asymptote of total richness of 15 maximum elasmobranch species was reached after trawls had covered 163.2 hm², on the 49th of 89 samples total (Figure 12). The 15 species plateau was also reached at a similar accumulation of sampling when richness accumulation was calculated based on samples being ordered from smallest to largest. There was no relationship between the size of sampling area and individual trawl richness (Figure 13) or the trawl’s calculated elasmobranch Shannon biodiversity index (Figure 14). Therefore, there was high heterogeneity of variance for richness regardless of the samples’ area, and thus indicated that all samples could be used in CPUE calculation and multivariate assemblage analysis.
Modeling abundance with environmental and fishing variables

Shark CPUE was best modeled with three significant variables (overall $p<0.0001$, $F_9=38.73$): Month ($F_{7,9}=9.85$, $p<0.0001$), TED type ($F_{1,9}=2.24$, $p=0.0413$), and turbidity ($F_{1,9}=4.98$, $p=0.0013$). Shark catch peaks in summer months, particularly June and early July when shrimp hauls bring in numerous pups in every net. This model was heavily influenced by the catch rates of the Atlantic sharpnose shark (*R. terraenovae*), which dominated overall shark catch. Relatively high secchi disk values were associated with a higher abundance of sharks, indicating that these species were more prevalent in clearer seawater. TED type influences the abundance of sharks caught by excluding individuals that can not pass through the spaced bars. It can be assumed that smaller bar spacing excludes more individuals from catch.

Ray abundance in shrimp trawls was best modeled with three significant variables (overall $p=0.0001$, $F_9=38.1$): Month ($F_{7,9}=1.65$, $p=0.0021$), duration of trawl ($F_{1,9}=4.97$, $p=0.0317$), and turbidity ($F_{1,9}=1.53$, $p=0.0148$). Ray catch rates were also highest in summer months but were not as variable month-to-month compared to sharks, particularly with *Hypanus* species which did not have dramatic seasonal changes in abundance. Many species of rays are adapted to live in low-clarity water, and in this study rays were caught at higher rates when trawls took place in more turbid water. Trawls that were longer in time duration caught ray species at a higher rate on average than short trawls.

The most abundant shark species captured was the Atlantic sharpnose shark (*R. terraenovae*). Sharpnose sharks were found in 67.8% of trawls, with a capture rate of 4.26 ± 0.86 individuals/hm$^2$ (mean ± SE). In summer months (June-August) when they are known to pup in estuarine environments, sharpnose abundance was greatest (6.6 individuals/hm$^2$) and as many as 80 individuals were captured in a single trawl (Loefer and Sedberry 2003). Almost all sharpnose sharks captured were juvenile or neonatal individuals, as larger sharks were presumably excluded by the TEDs. There were a few outliers and some adult individuals were captured via entanglement. The three significant variables in the generalized linear model were turbidity.
(F₁,₉=6.21, p=0.0017), TED type (F₁,₉=22.79, p=0.0024), and month (F₇,₉=14.95, p<0.0001). Sharpnose sharks were caught in greater numbers during trawls that occurred in clear, relatively less-turbid water. Capture rates and the exclusion of larger individuals was affected by TED type, as sharpnose were caught less prevalently on the vessel that utilized 3” bar spaced TEDs.

In this study, *Gymnura micrura* represented a significant portion of elasmobranch landings and was captured in 71.4% of shrimp trawls with a CPUE of 1.38 ± 0.19 individuals/hm². Individuals varied greatly in size, with neonates as small as 21 cm disk width and adults as large as 73 cm DW were caught. Variables in the generalized model that were correlated significantly with butterfly ray abundance were month (F₇,₉=2.39, p=0.0014), TED type (F₁,₉=22.96, p=0.0049), and Shrimp CPUE (F₁,₉=5.27, p=0.0127). Prevalence of this species in shrimp trawls was highest in summer months, but more variable from month to month that *R. terraenovae*. Early in the season (April) as well as late in the fall, populations of this species were low. High catch rates of smooth butterfly rays were positively correlated with high shrimp catch. *G. micrura* was also one of the largest species of ray encountered, and it is likely that their size at maturity allowed for them to be excluded from capture by TEDs. In this study there was a higher CPUE of *G. micrura* on vessels equipped with 4” bar-spaced TEDs.

The scalloped hammerhead shark (*Sphyrna lewini*) was the only species caught in shrimp trawls with any regularity that is also considered to be threatened by IUCN. This species was caught in 25% of trawls with an average CPUE of 0.308 ± 0.09 individuals/hm². Despite regular occurrence, in total only 59 individuals, all juvenile or neonate, were caught in the 89 trawls over two years. A binomial generalized linear model (X²₈=26.38, p=0.0009) was created based on presence-absence in trawls. The two significant variables were month (X²₇,₈=21.8, p=0.0028) and distance from shore (X²₁,₈=5.85, p=0.0156). These hammerheads were only caught in spring and summer months in water that was generally farther from the shore.
**Multivariate NMDS assemblage analysis**

Multivariate analysis of elasmobranch assemblage in the fishery was plotted onto NMDS plots (Figure 15). Points that are close to one another on plots have a similar assemblage of elasmobranchs caught in those trawls, both in terms of which species were present and in what abundance. Vectors were included on the graph if they were significantly correlated with differences in elasmobranch assemblage. Species vectors were included when assemblage groupings correlated ($r>0.6$) with high abundance of a particular species. These plots help to visualize how differences in the overall assemblage of species is driven by certain species and variables. For example, points of relatively high abundance for blacktip sharks (*C. limbatus*) were more correlated to higher temperatures during summer. Conversely, samples dominated by a large number of *R. terraenovae* were likely to be in summer, in turbid water, and these trawls were also likely to have co-occurrence with a relatively high abundance of bullnose ray, *Myliobatis freminivili*.

NMDS plotting did not reveal any distinct clustering in multivariate plotting of species assemblage in trawls. However, there were several significant variables that correlated to differences in assemblage. Temperature, turbidity, distance from shore, and season all correlated with differences in assemblage of elasmobranchs captured. Species vectors indicated that a number of species were responsible for the differences in plotted assemblage. Species that were strongly correlated with differences in assemblage include *R. terraenovae, C. limbatus*, and *H. sabinus*.

**Comparison of catch size composition by TED type**

Two different TEDs were utilized by vessels in this study and were differentiated by shape and the spacing of bars (4” spacing with round frame or 3” spacing with a squared frame), which can affect catch rates by excluding organisms at a different size points. Two size frequency distributions were created for both shark and ray species groups, each distribution showing all
individual mass values that were caught with one TED type, and the two distributions of TED type were compared in both species groups using a Kolmogorov-Smirnov goodness of fit test. For ray species, there was a significant difference for mass based on TED type, as those caught by the 3” spacing TEDs tended to be slightly heavier in mass than those caught by nets equipped with 4” spaced TEDs (Kolmogorov-Smirnov, $n=1065$ samples, $p=0.004$, $KS_a=1.74$). For sharks, individuals caught in nets with the 3” spacing TED were significantly smaller than those caught in nets with the 4” spacing TEDs (Figure 16, Kolmogorov-Smirnov, $n=934$ individuals, $KS_a=6.24$, $p=0.0002$). Sixty-three percent of the sharks caught in nets equipped with 3” spacing were under 200g, while only 25% of sharks caught with 4” spaced TEDs fit into this category. It should be noted that only one vessel of the six observed utilized the TED with 3” spacing, and while it was one of the more frequently observed vessels, trends and significant relationships observed could be based on unobserved factors beyond bar spacing such as the vessel in question having a different habitat or benthos that it trawled in.

DISCUSSION

Increased awareness of the decline in worldwide elasmobranch populations has led to regulation and monitoring of elasmobranchs stocks in many parts of the world, namely in western countries such as the United States and Canada (Stevens et al. 2000). In countries that regard shark meat as a cultural delicacy (e.g. Japan) or do not monitor shark populations, overfishing of elasmobranchs contributes to continuing declines in populations (Bonfil 1994; Baum et al. 2003). Elasmobranch species are apex and meso-predators that are a vital part of the ecosystem that they inhabit. Reductions in biodiversity and species composition have been correlated to the overexploitation of elasmobranchs in some systems (Shepherd and Myers 2005; Heithaus et al. 2007). Many species are also highly migratory, meaning that protecting a species in one region may be ineffective if other regions in the species’ range does not provide similar protections (Bonfil 1994; Dulvy et al. 2014). Understanding the ecological complexities of elasmobranch
bycatch by establishing baseline measurements to build on and compare to is an important step towards better conservation outcomes.

Another fishery-dependent study of shark abundance in this fishery, Belcher and Jennings (2011), found that a similar group of shark species was caught as bycatch in their 1995-1998 surveys. This study found similar prevalence of sharks in terms of frequency of occurrence with *R. terraenovae, S. tiburo, S. lewini, and C. limbatus*. Our study encountered, albeit very infrequently, two species that Belcher and Jennings (2011) did not: dusky shark (*C. obscurus*) and blacknose shark (*C. acronatus*). Their study documented catch of another two species that this study did not: spinner (*C. brevipinna*) and finetooth sharks (*C. isodon*), although these were also the least prevalent in that study. These similarities and differences between studies in terms of species observed and their prevalence as bycatch show that while the general composition of elasmobranch bycatch is dominated by a few species, a large amount of fishing effort must be observed over a long period of time to fully know which species are affected and to what degree.

*The Georgia marine environment and correlatess to elasmobranch catch*

It was important to account for differences in net size and trawling area in CPUE calculations, and each vessel in this study had subtle variations in fishing methods and equipment. The ability of one person to resample the same set of vessels over the course of the study in order to determine how these variations affect catch was a reason why the number of vessels observed was low in relation to the size of the fishery. When CPUE was calculated on the basis of area swept (hm²), it reduced bias of trawls with more or larger nets. Based on the achievement of an asymptote of 15 species at 163.3hm² when richness was plotted against accumulating area, it was determined to be a large enough overall sample size in terms of area and number of samples to estimate the abundance of elasmobranchs affected by this trawl fishery because no new species were found for the remainder of the study (Figure 12). If richness were to continue a steady increase through the entirety of sampling effort, it would be inaccurate and biased to make
conclusions on such data as it would be inadequate to estimate richness let alone population dynamics or catch rates.

Seasonality was a significant factor in relation to the catch rate in all species or group in which models were assembled. Sharks species were a larger proportion of the catch compared to ray species in spring and summer months (Figure 17). This was due to reproduction and migration patterns that are likely a product of temperature and prey availability being higher in the summer months (Kajiura and Tellman 2016). Because sharpnose sharks make up such a large proportion of the overall shark catch it is not a coincidence that significant predictor variables were the same in both models, indicating that Atlantic sharpnose abundance heavily influenced the overall shark abundance model.

Turbidity was also a significant driver of both Atlantic sharpnose shark abundance and conversely overall shark and ray abundance. Georgia is known for having relatively turbid coastal water due to high nutrient and phytoplankton levels as well as sedimentation from a number of large river watersheds (Schelske and Odum 1962). These sources of dissolved solids in the ocean water likely play a big role in the ecology of many species. Species that have the physiological ability to detect prey in turbid environments or use turbidity as a means of avoiding predator detection are more adapted to remaining in these areas during times of increased sedimentation, like Gymnura micrura. Large, migratory species such as Sphyrna lewini inhabit a wide range of habitats such as Caribbean waters on migration routes in addition to estuarine systems and are less likely to be specifically adapted for very turbid environments.

S. Atlantic coastal elasmobranchs as bycatch in the Georgia shrimp fishery

This study offers the first quantification of coastal ray species abundance via catch rates in the Georgia shrimp fishery. Ray species can occupy an important niche as mesopredators and biological engineers, and determining the factors influencing their abundance and fishery catch rates in a system with many species is important for conservation concerns. Longer trawls (by
time duration, not area sampled) caught rays at a lower overall rate, or CPUE, than shorter ones in this study. Turbidity was also a significant factor, likely because two of the most abundant ray species, *Hypanus sabinus* and *Gymnura micrura* were associated with being caught at higher frequency in more turbid water.

When modeling individual species abundance and determining which variables affect elasmobranch incidental catch, only seasonality was consistently significant (Figure 17). The Georgia coast has a sub-tropical climate, with high humidity and precipitation. Air temperatures are generally high (30°C +) from late spring to early fall, and water temperatures above 30°C are not uncommon. Temperature change throughout the year is likely to drive elasmobranch behavior, reproduction, and migration either indirectly or directly (Bizzarro et al. 2009; Kajiura and Tellman 2016). Understanding these population trends through the year and how they relate to fishing effort in conjunction with environmental variability is important for monitoring the conservation status of sensitive or ecologically important species.

The composition of the elasmobranch bycatch in this fishery was dominated by four species (89.9% of catch observed). Therefore, special attention towards monitoring of these populations would be valuable. However, three of these species (*R. terraenovae, H. sabinus, H. americanus*) have well-documented reproductive rates that are relatively high for elasmobranch species, in addition to a large range of suitable habitat (Snelson et al 1988; Henningsen 2000; Loefer and Sedberry 2003). It is unlikely that small-ranged, relatively small-fleet fisheries, such as the Georgia shrimp fishery, would have a significant effect on species such as these, which reproduce frequently at relatively young age. For example, Atlantic sharpnose sharks reach sexual maturity at around two years of age, and this allows individuals to begin contributing to potential population growth much sooner than other shark species such as the Scalloped hammerhead that does not reach maturity for at least eight years (Loef er and Sedberry 2003). The last of these four, *Gymnura micrura*, frequents the coastal Atlantic from Maryland to Brazil but little is known
regarding effective population size. Previous studies have indicated that this ray species reproduces year-round and are able to have multiple litters a year (Yokota et al. 2012).

Determining the environmental or fishing factors that may indicate whether or not a threatened species, such as *Sphyrna lewini*, is likely to be frequently caught as bycatch is important for conservation and management concerns. This is an example of a large, slow growing elasmobranch that has a low reproductive rate (Branstetter 1987). In this study a binomial generalized linear model based on presence or absence of scalloped hammerheads in trawls was created with two significant predictor variables: month and distance from shore. This species was only landed in spring and summer months, in trawling locations farther from shore than average. Only young of the year and neonatal scalloped hammerheads were captured in this study, suggesting larger age classes are excluded by TEDs. Despite occurring in 25% of trawls, only 59 individuals were caught through the two year study, which is extremely small in comparison to the 854 sharpnose shark individuals captured. It was not uncommon to observe more than 50 sharpnose individuals landed in a single trawl. This illustrates the contrast in the size, fecundity, and ecology between the two species and how populations differentiate in terms of risk of overexploitation.

*Turtle Excluder Devices and catch size selectivity*

The Georgia shrimp fishery has been compliant with regulations put in place by the National Marine Fisheries Service (NMFS) to reduce incidental catch of sensitive species. This fishery was also instrumental in the invention, development, and testing of Turtle Excluding Devices (TEDs). Mandatory federal TED compliance on bottom trawl gear was required by law in 1987 as an effort to reduce the bycatch of endangered sea turtles and marine mammals. However, the technology is efficient at excluding from catch anything that is larger than what the bar spacing allows (Blount 2007; Hataway et al. 2017; Garstin and Oxenford 2018). Despite the frustration from having to pay for the TEDs, fishermen usually do not have a problem with
mandated use because TEDs can reduce time that is spent sorting catch without a noticeable difference in shrimp catch. TED bar spacing is required to be at or less than 4 inches, but some fishermen opt for smaller spacing to further reduce the amount of bycatch and sorting time. It is imperative that regulations, mandatory gear requirements, and variations in equipment as pertains to TEDs are studied and reevaluated as populations and fishery effort changes

Turtle Excluder Device type was a significant factor, not only in size distribution, but also with catch rates of many species commonly caught in this project. Sharks, with a broader and more rounded body shape, were more likely to be affected and therefore excluded from trawls via TED than rays. Rays, with their dorsally compressed body shape, can fit through the TED bar spacing at a wider range of their life history depending on their orientation going through the net when captured in a trawl. In this study, the vessel in question that used 3” TED spacing caught significantly smaller shark and ray individuals, with virtually no individuals caught over 57 cm TL or 55 cm DW (versus maximum 88cm TL and 77cm DW with the 4’ TED). This means that catch is emphasized towards higher catch of mostly immature, pre-reproductive individuals and smaller coastal species that have relatively higher reproductive rates when this 1” reduction in spacing is implemented. This evaluation of TED effectiveness was consistent with other studies (Hataway et al. 2017; Garstin and Oxenford 2018). Conclusions from this limited sample (one vessel of six in this study utilized the smaller TED bar spacing, n=31 trawls out of 89 total) have the potential to be biased or due to extraneous circumstances relating to where the vessel was based and how they decided when and where to trawl. One of these circumstances may be that this vessel trawled in the area that had the highest amount of non-trawling boat traffic in this study, which may affect the abundance some species.

If these trends were to be validated and found repeatedly in similar studies within shrimp fisheries, and reduced TED bar spacing really can reduce trawling impact through exclusion of catch at a smaller size, it could have positive effects on the conservation of elasmobranch species. Such changes would have to be carefully implemented, as trawl fisheries in the US are in trouble
financially, and having fishermen create or buy new TEDs would be a significant and
unreasonable financial burden (Coburn et al. 2006; Jacobsen et al. 2012; Jenkin and Garrison
2012). Further study of bar spacing is needed on a larger scale to determine whether or not these
small differences in gear have significant conservation implications.
IV. CONCLUSION

Coastal and estuarine environments are known for their relatively high biodiversity due to a number of abiotic and biological factors. These habitats are also becoming affected by anthropogenic development and disturbance. The nature of trawl fisheries causes relatively high disturbance of natural environments (Diamond 2002). Trawl fisheries have notoriously low selectivity, aggregating and disturbing anything that is in the net’s path. This not only has the potential to remove non-target species, but also can cause physical damage to the habitat from the dragging of the gear along the benthos. However, Georgia’s nearshore ocean, beyond the estuarine waterways, has a long and shallow benthic slope and a lack of structure (i.e. coral, kelp, rock, etc) that make it a suitable location for a trawl fishery to persist without devastating habitat degradation (Hall et al. 2000; Zhoe 2008).

Management of the shrimp fishery in Georgia is primarily based on shrimp stock assessments and established regulations, such as spatial closures of intracoastal waterways and mandatory TED usage. Long-term monitoring of incidental catch such as elasmobranchs would be beneficial for determining the scale of the impact of the fishery on non-target resources (Brinson and Wallmo 2015). Additional study on how shrimp fishermen can sustainably maintain profits, whether by biological or economical processes, would be welcomed by members of this struggling community (Mackinson and Nottestad 1998; Blount 2007).

The Georgia shrimp fishery is well known for being instrumental in the development and testing of Turtle Excluder Devices (Blount 2007). This history illustrates their concern for coastal conservation. The fishery has reduced in size over the years, and aside from Savannah, there are still only small coastal fishing towns that are not extensively developed. It is unlikely that this small, shrinking commercial fishery with well-established regulation is having a larger environmental impact than it did when it was orders of magnitude bigger by fleet size and was unregulated. Fishermen would encourage study on how to reduce interactions with elasmobranchs, particularly of methods or deterrents that could reduce depredation from large
sharks. Having this concern of theirs be addressed in a scientific matter would be beneficial for all stakeholders in addition to shark populations. Any decision being made in regards to management of this fishery should include consideration for the current limited financial capacity of most fishermen (Coburn et al. 2006; Blount 2007; Jacobsen et al. 2012).

Consideration for the economic health and persistence of a fishery has been a significant topic in regulatory affairs since the passage of the Magnuson-Stevens Fishery Conservation and Management Act in 1976 (Coburn et al. 2006). This legislation set up the structure of U.S. marine fisheries management and regulatory processes to ensure the continuance of valuable fisheries. Over the course of the last three decades, fisheries management agencies have incorporated more anthropological and qualitative methods in evaluating the effects of industry matters on the perceptions and realities of the communities most effected; usually commercial fishers (Coburn et al. 2006). However, even these studies are focused more on resource availability and fishing community resilience or sensitivity from the effects of regulations and many issues such as depredation and non-target species population trends are often overlooked. By listening to resource users and focusing more time and effort towards issues within a fishery that the stakeholders feel is a significant economic threat, there is increased potential to have a more collaborative and supportive working relationship between different groups within fisheries.

Using a fishery-dependent, observational approach in studies like this via recruitment as a chance for “participatory science” opens up opportunities to study topics such as depredation, bycatch, and management of coastal resources (Mackinson and Nottestad 1998; Neis et al 1999; Brinson and Wallmo 2015). While participation can be limited due to infrequency and inconsistencies with communication, issues that focus on more than resource availability can be quantified and studied. Most coastal and fishery management agencies do not currently have the budget for large-scale fishery-independent studies on issues that are not based on stock-assessment of valuable resource species. Fishery-independent data can be standardized and comparisons from analysis can be readily made on biological concepts, but fishery-dependent
data can be more reflective on how resources are being used and offers insight on how management decisions and biological trends effects the daily lives of stakeholders. Most importantly, collaborative participatory science can break down barriers between stakeholders that are inclined to be wary of one another, such as fishermen and academia, so that communities can work together to solve complex problems.
## V. TABLES

Table 1: Variables collected or measured throughout the study.

<table>
<thead>
<tr>
<th>Category</th>
<th>Variable</th>
<th>Unit or range</th>
<th>Collection method</th>
<th>Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Depredation response variables</strong></td>
<td>Holes</td>
<td>Count</td>
<td>Inspection of nets</td>
<td></td>
</tr>
<tr>
<td>Damage Index</td>
<td>Small hole(＜6”)=1, Medium (6-12)=2, Large (12”+)=3</td>
<td></td>
<td>Inspection of nets</td>
<td>Hellinger</td>
</tr>
<tr>
<td>Estimated repair time</td>
<td>minutes</td>
<td>Inspection of nets</td>
<td>Interview with fishermen</td>
<td>log</td>
</tr>
<tr>
<td>Sharks</td>
<td>Count</td>
<td># of sharks attacking nets at time of haul</td>
<td>Interview with fishermen</td>
<td>log</td>
</tr>
<tr>
<td><strong>Environmental variables</strong></td>
<td>Temperature</td>
<td>Celcius</td>
<td>YSI</td>
<td>Log (NMDS)</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>mg/L</td>
<td>YSI</td>
<td>Log (NMDS)</td>
<td>Johnson (GLMs)</td>
</tr>
<tr>
<td>Salinity</td>
<td>ppt</td>
<td>YSI</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td>Depth</td>
<td>feet</td>
<td>Vessel instrumentation</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td>Turbidity</td>
<td>meters</td>
<td>Secchi disk</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td><strong>Fishing variables</strong></td>
<td>Speed</td>
<td>knots</td>
<td>Vessel instrumentation</td>
<td>log</td>
</tr>
<tr>
<td>Distance from shore</td>
<td>meters</td>
<td>Vector tool, ArcGIS 10.2</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td>Duration of trawl</td>
<td>hours</td>
<td>Watch</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td>Area swept</td>
<td>hm²</td>
<td>(Width of trawl x Speed x Duration)</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td>Vessel</td>
<td>-</td>
<td>Anonymous</td>
<td>log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td>TED</td>
<td>-</td>
<td>3” Square or 4” Round</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td>Net</td>
<td>-</td>
<td>Basic unit of measurement</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td>Trawl</td>
<td>-</td>
<td>2 or 4 nets per trawl</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td>Shrimp CPUE</td>
<td>Lbs/hm²</td>
<td>Shrimp lbs / Area swept</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Location</td>
<td>Lat/Long</td>
<td>Handheld GPS</td>
<td>log</td>
</tr>
<tr>
<td>Port</td>
<td>-</td>
<td>Tybee Island, Midway, Darien, Brunswick</td>
<td>Log (NMDS)</td>
<td>Johnson-Su (GLMs)</td>
</tr>
<tr>
<td><strong>Morphometric (samples)</strong></td>
<td>CPUE</td>
<td>#/hm²</td>
<td># of Species / Area swept</td>
<td>log(x+1)</td>
</tr>
<tr>
<td>Mass</td>
<td>g</td>
<td>Scale</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>cm</td>
<td>Measuring tape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>M or F</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age class</td>
<td>Neonatal, Young of the Year, Juvenile, or Adult</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td>Date, month, season, and year</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
Table 2. List of models and significant variables that were correlated with differences in the response variable. Models only included variables that were found to be significant according to F-tests. For month parameter estimates, only the month which had the largest estimate was listed. Partial ETA-squared is a way of calculating effect size. It measures the proportion of the total variance that each variable is contributing to the model.

<table>
<thead>
<tr>
<th>Response Variable</th>
<th>P-value</th>
<th>Df</th>
<th>R²</th>
<th>Significant variables</th>
<th>Effect test P-values</th>
<th>ETA²</th>
<th>Parameter Estimate (±SE)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shark CPUE</td>
<td>&lt;0.0001</td>
<td>9</td>
<td>0.69</td>
<td>Month</td>
<td>&lt;0.0001</td>
<td>0.483</td>
<td>0.74 (±0.08) June*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Turbidity</td>
<td>0.0013</td>
<td>0.063</td>
<td>0.233 (±0.07)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TED type</td>
<td>0.0413</td>
<td>0.029</td>
<td>-0.073 (±0.03)</td>
</tr>
<tr>
<td>Ray CPUE</td>
<td>&lt;0.0001</td>
<td>9</td>
<td>0.75</td>
<td>Month</td>
<td>0.0021</td>
<td>0.02</td>
<td>0.237 (±0.06) August*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Turbidity</td>
<td>0.0148</td>
<td>0.136</td>
<td>-0.152 (±0.06)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Trawl duration</td>
<td>0.0317</td>
<td>0.063</td>
<td>-0.00019 (±0.000008)</td>
</tr>
<tr>
<td>R. terraenovae CPUE</td>
<td>&lt;0.0001</td>
<td>9</td>
<td>0.7</td>
<td>Month</td>
<td>&lt;0.0001</td>
<td>0.586</td>
<td>0.75 (±0.07) June*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TED type</td>
<td>0.0024</td>
<td>0.235</td>
<td>-0.106 (±0.03)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Turbidity</td>
<td>0.0017</td>
<td>0.077</td>
<td>0.219 (±0.07)</td>
</tr>
<tr>
<td>G. micrura CPUE</td>
<td>&lt;0.0001</td>
<td>9</td>
<td>0.48</td>
<td>Month</td>
<td>0.0014</td>
<td>0.185</td>
<td>0.215 (±0.05) August*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TED type</td>
<td>0.0049</td>
<td>0.237</td>
<td>0.074 (±0.06)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shrimp CPUE</td>
<td>0.0127</td>
<td>0.066</td>
<td>0.07 (±0.03)</td>
</tr>
<tr>
<td>S. lewini</td>
<td>0.0009</td>
<td>8</td>
<td>0.28</td>
<td>Month</td>
<td>0.0028</td>
<td>0.308</td>
<td>2.05 (±1.4) October*</td>
</tr>
<tr>
<td>Presence/Absence</td>
<td></td>
<td></td>
<td></td>
<td>Distance from shore</td>
<td>0.0156</td>
<td>0.027</td>
<td>-0.75 (±0.37)</td>
</tr>
<tr>
<td>Depredation</td>
<td>0.0022</td>
<td>2</td>
<td>0.33</td>
<td>Temperature</td>
<td>0.0012</td>
<td>0.495</td>
<td>0.495 (±0.16)</td>
</tr>
<tr>
<td>Presence/Absence</td>
<td></td>
<td></td>
<td></td>
<td>Depth</td>
<td>0.0211</td>
<td>0.34</td>
<td>0.34 (±0.15)</td>
</tr>
</tbody>
</table>
Table 3: Elasmobranch species caught incidentally in 89 trawls over the course of the two year study (2016-2017). Mean catch-per-unit-effort (CPUE) was used to consider differences in gear size and trawl duration.

<table>
<thead>
<tr>
<th>Common name</th>
<th>Scientific name</th>
<th>Proportion of trawls present</th>
<th>Mean CPUE (# Individuals/hm²)</th>
<th># Individuals</th>
<th>Mean mass (g) (± SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic sharpnose shark</td>
<td><em>Rhizoprionodon terraenovae</em></td>
<td>0.678</td>
<td>4.257</td>
<td>854</td>
<td>252.07 (9.95)</td>
</tr>
<tr>
<td>Atlantic stingray</td>
<td><em>Hypanus sabinus</em></td>
<td>0.702</td>
<td>1.736</td>
<td>464</td>
<td>136.31 (7.34)</td>
</tr>
<tr>
<td>Smooth butterfly ray</td>
<td><em>Gymnura micrura</em></td>
<td>0.714</td>
<td>1.387</td>
<td>360</td>
<td>772.31 (45.9)</td>
</tr>
<tr>
<td>Southern stingray</td>
<td><em>Hypanus americanus</em></td>
<td>0.667</td>
<td>1.295</td>
<td>308</td>
<td>303.07 (18.88)</td>
</tr>
<tr>
<td>Bonnethead shark</td>
<td><em>Sphyrna tiburo</em></td>
<td>0.297</td>
<td>0.308</td>
<td>66</td>
<td>849.94 (72.19)</td>
</tr>
<tr>
<td>Scalloped hammerhead shark</td>
<td><em>Sphyra lewini</em></td>
<td>0.25</td>
<td>0.281</td>
<td>59</td>
<td>622.61 (51.12)</td>
</tr>
<tr>
<td>Bullnose ray</td>
<td><em>Myliobatis freminivili</em></td>
<td>0.179</td>
<td>0.167</td>
<td>34</td>
<td>496.85 (34.26)</td>
</tr>
<tr>
<td>Roughtail stingray</td>
<td><em>Bathytoshia centroura</em></td>
<td>0.071</td>
<td>0.043</td>
<td>7</td>
<td>428.29 (101.8)</td>
</tr>
<tr>
<td>Cownose ray</td>
<td><em>Rhinoptera bonasus</em></td>
<td>0.119</td>
<td>0.034</td>
<td>11</td>
<td>1188.9 (100.5)</td>
</tr>
<tr>
<td>Dusky shark</td>
<td><em>Carcharhinus obscurus</em></td>
<td>0.036</td>
<td>0.03</td>
<td>5</td>
<td>900.33 (118.4)</td>
</tr>
<tr>
<td>Atlantic guitarfish</td>
<td><em>Pseudobatos lentiginosus</em></td>
<td>0.059</td>
<td>0.027</td>
<td>9</td>
<td>170.71 (30.59)</td>
</tr>
<tr>
<td>Blacktip shark</td>
<td><em>Carcharhinus limbatis</em></td>
<td>0.048</td>
<td>0.025</td>
<td>5</td>
<td>1476.63 (80.84)</td>
</tr>
<tr>
<td>Blacknose shark</td>
<td><em>Carcharhinus acronotus</em></td>
<td>0.024</td>
<td>0.016</td>
<td>4</td>
<td>786.67 (356.67)</td>
</tr>
<tr>
<td>Spotted eagle ray</td>
<td><em>Aetobatus narinari</em></td>
<td>0.024</td>
<td>0.0006</td>
<td>2</td>
<td>1200 (100)</td>
</tr>
<tr>
<td>Clearnose skate</td>
<td><em>Raja eglanteria</em></td>
<td>0.012</td>
<td>0.0002</td>
<td>1</td>
<td>1010</td>
</tr>
<tr>
<td>Sharks</td>
<td>Selachimorpha</td>
<td><strong>0.77</strong></td>
<td><strong>4.917</strong></td>
<td><strong>993</strong></td>
<td></td>
</tr>
<tr>
<td>Rays</td>
<td>Batoidea</td>
<td><strong>0.964</strong></td>
<td><strong>4.696</strong></td>
<td><strong>1185</strong></td>
<td></td>
</tr>
</tbody>
</table>
Table 4. Vessels characteristics and sampling effort observed over the course of the study.

<table>
<thead>
<tr>
<th>Vessel ID</th>
<th>County</th>
<th>Total Nets Observed</th>
<th>Spring Trawls</th>
<th>Summer Trawls</th>
<th>Fall Trawls</th>
<th>Nets</th>
<th>Mean Trawl Duration (# Hours (±SE))</th>
<th>Mean Speed km/h (±SE)</th>
<th>Mean Estimated Repair Time (Minutes/Trawl (±SE))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Glynn</td>
<td>64</td>
<td>6</td>
<td>11</td>
<td>2</td>
<td>2 or 4</td>
<td>2.9 (0.18)</td>
<td>4.35 (0.16)</td>
<td>44.7 (9.5)</td>
</tr>
<tr>
<td>2</td>
<td>Glynn</td>
<td>6</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>4.4 (0.39)</td>
<td>4.72 (0.35)</td>
<td>67.5 (20.6)</td>
</tr>
<tr>
<td>3</td>
<td>McIntosh</td>
<td>72</td>
<td>0</td>
<td>25</td>
<td>11</td>
<td>2</td>
<td>1.8 (0.13)</td>
<td>4.67 (0.12)</td>
<td>20.0 (6.9)</td>
</tr>
<tr>
<td>4</td>
<td>Glynn</td>
<td>6</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2.5 (0.55)</td>
<td>4.82 (0.49)</td>
<td>30.0 (29.2)</td>
</tr>
<tr>
<td>5</td>
<td>Chatham</td>
<td>62</td>
<td>8</td>
<td>10</td>
<td>13</td>
<td>2</td>
<td>2.3 (0.14)</td>
<td>4.04 (0.13)</td>
<td>22.4 (7.4)</td>
</tr>
<tr>
<td>6</td>
<td>Liberty/Bryan</td>
<td>8</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>3.8 (0.39)</td>
<td>5.79 (0.35)</td>
<td>18.8 (20.6)</td>
</tr>
</tbody>
</table>
VI. FIGURES

Figure 1. Location of each trawl over the entire study (n=96 trawls & 218 nets total, elasmobranch catch was recorded in n=89 trawls) along the Georgia coast where shark depredation was evaluated. Also displayed is the seasonality (Spring is defined as April-May, Summer June-August, and Fall September-November) and total damage index resulting from shark depredation for each trawl.
Figure 2. Number of observed sharks per trawl (A) and the extent of damage incurred on nets, per trawl (B) related to vessel speed during trawls. Each point represents a trawl (n=96). (A) Number of sharks and speed analyzed using a nonparametric spearman rank correlation ($\rho=-0.2814$, $p=0.005$, $n=96$ trawls), and found that as vessel trawled faster less sharks were present at hauls. (B) Damage Index (severity and presence/absence of damage) was Hellinger-transformed for analysis ($n=96$ trawls $r=-0.24$, $p=0.04$) and compared to vessel speed for each trawl. As speed increased, the shark presence decreased as did the resulting damage.
Figure 3. Number of sharks observed as a function of total time that nets were submerged (Number of nets in trawl x the duration of the trawl in hours). There was a positive correlation, with more sharks observed attacking trawls that had been longer with four nets as opposed to two, likely due to increasing time and smell signal released in to the water during the trawl (Spearman-rank correlation: $\rho=0.2799$, $p=0.006$, $n=96$ trawls).
Figure 4. The proportion of nets that had shark damage present over the course of the year. Month was a significant factor for damage of gear. Depredation was common (35-55\% of the time) for the majority of the shrimping season April-September before decreasing rapidly as the water temperature decreased in October (Chi-square test; \( n=218 \) nets, \( df=7, \ X^2=15.32, p=0.032 \)).
Figure 5. Nets were classified by presence or absence of depredation by sharks. Damaged nets occurred in significantly warmer water temperatures compared to undamaged nets (Kruskal-Wallis, n=218, Z=2.31, p=0.02). When shark damage was present in a trawl, the mean temperature of the water was 27.12°C (±0.294°C SE) compared to 26°C (0.286°C SE) in trawls where nets emerged undamaged.
Figure 6. Depredation Index (Hellinger transformed) as a function of the number of sharks observed during hauls. There was a positive regression between the number of sharks observed and the amount of damage incurred on nets ($n=96$ trawls, $r^2=0.229$, $F=27.97$, $P<0.001$). More sharks observed near the trawls equates to more frequent and severe depredation.
Figure 7. Frequency of coded qualitative responses to questions asked of stakeholders during observation. Y-axis numeration represents the number of respondents with answers falling underneath the code on the x-axis. The questions addressed in each graph are as follows: A) General perception of the state of the Georgia shrimp fishery. B) What the stakeholder perceived as the general trend in frequency of shark depredation over the last decade. C) Number of hours per day the respondents estimate that they spend repairing nets damaged by sharks on average. D) What the fishermen or crewmember believe would be the most effective way to reduce shark depredation of the shrimp fishery.
Figure 8. A positive regression between estimated repair time (minutes) as reported by fishermen compared to damage index per trawl. As damage severity increased, the reported time that it would take to sew the nets increased accordingly. One outlier was excluded from analysis because it was a leverage point. Fishermen and crew members were consistent in predicting this relationship ($n=95$, $r^2 = 0.6353$, $F=9.2645$, $P<0.001$).
Figure 9. The relative location of holes on shrimp nets caused by shark depredation. Each point represents an instance of damage in the study. The majority of damage was located in the 5m section preceding the Turtle Excluding Device (TED) as the net funnels catch toward the bag. The area of the net behind the TED was likely attacked with similar frequency, but damage was not as prevalent due to the presence of chaffing gear. Any mitigation technique used to reduce depredation should focus on areas of heavy damage to increase effectiveness and cost efficiency.
Figure 10. Concept map of topics regarding shark depredation in the Georgia shrimp fishery, and associated interview response codes. Light blue boxes indicate recurring themes and topics in interviews. Red boxes directly refer to a question or topic that was brought up in all interviews. Blue arrows point to inductive codes corresponding to each question. Codes that best represent the most frequent responses for that topic is highlighted in yellow.
Figure 11. Species accumulation curve (Total number of species encountered as the number of samples increases). Richness estimates simulations were based on 999 randomizations of data. Observed accumulation curve fell between 95% confidence interval of estimated S, and was similar to Chao1 and Coleman estimations, meaning that it was unlikely that the sampling effort was inefficient due to missing rare or spatially aggregated species.
Figure 12. Species accumulation curve as area sampled accumulated during the study. A asymptote of 15 total elasmobranch species was reached after 163.3hm² area was sampled. Achieving a stable asymptote of richness indicated that enough ocean floor area was sampled by the observed trawlers to characterize the species assemblage of elasmobranchs. The blue data series shown shows the species accumulation when data were ordered from smallest to largest trawl area. These curves (both by slope and asymptote) were very similar in relation to each other as well as the rarefaction curves in Figure 11, indicating that sample size was large enough to characterize elasmobranch richness affected by this fishery.
Figure 13. Species richness plotted against individual trawl’s area swept. Each point represents a trawl and the number of elasmobranch species captured (y-axis) versus the size of the sample in terms of area covered. There was no relationship between the size of the sample and elasmobranch species richness ($r^2=0.0005$).
Figure 14. Each point represents a trawl’s calculated Shannon Diversity index plotted against the area swept of the sample. Longer and larger trawls were not more or less diverse than smaller trawls based on richness (as shown in Figure 13), and it is likely that the slight positive slope of the Shannon relationship was due to a small increase in species evenness in longer trawls. Overall there was no relationship between Shannon Diversity Index and the size of the sample (by area, $r^2=0.0226$).
Figure 16. Non-metric multidimensional scaling (NMDS) multivariate analysis on log+1 transformed elasmobranch CPUE matrix. Number point represented a trawl/sample and its associated elasmobranch assemblage. Points that were close to environmental vectors had a similar assemblage that correlated with that variable. Points near species vectors had an assemblage that is dominated by a relatively high proportion of that species. Significant vector matrices and their associated coordinates and p-values are listed in Appendix 1. As an example, the vector for the variable “fall”, as well as the vector for the species *H. sabinus* are near a group of points. Because these points are close together, they are likely to have a similar composition of species, and this composition is highly correlated with the trawls taking place in fall. The species vector means that this group of trawls was dominated by a relatively high proportion of *H. sabinus*. 
Figure 17. Relative frequency distribution of shark mass according to TED type. A) net equipped with a 4” round TED (n= 58 trawls and 5 vessels) or B) a 3” square TED (n= 31 trawls and 1 vessel). TEDs with 3” spacing had a relative frequency distribution skewed towards catching smaller sharks (under 300g) than 4” TEDs (Kolmogorov-Smirnov Goodness-of-Fit test $KS_{a}=6.24$, $p=0.0002$).
Figure 18. Catch-per-unit-effort of sharks (A) and batoids (B) by season (Spring: March-May, Summer: June-August, Fall: September-November). Bars are mean ± SE. Shark abundance was heavily influenced by *R. terraenovae*, which had the highest CPUE in the study and abundance peaked in summer months. *Hypanus* abundance was relatively consistent across seasons while *G. micrura* changed greatly, peaking in summer months.
VII. REFERENCES


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Kajiura, S.M., and Tellman, S.L. 2016. Quantification of massive seasonal aggregations of Blacktip sharks (*Carcharhinus limbatus*) in southeast Florida. PLOS One, DOI:10.1371/journal.pone.0150911


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Zhoe, S. 2008. Fishery by-catch and discards: a positive perspective from ecosystem-based fishery management. Fish and Fisheries, 8: 308-315
### APPENDIX 1: NMDS Vectors and Correlations (From Figure 16)

#### VECTORS

<table>
<thead>
<tr>
<th>Species</th>
<th>NMDS1</th>
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<th>r²</th>
<th>Pr(&gt;r)</th>
</tr>
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<tr>
<td>R. terraenovae</td>
<td>0.24871</td>
<td>-0.96858</td>
<td>0.5591</td>
<td>0.001 ***</td>
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<tr>
<td>H. sabinus</td>
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<td>0.1766</td>
<td>0.001 ***</td>
</tr>
<tr>
<td>H. americanus</td>
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<td>1.00000</td>
<td>0.1569</td>
<td>0.002 **</td>
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<tr>
<td>G. micrura</td>
<td>0.60880</td>
<td>0.79333</td>
<td>0.1114</td>
<td>0.007 **</td>
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<tr>
<td>S. tiburo</td>
<td>0.92603</td>
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<td>0.1238</td>
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<td>C. limbatus</td>
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<td>-0.37745</td>
<td>0.0402</td>
<td>0.199</td>
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<td>R. bonasus</td>
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<td>A. narinari</td>
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<td>B. centoura</td>
<td>0.59190</td>
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Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 1

Permutation: free

Number of permutations: 999

#### VECTORS

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<tr>
<th>Depth</th>
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<tr>
<td>Latitude</td>
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<tr>
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</tr>
<tr>
<td>FalSepNov</td>
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</tr>
<tr>
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<tr>
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Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 1

Permutation: free

Number of permutations: 999
APPENDIX 2: NMDS plots and Correlations (Based on sharks and rays aggregated, not broken down by species)

***VECTORS

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<th>Pr(&gt;r)</th>
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<td>Rays</td>
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Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Permutation: free
Number of permutations: 999

***VECTORS

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<th>Pr(&gt;r)</th>
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<td>Turbidity</td>
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<tr>
<td>Temp</td>
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<tr>
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Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Permutation: free
Number of permutations: 999
APPENDIX 3: Interview Themes, Guiding Questions and Associated Codes

1. What is the state of the Georgia shrimp fishery as a whole?
   Codes: Positive, Negative, Other

2. How do depredation events by sharks affect the fishery as a whole?
   Codes: Not a Problem, Nuisance/Annoyance, Economic Hardship

3. Do you notice that shark depredation is more frequent in certain locations?
   Codes: Yes-Habitat, Yes-Water Clarity, Yes-Depth, No

4. What time of the year does shark depredation become the most frequent?
   Codes: Spring, Summer, Fall

5. What environmental variables do you think affect the frequency of shark depredation?
   Codes: Depth, Temperature, Turbidity, Location, Timing

6. How has shark depredation frequency changed over the years?
   Codes: Increase, Decrease, Other

7. What methods have been tried to reduce the frequency of shark depredation?
   Codes: Behavioral, Chemical, Sensory, Mechanical/Physical, Other
   a. Did they work? Codes: Yes/No/Sometimes
   b. Were they cost effective? Codes: Yes/No/Depends
   c. Do you or anyone you know currently use these methods? Codes: Yes/No

8. How does depredation of nets by sharks affects your daily life?
   a. How much time do you typically spend repairing damaged nets?
      Codes: Less than an hour, 1-3 hours, 3+ hours
   b. Do you think that net damage from sharks negatively affects the amount of shrimp catch? Codes: Yes, No, Situational
   c. How do you repair them, and where did you learn how to do this? Does everyone in the fishery have this skill?
      Codes: Family, Captain, Crew, Don’t do repairs

9. Do you think that the Georgia Department of Natural Resources is sympathetic to your problems associated with sharks? Codes: Yes, No, Other

10. What do you think would be a reasonable solution to this problem?
    Codes: Shark population reduction-Commercial/Recreational/Culls, Deregulation, Other

11. If a user-friendly and effective deterrent array was available for low cost, would you use it?
    Codes: Yes, No, Depends
12. What affects your choice of trawling location? How do you decide?
   Codes: Tradition, Previous Success, Convenience, Seasonal Trends, Shark Avoidance

13. Did the composition and amount of bycatch change when you started using a TED (Turtle Excluder Device)?
   Codes: Yes-Reduced, Yes-Increased, No
INFORMED CONSENT

My name is Matt Scanlon and I am a graduate student in the Department of Biology at Georgia Southern University.

Purpose of this Study: The purpose of this research is to observe and record the frequency of shark interactions with shrimp nets. This project will address the following objectives:

1. Count and record shark-induced damage to trawl gear.
2. Count and record the types of species numbers of sharks and rays that are caught.

To participate in this study, we ask that you allow myself or an associate observe and collect sharks and rays that are affecting your trawl gear and ask you questions about this issue. We will record information about your trawl activity on a data sheet. With your permission, we will measure the bycatch in our lab, and use it for other research projects. With your permission, we will take photos and videos of nets and shark/ray activity in the water and on board. We will use these images in scientific presentations, publications, and for outreach.

Discomforts and Risks: There are very few risks associated with your participation in this project. We understand that work space on your vessel may be limited. Allowing your crew to complete their tasks is a primary concern. Therefore, researchers will follow any and all orders and safety procedures stated by the captain and crew.

Benefits: This study is meant to benefit shrimp fishermen and the scientific community, but may not benefit you directly. The ultimate goal of this project is to implement a deterrent system that may reduce shark damage to shrimp nets and elasmobranch bycatch. We hope to eventually reduce costs to fishermen through reducing gear damage while increasing target catch. We anticipate that any information about the topic may improve management decisions.

Duration/Time Required: We plan to observe elasmobranch interactions 1-2 times per week for the remainder of 2016 and continue observations through 2018.

Statement of Confidentiality: Participants will not be identified by name in the data set or any reports using information obtained from this study. Future uses of records and data will be subject to standard data use policies which protect the anonymity of individuals and institutions. All records with identifying information will be placed in a locked file cabinet in a locked office.

Right to Ask Questions: You have the right to ask questions and have those questions answered. If you have questions about this study, please contact the researcher named above or the researcher’s faculty advisor, whose contact information is located at the end of the informed consent. For questions concerning your rights as a research participant, contact Georgia Southern University Office of Research Services and Sponsored Programs at 912-478-5465.

Voluntary Participation: Your participation in this study is completely voluntary and you may withdraw your participation at any time without penalty or retribution. You have the right to refuse to answer any question that may be asked. You must be 18 years of age or older to consent to participate in this research study. If you consent to participate in this research study and to the terms above, please tell the researcher.

You will be given a copy of this consent form to keep for your records. This project has been reviewed and approved by the GSU Institutional Review Board under tracking number H17015.

Title of Project: Characterizing elasmobranch interactions with trawl nets in the Georgia shrimp fishery
Principal Investigator: Matthew Scanlon (951)532-6868 ms11728@georgiasouthern.edu
Faculty Advisor: Dr. Christine Bedore (912) 478-1252 cbedore@georgiasouthern.edu