Evaluating protected species bycatch in the U.S. Southeast Gillnet Fishery

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Abstract

Incidental capture or 'bycatch' of non-targeted species is a global fisheries issue that threatens ocean ecosystems and the conservation and recovery of protected species. Many protected species are at a high risk of incidental capture and mortality in commercial fisheries, which could have an impact on already decreasing populations. From 1998-2017, U.S. federal fisheries observers aboard fishing vessels in the U.S. Southeast Gillnet Fishery collected data on captures of encountered protected species. Data collected by the observers were used to describe protected species incidental capture within this fishery. A generalized linear zero-inflated negative binomial two-part model (GLM-ZINB) was applied to determine which environmental and fishing characteristic factors influence the probability of incidental capture of protected species including leatherback, *Dermochelys coriacea,* and loggerhead, *Caretta caretta,* sea turtles, bottlenose dolphins, *Tursiops truncatus*, and giant manta ray, *Manta birostris.* While a variety of factors were considered in our models, no one single factor was found to influence all protected species. Incidental capture of leatherback turtles was influenced by season, depth, and gillnet depth, while loggerhead turtles were influenced by season, sea surface temperature, and target species of the fishery. Bottlenose dolphin bycatch was most influenced by soak duration, gear type, and season, while giant manta ray captures were influenced by soak duration, gear type, and depth. Environmental and fishing characteristic factors associated with incidental capture of protected species can be used to help guide fishery managers as to what species-specific regulations could be implemented to help mitigate capture.

Keywords: Protected species, endangered, commercial fisheries, threatened, bycatch

1. Introduction

Incidental capture and subsequent discard of non-targeted species or 'bycatch' is a global fisheries issue that threatens ocean ecosystems and the conservation and recovery of protected species (NOAA, 2019). Frequent incidental captures of non-targeted protected species can have detrimental effects on populations and food web dynamics, which contribute to conservation concern (Crowder and Murawski, 1998; Tasker et al., 2000; Raby et al., 2011). Many of the species that are at high risk of incidental capture and fishing mortality are protected under the U.S. Endangered Species Act (ESA), Marine Mammal Protection Act (MMPA), and the Migratory Bird Treaty Act, though protections and management across these taxonomic groups are not universal.

Gillnet fishing gear, including drift, sink (i.e., anchored), and strike gillnets, are globally used for the capture of targeted fish species (Valdemarsen, 2001). Gillnets are largely an unbiased mode of commercial fishing, meaning that both target and non-target species can become entangled in the fishing gear (Northridge, 1991). Gillnet bycatch is a major source of mortality in many species of teleosts, elasmobranchs, seabirds, sea turtles, and marine mammals. Many of these species caught as bycatch have populations that have historically declined or are still declining, and many are protected under the ESA or other conservation measures. For example, Zollet (2009) identified 41 protected species captured in gillnet gear in U.S. east coast commercial fisheries. Determining factors that may contribute to the incidental capture of protected species could help prevent future interactions through fisheries mitigation strategies and assist in developing recovery actions for these species.

Population declines of many sea turtle species have been attributed to incidental capture in fisheries, particularly coastal gillnet fisheries, oceanic driftnets, and bottom nets (National Research Council, 1990; Lewison et al., 2004; Wallace et al., 2010; Fiedler et al., 2012). Similarly, many marine mammals, sharks and rays, and seabirds are easily entangled in gillnet gear and often suffer fishing mortality that can have considerable impacts on species populations (Stevens et al., 2000; Tasker et al., 2000; Read et al., 2006). Air breathing species that require frequent surface intervals (e.g., sea turtles, marine mammals, and birds) along with species with a low intrinsic rate of population growth (e.g., sharks and rays) are highly vulnerable to fishing mortality (Dulvy et al., 2008; Hall et al., 2000; Northridge et al., 2017). Many studies have investigated incidental capture of protected species over the last few decades although a few have assessed this on a multi-species or multi-taxa level (Sims et al., 2008; Northridge et al., 2017).

The U.S. Southeast Gillnet Fishery is active year round from North Carolina and into the Gulf of Mexico. Many states have banned gillnet fishing in state waters over the last decades and most gillnet fishing is restricted to Federal waters (i.e., 9 miles offshore in the Gulf of Mexico and 3 miles offshore in the U.S. south Atlantic). Fishers target a wide variety of species from sharks such as dogfish (Squalidae), coastal pelagic species (e.g., Spanish mackerel, *Scomberomorus maculatus*), and some groundfish (e.g., Atlantic croaker, *Micropogonias undulatus*) depending on time of the year and market conditions. Observer coverage of this fishery was initially sporadic with coverage focused on vessels targeting king mackerel, *Scomberomorus cavalla,* and sharks with drift net gear (Schaeffer et al., 1989; Trent et al., 1997, respectively). Shark-targeted gillnet effort of large coastal sharks began to decline with Amendments 2 and 3 to the Consolidated Atlantic HMS-FMP (NMFS, 2010). The large coastal shark trip limit in these amendments essentially ended the strike net fishery and limited the number of fishers targeting sharks with drift and sink gillnet gear. This in turn led to the subsequent increased effort targeting teleosts by vessels that traditionally targeted sharks (Mathers et al., 2017 and references therein). Consequently, since 2006, observer coverage has expanded to include all vessels using gillnet gear regardless of target (Baremore et al., 2007). Take reduction plans in place for Atlantic large whales such as right (*Eubalaena glacialis*), humpback (*Megaptera novaeangliae*), and fin whales (*Balaenoptera physalus*) as well as for bottlenose dolphins (*Tursiops truncatus*), and harbor porpoise (*Phocoena phocoena*) are currently in place and have the potential to reduce the possible interactions with protected species by enforcing time/area closures and mesh restrictions (NMFS, 1997, 1998, 2006). These fishery regulations reduce the amount of vessels fishing and thereby interacting with protected species at certain times of the year.

Estimates of protected species bycatch have raised concern that this fishery may be impeding the recovery of some of these species. For example, fishers using gillnet gear and targeting shark incidentally captured an estimated 36 (95% confidence limits 0-608) loggerhead, *Caretta caretta,* and 12 (95% confidence limits 0-31) Kemp's ridley, *Lepidochelys kempii,* sea turtles from 2007-2010, respectively (Carlson and Richards, 2011). Carlson and Mathers (2017) determined 24 (95% confidence limits 0-414) giant manta ray, *Manta birostris,* were caught by the southeast gillnet fishery targeting sharks in 2012. Herein, we describe protected species bycatch and evaluate environmental variables and fishing techniques associated with their capture. An understanding of factors related to the capture could aid in the management of this fishery and contribute to the recovery actions for several protected species.

2. Methods

2.1. Observer Coverage

National Marine Fisheries Service, Panama City Laboratory, FL USA currently administers the Southeast Gillnet Fishery Observer Program. Scientific observers are trained in the collection of biological and fishery data and species identification. Observers are required to record catch and effort information from each gillnet set on every trip. Observers recorded data associated with three types of gillnet gear: drift, sink (anchored), and strike nets. Drift gillnets are not anchored, secured, or weighted to the bottom at either end of the net and are allowed to drift with currents. Anchored gillnets or sink nets can be set anywhere within the water column and are anchored, secured, or weighted to the bottom by a weight or lead line. Strike nets are actively set around a school of a target species and immediately retrieved and can either fish from the surface to the bottom or function more like a drift net. All gillnet types are typically comprised of monofilament twine and stretch mesh can range between 6.4-30.5 cm and reach lengths of 46-3,200 m. Initially, observer coverage focused on vessels targeting sharks using drift gillnet gear with 100% observer coverage (Trent el al., 1997; Baremore et al. 2007). In 2005, observer coverage was expanded to include all vessels that have an active directed shark permit and fish with sink gillnet gear. These vessels were not previously subject to observer coverage because they either were not targeting sharks or were not fishing gillnets in a drift or strike fashion. In 2006, further expansion of the gillnet observer program included all vessels fishing gillnet gear regardless of target, and for coverage to be extended to cover the full geographic range of gillnet fishing effort in the southeast United States. Vessels were randomly selected for observer coverage on a quarterly basis from a pool of vessels that had reported fishing with gillnet gear during the same quarter in the previous year for the Gulf of Mexico and South Atlantic. Observer coverage has ranged from 5-15% depending on the year and availability of funding.

2.2. Data treatment and analysis

Observations of protected species interactions in the gillnet fishery have been recorded since 1993. Observations were made on all species as the gillnet gear was hauled aboard. The observer remained on the deck of the vessel in a position with an unobstructed view and recorded species and numbers of individuals caught. When species identification was questionable, the crew stopped hauling so that the observer could examine the animal(s) for positive identification. Status (alive or dead at-vessel when boated) of individuals was recorded. Information on abiotic data (e.g., sea surface temperature and depth) was recorded as well as location, time of day, and fishing gear specifics (e.g., net length, net depth, mesh size, and soak duration) for each gillnet set. Due to few and sporadic observations in early years, we restricted our analysis to data collected from 1998 to 2017. Data were further refined by removing all undefined or missing fields (e.g., missing latitude/longitude fields, date, soak time, etc.). For each month of every year, averages were taken of sea surface temperature at the same latitude where the set was recorded and used to fill in any gaps in data on sea surface temperature. In events that protected species were encountered, each individual was counted and recorded within a fishing trip. As many interactions with protected species are rare events, to reduce the number of zeros in the models, frequency distributions were applied to determine if data could be subset based on cumulative frequency percent (e.g., data subset by target species or by gear type).

Protected species identified within the dataset included loggerhead, green, *Chelonia mydas*, leatherback, *Dermochelys coriacea*, hawksbill, *Eretmochelys imbricata*, and Kemp's ridley sea turtles, giant manta rays, smalltooth sawfish, *Pristis pectinata*, common loon, *Gavia immer*, brown pelican, *Pelecanus occidentalis*, Atlantic spotted dolphin, *Stenella frontalis*, bottlenose dolphins, *Tursiops truncatus*, and Atlantic sturgeon, *Acipenser oxyrinchus oxyrinchus,* (Table 1). Due to the relatively low number of observations within the data (n ≤ 5) for some species that precluded any model convergence, four species were able to be modeled: ESA threatened loggerhead sea turtle, ESA endangered leatherback sea turtle, MMPA depleted bottlenose dolphin, and ESA threatened giant manta ray (Table 1).

Frequency distributions indicated that the datasets for each species was highly zero-inflated, thus we used a two-component mixture generalized linear model (GLM) to determine which factors influence the probability of catching a protected species. Analyses were conducted considering each species as its own group. Count data are characterized by a high proportion of zero values (i.e., zero-inflated) relative to an event present in high counts and was observed within our dataset. Thus, we used a zero-inflated negative binomial (ZINB) model since it can handle the excessive number of zeros and overdispersion within the data (Zuur et al., 2009). ZINB models account for two sources of zeros: 'true' zeros and zeros generated from a count component. Within our model, the negative binomial distribution modeled the count process, while a binary model with a logit link function was used to capture the probability of zero inflation (Zuur et al., 2009). The probability functions about the capture probability of each protected species (*Yi)* is*:*

$$f(y_i = 0) = \pi_i + (1 - \pi_i) \times (k / \mu_i + k)^k$$

$$f(y_i | y_i > 0) = (1 - \pi_i) \times f_{NB}^{(y)}$$

Where π_i is the probability of having a false zero*,* μ_i is the mean, *NB* is the negative binomial distribution, and *k* is a parameter (i.e., factor). We applied the 'zeroinfl' function from the 'pscl' package (R version 3.5.0) for our analyses.

Several factors were selected that may have potentially influenced the catch of protected species based on our hypotheses and assumed importance in other studies (Table 2). These factors were a combination of continuous and categorical explanatory variables and included region, latitude, season, sea surface temperature, depth, net depth, net length, mesh size, gear type, target, and soak time (Table 2). All of the factors were evaluated for independence by a Kruskall-Wallace test and for collinearity with a Spearman rank test. Initially, a null model was run with no factors included. Each factor was added to the model independently in a forward stepwise manner and results were ranked from the relative least to greatest change in Akaike information criterion (ΔAIC) when compared to the null model (McCracken, 2004; Murray, 2009; Carlson et al., 2016). The factor with the lowest ΔAIC was then incorporated into the model and likelihood ratio tests were applied to compare the models for significance (e.g., chi-square values and p-value of <0.05). Factors found to be not significant and/or if the model would not converge with a particular factor were dropped from the model (Zuur et al., 2009). Final models were validated by plotting Pearson residuals against the fitted values from the model and plotting Pearson residuals against each explanatory variable (Zuur et al., 2009).

3. Results

3.1. Leatherback Sea Turtle

Between 1998 and 2017, shark-targeted drift net sets contributed to >90% of leatherback gillnet interactions with one interaction in a mackerel-targeted sink net (10%). Thus, data were subset to shark-targeted drift net sets and consisted of 268 gillnet trips and 310 gillnet sets. Leatherback interactions occurred on 13 trips resulting in 16 individual leatherback turtle interactions that included two at-vessel mortalities (Table 1). All leatherback and gillnet interactions occurred in the south Atlantic on the east coast of Florida (Fig. 1). All leatherback turtles were caught in the winter between the months of October-March except for one interaction in the summer months of April-September. Observers recorded interactions in sea surface temperatures between 20.5-24.4°C (mean 22.4 °C) and at depths between 12-20m (mean 15m). The most significant independent factor influencing capture of leatherback turtles was season ($X^2 = 15.9$, df = 1, p = < 0.001) (Table 1) whereas a combination of season, bottom depth, and net depth were the most associated with leatherback capture ($X^2 = 23.7$, df = 3, p <0.001) (Table 3).

3.2. Loggerhead Sea Turtle

A total of 1,071 trips consisting of 3,401 gillnet sets, were analyzed between 1998 and 2017. Loggerhead interactions with the gillnet fishery occurred on 16 trips resulting in 17 individual animals recorded including four animals that suffered at-vessel mortality (Table 1). Loggerhead interactions occurred in the south Atlantic in both winter and summer months with 10 (62.5%) interactions in the winter and six (37.5%) interactions in the summer (Fig. 1). Fishery observers recorded captured loggerheads in temperatures between 21.6-29.4 °C (mean 24.8 °C) and depths between 1.5-24.4 meters (mean 14.8 meters). Loggerheads were captured in drift (56.2%), sink (18.8%), and strike (25.0%) nets primarily in the shark (87.5%) and mackerel (12.5%) targeted fisheries. The most significant independent factor influencing the capture of loggerhead turtles was target ($X^2 = 33.5$, df = 4, p <0.001) (Table 4) whereas the combination of target, season, and sea surface temperature were the most associated with loggerhead capture (X^2 = 39.4, df = 6, p <0.001) (Table 4).

3.3. Bottlenose Dolphin

A total of 1,276 gillnet trips and 3,479 gillnet sets were analyzed between 1998 and 2017. During this period, 11 gillnet trips reported interactions that resulted in 13 individual animals captured. All 13 individuals suffered at-vessel mortality as a result of their interaction with the gillnet fishery (Table 1). Dolphin interactions occurred primarily in the south Atlantic (>90%) with one capture in the Gulf of Mexico (10%) in water temperatures that ranged between 21.1-26.6°C (mean 22.7°C) and depths between 2.4-18.6 meters (mean 13.9 meters) (Fig. 1). Dolphin interactions occurred in all seasons (February-October), primarily in the winter (80%) compared to the summer (20.0%). Interactions occurred in the shark (70%) and mackerel (30%) targeted fisheries in drift (80%) and strike (20%) nets. The most significant independent factor influencing the capture of bottlenose dolphin was soak duration ($X^2 = 20.2$, df = 1, $p < 0.001$) (Table 5) whereas the combination of soak duration, gear, and season were the most associated with dolphin capture ($X^2 = 32.4$, df = 4, $p < 0.001$) (Table 5).

3.4. Giant Manta Ray

All giant manta ray interactions occurred in the south Atlantic region (100%) between 1998 and 2017, and thus data were subset to this region and consisted of 1,075 gillnet trips with 3,346 gillnet sets. There were six gillnet trips that interacted with giant manta rays resulting in seven individual animals being captured, including one at-vessel mortality (Fig.1, Table 1). Giant manta rays were captured in the summer (60%) and in the winter (40%). Fishery observers recorded captures in temperatures between 21.7-29.0°C (mean 24.2 °C) and depths 10.3-29.9 meters (mean 17.5 meters). Giant manta rays were captured in drift (80%, n=6) and strike (20%, n=1) nets primarily from the shark (80%) and mackerel (20%) targeted fisheries. The most significant independent factor influencing the capture of giant manta rays was gear type ($X^2 = 16.4$, df = 2, $p < 0.001$) (Table 6) whereas the combination of gear type, soak duration, and bottom depth were the most associated with giant manta ray capture ($X^2 = 22.0$, df = 4, $p < 0.001$) (Table 6).

4. Discussion

4.1 General discussion

The present study evaluated protected species bycatch from multiple taxa in the U.S. Southeast Gillnet Fishery. Gillnets are a globally ubiquitous fishing gear that is highly efficient yet generally non-selective (Northridge, 1991). Many previous studies have assessed bycatch of protected species on a single taxa and the majority of these studies have been conducted on marine mammals (Northridge et al., 2017). Although take reduction plans are in place for several protected species (e.g., large whales, dolphins, sea turtles), fishery interactions with protected species still occurs. Coastal, drift, and sink gillnet fisheries have all been documented to incidentally capture protected species including marine fishes, mammals, turtles, and seabirds (Lewison et al., 2004; Read et al., 2006; Murray, 2009; Zollett, 2009; Warden, 2010; current study). Identifying factors that may be associated with gillnet fisheries on a species-specific level can inform fisheries managers as to what mitigation strategies should be considered and implemented to help reduce incidental capture of protected species.

4.2 Leatherback Sea Turtles

Incidental captures of sea turtles in gillnet fisheries is well documented in the literature though few studies have investigated bycatch factors in gillnet fisheries. The best fitting model in our study indicated that incidental capture of leatherback turtles was associated with season, depth, and net depth. Leatherback turtles were incidentally captured the most during the winter months of January-March and in relatively deep nets fished in water depths less than 20m off of the east coast of Florida. Though primarily a pelagic species, leatherback turtles inhabit coastal waters off the east coast of Florida during times of internesting, typically in cooler months (Eckert et al., 2006; Bailey et al. 2012). This region off the east coast of Florida had some of the highest numbers of gillnet sets and, thus, a combination of increased fishing pressure in areas where turtles may be in high numbers due to migrations between foraging sites likely contributed to the increased incidental capture of leatherbacks. Mitigation strategies in the form of 'low-profile' gillnets, (i.e., nets without tie downs and panel heights < 2m) have shown that turtle incidental capture can be reduced in a demersal gillnet and surface gillnet fishery in Pamlico Sound, North Carolina and in Trinidad, respectively (Price and Van Salisbury, 2007; Eckert et al., 2008; Gearhart et al., 2009). Similar mitigation strategies could be put in place for coastal areas during winter months where only the use of low-profile nets along with a depth restriction (e.g., gear fishes in greater than 20m depth) to help mitigate incidental capture. In addition to implementing potential net depth and fishing depth restrictions, the fact that shark-targeted drift net fishing has been reduced dramatically will overall reduce leatherback interactions in the gillnet fishery (Mathers et al. 2020).

4.3 Loggerhead Sea Turtles

The best fitting model in our study indicated that incidental capture of loggerhead turtles was associated with target species, season, and sea surface temperature. Loggerheads were captured during both winter and summer months in our study, primarily in shark-targeted sets. It has been noted that target species is likely an effect of gear use and design and not specifically the species targeted itself (Northridge et al., 2017). This is likely true in the instance of loggerhead turtles given that they do not feed on the targeted species within this study (i.e., shark and mackerel). Loggerhead turtles nest from Cape Canaveral southward to Broward County, FL, typically from April to September making this an area with high concentrations of turtles (Meylan et al., 1983). The majority of loggerhead interactions with the gillnet fishery occurred in this region and were captured both within and outside of the nesting season. The region of capture was also where the highest concentration of gillnet sets were made. Loggerheads were also captured in warm sea surface temperatures, similar to Murray (2009) from a study characterizing sea turtle incidental catch in the U.S. mid-Atlantic gillnet fishery, which overlaps with our study in North Carolina. Implementing fishing restrictions based on sea surface temperature would logistically be difficult to do and given that target species is likely a gear effect, restrictions on gillnet fishing could be based on season.

4.4 Bottlenose Dolphins

Marine mammal incidental capture with gillnet fisheries has been well documented in the literature (Northridge et al., 2017). A variety of factors have been found to associate with incidental capture of marine mammals, many that are gear-specific. In our study, bottlenose dolphin interactions were found to be associated with soak duration, gear type, and season. Seventy-three percent of interactions occurred during the winter months of February-March, primarily in drift nets and in soak durations longer than six hours. In the U.S. Northwestern Atlantic Gillnet Fisheries, porpoise incidental capture was also associated with season, with more interactions occurring in winter-spring months (Orphanides, 2010). Changes in migration patterns, foraging behavior, or animal density across seasons may account for differences among regions studied (Northridge et al., 2017). It is reasonable to hypothesize that drift nets left in the water for more than six hours increases the chance that bottlenose dolphins, or any other species, could be entangled within the fishing gear, as we have seen in this study. Currently, the coastal bottlenose dolphin take reduction plan has soak time restrictions in place for gillnet gear. The limits of soak times were implemented with the intent to reduce bycatch of bottlenose dolphins, as well as allow closer monitoring of the net to reduce the potential for serious injury and mortality should a dolphin become entangled (NMFS 2006). Shorter soak times during winter months in conjunction with a restriction on drift nets could be an additional way forward with mitigating incidental capture of bottlenose dolphins and likely other marine mammals.

4.5 Giant Manta Ray

While there is an abundance of literature evaluating environmental and fisheries characteristics that may influence incidental capture of marine mammals, sea turtles, and seabirds, there are few studies that focus on marine fishes. ESA protected marine fishes such as smalltooth sawfish, Atlantic sturgeon, and giant manta ray have all been reported as bycatch in commercial fisheries (Collins et al., 2000; NMFS, 2010; Croll et al., 2016). Mortality estimates of some of these species may be large, which poses a threat to the recovery of populations (Stein et al., 2004; Croll et al., 2016). Our best fit model indicated that gear type, soak duration, and depth were associated with the probability of giant manta ray capture. Drift nets were responsible for incidentally capturing the most giant manta rays in combination with water depths between 10-12m and soak durations that lasted more than eight hours. Giant manta rays exhibit a high degree of plasticity in terms of the depths that they frequent in offshore habitats (Stewart et al., 2016). When feeding, these animals can be found in surface waters down to 10m though diving behavior to depths greater than 300m has been documented (Stewart et al., 2016). Drift gillnets are kept afloat at the proper depth using a system of weights and buoys and in our data, these nets typically fished from the surface down to 7m, well within the depth range of giant manta rays. Continued long soak durations of drift nets will likely increase the number of incidental captures in the future, as indicated by our model. Mitigation strategies for this ESA threatened species could include a restriction of the use of drift gillnets as well as a reduction of soak duration to avoid incidental capture and possible fishing mortality. The limits of soak times implemented with the intent to reduce bycatch of bottlenose dolphins, as well as allow closer monitoring of the net (NMFS, 2006) will also reduce the potential for serious injury and mortality of giant manta ray.

4.6 Other protected species

Although low numbers within the data precluded model convergence, incidental capture of other protected species of fishes, sea turtles, and seabirds occurred in the U.S. Southeast Gillnet Fishery. Hawksbill and Kemp's ridley sea turtles along with Atlantic spotted dolphins, Atlantic sturgeon, and smalltooth sawfish were incidentally captured in shark-targeted drift nets. A brown pelican, common loon, and green sea turtle were captured in teleost-targeted sink nets and most Atlantic sturgeon interactions also occurred in teleost-targeted sink nets.

Factors influencing incidental capture of protected species in gillnet fisheries vary among species across taxonomic groups and by location (Northridge et al., 2017). For example, mortality rates were high for green turtles that were incidentally captured in gillnets in southern Brazil in cold sea surface temperatures, whereas increased mortality for loggerhead turtles was the highest in warmer temperatures in the Mediterranean Sea (Alessandro and Antonello, 2009; López-Barrera et al., 2012). Water depth also has varying impacts on porpoise bycatch rates with some species more impacted in deeper waters compared to others in shallower waters (NMFS, 1998; Orphanides, 2010). Other factors such as large mesh size has also been shown to correlate with higher sea turtle and porpoise interactions (NMFS, 1998; Price and Van Salisbury, 2007; Murray, 2009; López-Barrera et al., 2012). For example, porpoise bycatch rates in dogfish and monkfish targeted gillnet fisheries in the U.S. mid-Atlantic are high, likely due to the large mesh sizes used in the gillnets of each fishery (NMFS, 1998; Orphanides, 2010). Incidental capture of seabirds in gillnet fisheries have been correlated with sea surface temperature and water depth (Northridge et al, 2017). Common loons were noted to have higher capture rates in U.S. Atlantic coast gillnet fisheries in low sea surface temperatures and in mid-water depths whereas other species of seabird are often reported as bycatch in shallow water areas (ICES, 2008; Warden, 2010). Additionally, behaviorial characteristics such as feeding behaviors of pursuit diving piscivourous seabirds and aggregations of birds in breeding colonies may make some species more susceptible to incidental capture (Norman, 2000; Dagys and Zydelis, 2002; Northridge et al., 2017). Similarly, bycatch of porpoises have been attributed to foraging near or out of gillnets (Northridge et al., 2017).

Consolidated information of the bycatch of protected species in the U.S. east coast commerical fisheries indicated that the Mid-Atlantic and Northeast gillnet fisheries had some of the largest numbers of documented species that were incidentally captured (Zollet, 2009). For example, Atlantic sturgeon have been incidentally captured in seven of 12 gillnet fisheries on the U.S. east coast, including sink nets, drift nets, and inshore gillnets (Zollet, 2009). Sink gillnets have been identified as a source of high mortality for Atlantic sturgeon (Stein et al., 2004), and the majority of incidental captures in our study occurred in sink gillnets. Atlantic sturgeon are benthic feeders (ASMFC 2017) and thus makes them highly susceptible to capture in sink gillnets. Out of the 12 gillnet fisheries analyzed in the meta-analysis by Zollet (2009), smalltooth sawfish were found to have been incidentally captured only in the southeastern U.S. Atlantic shark gillnet fishery. Similarly, one smalltooth sawfish was captured in shark-targeted gillnet sets within our study. Smalltooth sawfish are generally a benthic, shallow water (<10m) species though they have been found to occur in approximately 100m depth (NMFS, 2009; Dulvy et al., 2016; Carlson et al., 2014). Though they spend time resting on the benthos, large sawfish have been documented to swim mid-water column (D. Grubbs, personal communication), which can make them more susceptible to capture in both sink and drift gillnets. Identification of factors that may be associated with the probability of incidental capture of marine fishes is scarce, and it is largely unknown which factors may influence smalltooth sawfish and Atlantic sturgeon bycatch in the U.S. Both of these species are listed as *Critically Endangered* on the International Union for Conservation of Nature (IUCN) Red List throughout their range and thus bycatch potentially leading to mortality can have large impacts on dwindling populations of threatened and endangered species (Zollet, 2009).

5. Conclusion

The present study represents a broad-scale evaluation of protected species incidentally captured in the U.S. Southeast Gillnet Fishery. Information on total number of protected species, magnitude of mortality, and species composition have been provided and has improved our understanding of protected species-gillnet fishery interactions. Comparative to other gillnet, entanglement, and artisanal fisheries across the globe that have relatively high numbers of interactions, these interactions are still a rare event in the U.S. Southeast Gillnet Fishery. Several environmental and fishing gear factors were considered in our models, yet no one single factor was correlated with incidental capture of all protected species analyzed in our study. However, a few factors were found to have an influence on more than one species including season, soak duration, and gear type. Many species have migratory patterns that are tied to season, reproduction, and feeding ecology and the time of the year, type of gear fished, and the duration that fishing gear is in the water can all have an impact on incidental capture of protected species. Actions have been taken to mitigate fishery interactions with sea turtles and marine mammals such as implementing turtle excluder devices in net gear and creating time-area closures (Northridge et al., 2017 and references therein; NOAA, 2004). However, mitigation actions to reduce species-specific bycatch is lacking. We suggest that future research using controlled experiments (e.g., Jordan et al., 2013) investigating potential mitigation strategies for marine fishes be examined and although the current study was only able to model one elasmobranch, our results can be used as a baseline for future research.

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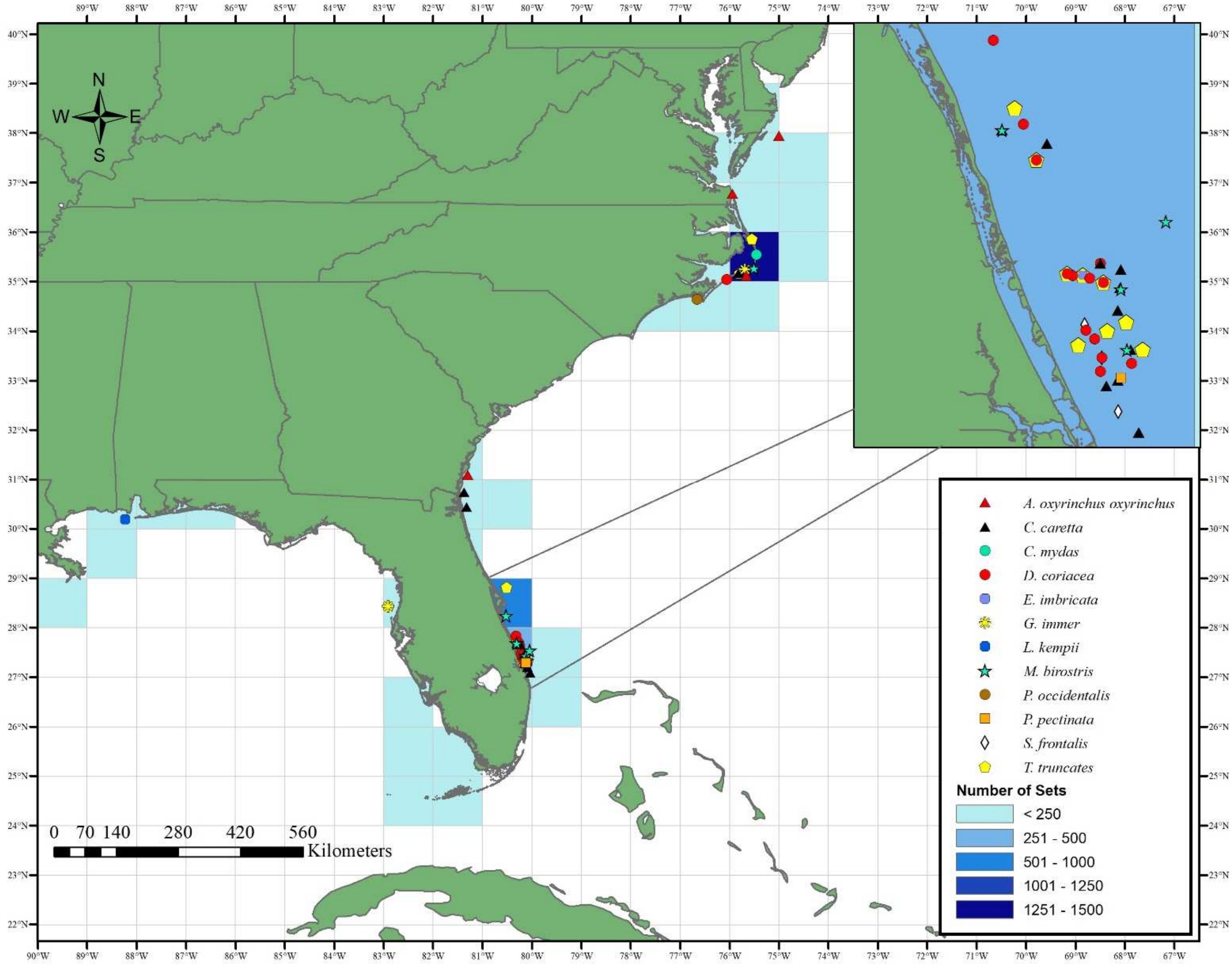

Figure 1. Distribution of observed gillnet fishing effort and locations of protected species interactions (1998-2017).

**note Figure 1 should be used in color

Table 1. List of protected species that have had interactions with U.S. Southeast Gillnet Fishery from 1998-2017. Number of interactions refers to the number of individual animals documented and at-vessel mortalities are included within the total number of interactions.

Scientific name	Common name	Number of Interactions	At-Vessel Mortality	Conservation Status
Sea Turtles				
Caretta caretta	Loggerhead turtle	n = 17	n = 4	ESA threatened; IUCN: vulnerable
Chelonia mydas	Green turtle	n = 1	n = 0	ESA threatened; IUCN: endangered
Dermochelys coriacea	Leatherback turtle	n = 16	n = 2	ESA endangered; IUCN: vulnerable
Eretmochelys imbricata	Hawksbill turtle	n = 1	n = 1	ESA endangered; IUCN: critically endangered
Lepidochelys kempii	Kemp's ridley turtle	n = 1	n = 0	ESA endangered; IUCN: critically endangered
Marine Fishes				
Manta birostris	Giant manta ray	n = 7	n = 1	ESA threatened; IUCN: vulnerable
Pristis pectinata	Smalltooth sawfish	n = 1	unknown	ESA endangered; IUCN critically endangered
Acipenser oxyrinchus oxyrinchus	Atlantic sturgeon	n = 5	n = 2	ESA endangered; IUCN critically endangered
Seabirds				

Scientific name	Common name	Number of Interactions	At-Vessel Mortality	Conservation Status
Gavia immer	Common loon	n = 2	n = 2	MBTA protected; IUCN: least concern
Pelecanus occidentalis	Brown pelican	n = 1	n = 0	MBTA protected; IUCN: least concern
Marine Mammals				
Stenella frontalis	Atlantic spotted dolphin	n =4	n = 1	MMPA protected; IUCN: least concern
Tursiops truncatus	Common bottlenose dolphin	n = 13	n = 13	MMPA protected; IUCN: least concern

ESA=Endangered Species Act, IUCN=International Union for Conservation of Nature Red List, MBTA= Migratory Bird Treaty Act, MMPA=Marine Mammal Protection Act.

Table 2. Candidate factors hypothesized to influence the incidental capture of protected species in the US southeastern gillnet fishery.

Variable	Type	Description	Biological interpretation
Space			
Region	Categorical	Gulf of Mexico, US south Atlantic	Some areas are more likely to have encounters due to high animal density
Latitude	Categorical	24°N to 36°N	or unmeasured characteristics
Time			
Season	Categorical	Summer = April-September Winter = October-March	Seasonal migration patterns, distribution, or behavior of species may differ over time increasing susceptibility to capture
Environment			
Sea Surface Temperature	Continuous	20.5 to 24.4 °C	Ocean characteristics may affect the dispersal
Depth	Continuous	1.2 to 110.0 meters Mean depth of set	and movements of species
Fishery			
Net Depth	Continuous	0.9 to 59.0 meters Depth of gillnet	Certain gear and/or fishery characteristics may make some species more susceptible to capture
Net Length	Continuous	14.0 to 3,246.0 meters Length of gillnet	
Mesh size	Categorical	3.2 to 38.0 cm Stretch mesh	
Gear	Categorical	Sink, drift, or strike gillnet	
Target	Categorical	Shark, mackerel, dogfish, or teleost	
Soak	Continuous	0.05 to 91.0 hours Time net enters water until hauled from water	

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Table 3 Results of the model selection for the zero-inflated negative binomial for *Dermochelys coriacea*.

Factor	df	AIC	ΔAIC	Likelihood ratio test	
Null model	3	122.1			
Mesh size	11	125	20.6	X^2 = 13.1	(df = 1, p = 0.11)
Net depth	4	122.8	18.4	X^2 = 1.3	(df = 1, p = 0.26)
Depth	4	122.2	17.8	X^2 = 1.9	(df = 1, p = 0.16)
Region	4	120.7	16.3	X^2 = 3.4	(df = 1, p = 0.07)
Month	11	118.8	14.4	X^2 = 19.3	(df = 8, p = 0.01)
Latitude	8	118.2	13.8	X^2 = 13.9	(df = 5, p = 0.02)
SST	4	114.8	10.4	X^2 = 9.33	(df = 1, p = 0.002)
Season	**4**	**108.3**	**3.9**	**X^2 = 15.9**	**(df = 1, p < 0.001)**
Season + Net depth	5	106.4	2	X^2 = 19.7	(df = 2, p <0.001)
Season + Depth	5	105.8	1.4	X^2 = 20.3	(df = 2, p < 0.001)
Season + Depth + Net depth	**6**	**104.4**	**0**	**X^2 = 23.7**	**(df = 3, p <0.001)**

SST= Sea surface temperature

Table 4. Results of the model selection for the zero-inflated negative binomial for *Caretta caretta*.

Factor	df	AIC	ΔAIC	Likelihood ratio test	
Null model	2	207.5			
Mesh size	53	266.9	86.8	$X^2 =$ 42.6	(df = 51, p = 0.8)
Depth	4	211.3	31.2	$X^2 =$ 0.2	(df = 2, p = 0.9)
Season	4	210	29.9	$X^2 =$ 1.4	(df = 2, p = 0.5)
Region	4	209.9	29.8	$X^2 =$ 1.6	(df = 2, p = 0.4)
SST	4	206.2	26.1	$X^2 =$ 5.3	(df = 2, p = 0.07)
Soak	4	204	23.9	$X^2 =$ 7.5	(df = 2, p = 0.02)
Net depth	4	203.1	23	$X^2 =$ 8.4	(df = 2, p = 0.02)
Latitude	14	198.2	18.1	$X^2 =$ 33.3	(df = 12, p < 0.001)
Gear	5	193.3	13.2	$X^2 =$ 20.2	(df = 3, p < 0.001)
Target	**6**	**182**	**1.9**	**$X^2 =$ 33.5**	**(df = 4, p <0.001)**
Target + Season	7	182.6	2.5	$X^2 =$ 34.9	(df = 5, p <0.001)
Target + Gear	8	182.8	2.7	$X^2 =$ 36.7	(df = 6, p <0.001)
Target + Season + SST	**8**	**180.1**	**0**	**$X^2 =$ 39.4**	**(df = 6, p <0.001)**

SST = Sea surface temperature

Table 5. Results of the model selection for the zero-inflated negative binomial for *Tursiops truncatus*.

Factor	df	AIC	ΔAIC	Likelihood ratio test	
Null model	3	164.9			
Mesh	53	240	99.5	$X^2 =$ 24.9	(df = 50, p = 0.10)
Latitude	14	171.9	31.4	$X^2 =$ 15.0	(df = 11, p = 0.18)
Depth	4	166.9	26.4	$X^2 =$ 0.02	(df = 1, p = 0.90)
SST	4	166.8	26.3	$X^2 =$ 0.11	(df = 1, p = 0.74)
Region	4	166.8	26.3	$X^2 =$ 0.12	(df = 1, p = 0.73)
Month	14	162.5	22	$X^2 =$ 6.1	(df = 11, p = 0.01)
Season	4	160.8	20.3	$X^2 =$ 6.1	(df = 1, p = 0.01)
Net depth	4	159.9	19.4	$X^2 =$ 7.02	(df = 1, p = 0.008)
Target	6	154.7	14.2	$X^2 =$ 16.2	(df = 3, p = 0.001)
Gear	5	148.8	8.3	$X^2 =$ 20.1	(df = 2, p < 0.001)
Soak	**4**	**146.7**	**6.2**	$\mathbf{X^2 =}$ **20.2**	**(df = 1, p < 0.001)**
Soak + Season	5	145.8	5.3	$X^2 =$ 23.1	(df = 2, p <0.001)
Soak + Target	7	143.9	3.4	$X^2 =$ 29.0	(df = 4, p < 0.001)
Soak + Gear	6	142.3	1.8	$X^2 =$ 28.6	(df = 3, p < 0.001)
Soak + Gear + Season	**7**	**140.5**	**0**	$\mathbf{X^2 =}$ **32.4**	**(df = 4, p < 0.001)**

SST= Sea surface temperature

Table 6. Results of the model selection for the zero-inflated negative binomial for *Manta birostris*.

Factor	df	AIC	ΔAIC	Likelihood ratio test	
Null model	3	99.1			
Mesh size	51	174.5	89	$X^2 = 20.6$	(df = 48, p = 0.10)
Season	4	100.7	15.2	$X^2 = 0.41$	(df = 1, p = 0.52)
SST	4	100.5	15	$X^2 = 0.57$	(df = 1, p = 0.45)
Depth	4	100	14.5	$X^2 = 1.07$	(df = 1, p = 0.30)
Net depth	4	97.4	11.9	$X^2 = 3.68$	(df = 1, p = 0.06)
Net length	4	92.7	7.2	$X^2 = 8.40$	(df = 1, p = 0.004)
Soak	4	91.1	5.6	$X^2 = 10.0$	(df = 1, p = 0.002)
Target	6	93	7.5	$X^2 = 12.1$	(df = 3, p = 0.007)
Gear	**5**	**86.7**	**1.2**	$\mathbf{X^2 = 16.4}$	**(df = 2, p = 0.0003)**
Gear + Depth	6	86.7	1.2	$X^2 = 18.3$	(df = 3, p = 0.0004)
Gear + Soak	6	85.5	0	$X^2 = 21.6$	(df = 3, p < 0.001)
Gear + Soak + Depth	**7**	**85.5**	**0**	$\mathbf{X^2 = 22.0}$	**(df = 4, p = 0.0002)**

SST= Sea surface temperature