

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

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1 Abstract

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

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

22 1. Introduction

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

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

41 protected species could help prevent future interactions through fisheries mitigation strategies
42 and assist in developing recovery actions for these species.

43 Population declines of many sea turtle species have been attributed to incidental capture
44 in fisheries, particularly coastal gillnet fisheries, oceanic driftnets, and bottom nets (National
45 Research Council, 1990; Lewison et al., 2004; Wallace et al., 2010; Fiedler et al., 2012).
46 Similarly, many marine mammals, sharks and rays, and seabirds are easily entangled in gillnet
47 gear and often suffer fishing mortality that can have considerable impacts on species populations
48 (Stevens et al., 2000; Tasker et al., 2000; Read et al., 2006). Air breathing species that require
49 frequent surface intervals (e.g., sea turtles, marine mammals, and birds) along with species with
50 a low intrinsic rate of population growth (e.g., sharks and rays) are highly vulnerable to fishing
51 mortality (Dulvy et al., 2008; Hall et al., 2000; Northridge et al., 2017). Many studies have
52 investigated incidental capture of protected species over the last few decades although a few
53 have assessed this on a multi-species or multi-taxa level (Sims et al., 2008; Northridge et al.,
54 2017).

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

78 Estimates of protected species bycatch have raised concern that this fishery may be
79 impeding the recovery of some of these species. For example, fishers using gillnet gear and
80 targeting shark incidentally captured an estimated 36 (95% confidence limits 0-608) loggerhead,
81 *Caretta caretta*, and 12 (95% confidence limits 0-31) Kemp's ridley, *Lepidochelys kempii*, sea
82 turtles from 2007-2010, respectively (Carlson and Richards, 2011). Carlson and Mathers (2017)

83 determined 24 (95% confidence limits 0-414) giant manta ray, *Manta birostris*, were caught by
84 the southeast gillnet fishery targeting sharks in 2012. Herein, we describe protected species
85 bycatch and evaluate environmental variables and fishing techniques associated with their
86 capture. An understanding of factors related to the capture could aid in the management of this
87 fishery and contribute to the recovery actions for several protected species.

88

89 2. Methods

90 2.1. Observer Coverage

91 National Marine Fisheries Service, Panama City Laboratory, FL USA currently
92 administers the Southeast Gillnet Fishery Observer Program. Scientific observers are trained in
93 the collection of biological and fishery data and species identification. Observers are required to
94 record catch and effort information from each gillnet set on every trip. Observers recorded data
95 associated with three types of gillnet gear: drift, sink (anchored), and strike nets. Drift gillnets are
96 not anchored, secured, or weighted to the bottom at either end of the net and are allowed to drift
97 with currents. Anchored gillnets or sink nets can be set anywhere within the water column and
98 are anchored, secured, or weighted to the bottom by a weight or lead line. Strike nets are actively
99 set around a school of a target species and immediately retrieved and can either fish from the
100 surface to the bottom or function more like a drift net. All gillnet types are typically comprised of
101 monofilament twine and stretch mesh can range between 6.4-30.5 cm and reach lengths of 46-
102 3,200 m. Initially, observer coverage focused on vessels targeting sharks using drift gillnet gear
103 with 100% observer coverage (Trent et al., 1997; Baremore et al. 2007). In 2005, observer
104 coverage was expanded to include all vessels that have an active directed shark permit and fish
105 with sink gillnet gear. These vessels were not previously subject to observer coverage because
106 they either were not targeting sharks or were not fishing gillnets in a drift or strike fashion. In
107 2006, further expansion of the gillnet observer program included all vessels fishing gillnet gear
108 regardless of target, and for coverage to be extended to cover the full geographic range of gillnet
109 fishing effort in the southeast United States. Vessels were randomly selected for observer
110 coverage on a quarterly basis from a pool of vessels that had reported fishing with gillnet gear
111 during the same quarter in the previous year for the Gulf of Mexico and South Atlantic. Observer
112 coverage has ranged from 5-15% depending on the year and availability of funding.

113 2.2. Data treatment and analysis

114 Observations of protected species interactions in the gillnet fishery have been recorded
115 since 1993. Observations were made on all species as the gillnet gear was hauled aboard. The
116 observer remained on the deck of the vessel in a position with an unobstructed view and recorded
117 species and numbers of individuals caught. When species identification was questionable, the
118 crew stopped hauling so that the observer could examine the animal(s) for positive identification.
119 Status (alive or dead at-vessel when boated) of individuals was recorded. Information on abiotic
120 data (e.g., sea surface temperature and depth) was recorded as well as location, time of day, and
121 fishing gear specifics (e.g., net length, net depth, mesh size, and soak duration) for each gillnet
122 set. Due to few and sporadic observations in early years, we restricted our analysis to data
123 collected from 1998 to 2017. Data were further refined by removing all undefined or missing

124 fields (e.g., missing latitude/longitude fields, date, soak time, etc.). For each month of every year,
125 averages were taken of sea surface temperature at the same latitude where the set was recorded
126 and used to fill in any gaps in data on sea surface temperature. In events that protected species
127 were encountered, each individual was counted and recorded within a fishing trip. As many
128 interactions with protected species are rare events, to reduce the number of zeros in the models,
129 frequency distributions were applied to determine if data could be subset based on cumulative
130 frequency percent (e.g., data subset by target species or by gear type).

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

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

$$152 \quad f(y_i = 0) = \pi_i + (1 - \pi_i) \times (k / \mu_i + k)^k$$

$$153 \quad f(y_i | y_i > 0) = (1 - \pi_i) \times f_{NB}^{(y)}$$

154

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

158

159 Several factors were selected that may have potentially influenced the catch of protected
160 species based on our hypotheses and assumed importance in other studies (Table 2). These
161 factors were a combination of continuous and categorical explanatory variables and included
162 region, latitude, season, sea surface temperature, depth, net depth, net length, mesh size, gear
163 type, target, and soak time (Table 2). All of the factors were evaluated for independence by a
164 Kruskal-Wallis test and for collinearity with a Spearman rank test. Initially, a null model was

165 run with no factors included. Each factor was added to the model independently in a forward
166 stepwise manner and results were ranked from the relative least to greatest change in Akaike
167 information criterion (Δ AIC) when compared to the null model (McCracken, 2004; Murray,
168 2009; Carlson et al., 2016). The factor with the lowest Δ AIC was then incorporated into the
169 model and likelihood ratio tests were applied to compare the models for significance (e.g., chi-
170 square values and p-value of <0.05). Factors found to be not significant and/or if the model
171 would not converge with a particular factor were dropped from the model (Zuur et al., 2009).
172 Final models were validated by plotting Pearson residuals against the fitted values from the
173 model and plotting Pearson residuals against each explanatory variable (Zuur et al., 2009).

174 3. Results

175 3.1. Leatherback Sea Turtle

176 Between 1998 and 2017, shark-targeted drift net sets contributed to $>90\%$ of leatherback
177 gillnet interactions with one interaction in a mackerel-targeted sink net (10%). Thus, data were
178 subset to shark-targeted drift net sets and consisted of 268 gillnet trips and 310 gillnet sets.
179 Leatherback interactions occurred on 13 trips resulting in 16 individual leatherback turtle
180 interactions that included two at-vessel mortalities (Table 1). All leatherback and gillnet
181 interactions occurred in the south Atlantic on the east coast of Florida (Fig. 1). All leatherback
182 turtles were caught in the winter between the months of October-March except for one
183 interaction in the summer months of April-September. Observers recorded interactions in sea
184 surface temperatures between 20.5-24.4°C (mean 22.4 °C) and at depths between 12-20m (mean
185 15m). The most significant independent factor influencing capture of leatherback turtles was
186 season ($X^2 = 15.9$, $df = 1$, $p = < 0.001$) (Table 1) whereas a combination of season, bottom depth,
187 and net depth were the most associated with leatherback capture ($X^2 = 23.7$, $df = 3$, $p < 0.001$)
188 (Table 3).

189 3.2. Loggerhead Sea Turtle

190 A total of 1,071 trips consisting of 3,401 gillnet sets, were analyzed between 1998 and
191 2017. Loggerhead interactions with the gillnet fishery occurred on 16 trips resulting in 17
192 individual animals recorded including four animals that suffered at-vessel mortality (Table 1).
193 Loggerhead interactions occurred in the south Atlantic in both winter and summer months with
194 10 (62.5%) interactions in the winter and six (37.5%) interactions in the summer (Fig. 1). Fishery
195 observers recorded captured loggerheads in temperatures between 21.6-29.4 °C (mean 24.8 °C)
196 and depths between 1.5-24.4 meters (mean 14.8 meters). Loggerheads were captured in drift
197 (56.2%), sink (18.8%), and strike (25.0%) nets primarily in the shark (87.5%) and mackerel
198 (12.5%) targeted fisheries. The most significant independent factor influencing the capture of
199 loggerhead turtles was target ($X^2 = 33.5$, $df = 4$, $p < 0.001$) (Table 4) whereas the combination of
200 target, season, and sea surface temperature were the most associated with loggerhead capture (X^2
201 $= 39.4$, $df = 6$, $p < 0.001$) (Table 4).

202

203

204 3.3. Bottlenose Dolphin

205 A total of 1,276 gillnet trips and 3,479 gillnet sets were analyzed between 1998 and 2017.
206 During this period, 11 gillnet trips reported interactions that resulted in 13 individual animals
207 captured. All 13 individuals suffered at-vessel mortality as a result of their interaction with the
208 gillnet fishery (Table 1). Dolphin interactions occurred primarily in the south Atlantic (>90%)
209 with one capture in the Gulf of Mexico (10%) in water temperatures that ranged between 21.1-
210 26.6°C (mean 22.7°C) and depths between 2.4-18.6 meters (mean 13.9 meters) (Fig. 1). Dolphin
211 interactions occurred in all seasons (February-October), primarily in the winter (80%) compared
212 to the summer (20.0%). Interactions occurred in the shark (70%) and mackerel (30%) targeted
213 fisheries in drift (80%) and strike (20%) nets. The most significant independent factor
214 influencing the capture of bottlenose dolphin was soak duration ($X^2 = 20.2$, $df = 1$, $p < 0.001$)
215 (Table 5) whereas the combination of soak duration, gear, and season were the most associated
216 with dolphin capture ($X^2 = 32.4$, $df = 4$, $p < 0.001$) (Table 5).

217 3.4. Giant Manta Ray

218 All giant manta ray interactions occurred in the south Atlantic region (100%) between
219 1998 and 2017, and thus data were subset to this region and consisted of 1,075 gillnet trips with
220 3,346 gillnet sets. There were six gillnet trips that interacted with giant manta rays resulting in
221 seven individual animals being captured, including one at-vessel mortality (Fig.1, Table 1). Giant
222 manta rays were captured in the summer (60%) and in the winter (40%). Fishery observers
223 recorded captures in temperatures between 21.7-29.0°C (mean 24.2 °C) and depths 10.3-29.9
224 meters (mean 17.5 meters). Giant manta rays were captured in drift (80%, $n=6$) and strike (20%,
225 $n=1$) nets primarily from the shark (80%) and mackerel (20%) targeted fisheries. The most
226 significant independent factor influencing the capture of giant manta rays was gear type ($X^2 =$
227 16.4 , $df = 2$, $p < 0.001$) (Table 6) whereas the combination of gear type, soak duration, and
228 bottom depth were the most associated with giant manta ray capture ($X^2 = 22.0$, $df = 4$, $p <$
229 0.001) (Table 6).

230 4. Discussion

231 4.1 General discussion

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

244 4.2 Leatherback Sea Turtles

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

265 4.3 Loggerhead Sea Turtles

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

282

283

284 4.4 Bottlenose Dolphins

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

303 4.5 Giant Manta Ray

304 While there is an abundance of literature evaluating environmental and fisheries
305 characteristics that may influence incidental capture of marine mammals, sea turtles, and
306 seabirds, there are few studies that focus on marine fishes. ESA protected marine fishes such as
307 smalltooth sawfish, Atlantic sturgeon, and giant manta ray have all been reported as bycatch in
308 commercial fisheries (Collins et al., 2000; NMFS, 2010; Croll et al., 2016). Mortality estimates
309 of some of these species may be large, which poses a threat to the recovery of populations (Stein
310 et al., 2004; Croll et al., 2016). Our best fit model indicated that gear type, soak duration, and
311 depth were associated with the probability of giant manta ray capture. Drift nets were responsible
312 for incidentally capturing the most giant manta rays in combination with water depths between
313 10-12m and soak durations that lasted more than eight hours. Giant manta rays exhibit a high
314 degree of plasticity in terms of the depths that they frequent in offshore habitats (Stewart et al.,
315 2016). When feeding, these animals can be found in surface waters down to 10m though diving
316 behavior to depths greater than 300m has been documented (Stewart et al., 2016). Drift gillnets
317 are kept afloat at the proper depth using a system of weights and buoys and in our data, these
318 nets typically fished from the surface down to 7m, well within the depth range of giant manta
319 rays. Continued long soak durations of drift nets will likely increase the number of incidental
320 captures in the future, as indicated by our model. Mitigation strategies for this ESA threatened
321 species could include a restriction of the use of drift gillnets as well as a reduction of soak
322 duration to avoid incidental capture and possible fishing mortality. The limits of soak times
323 implemented with the intent to reduce bycatch of bottlenose dolphins, as well as allow closer

324 monitoring of the net (NMFS, 2006) will also reduce the potential for serious injury and
325 mortality of giant manta ray.

326 4.6 Other protected species

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

333 Factors influencing incidental capture of protected species in gillnet fisheries vary among
334 species across taxonomic groups and by location (Northridge et al., 2017). For example,
335 mortality rates were high for green turtles that were incidentally captured in gillnets in southern
336 Brazil in cold sea surface temperatures, whereas increased mortality for loggerhead turtles was
337 the highest in warmer temperatures in the Mediterranean Sea (Alessandro and Antonello, 2009;
338 López-Barrera et al., 2012). Water depth also has varying impacts on porpoise bycatch rates with
339 some species more impacted in deeper waters compared to others in shallower waters (NMFS,
340 1998; Orphanides, 2010). Other factors such as large mesh size has also been shown to correlate
341 with higher sea turtle and porpoise interactions (NMFS, 1998; Price and Van Salisbury, 2007;
342 Murray, 2009; López-Barrera et al., 2012). For example, porpoise bycatch rates in dogfish and
343 monkfish targeted gillnet fisheries in the U.S. mid-Atlantic are high, likely due to the large mesh
344 sizes used in the gillnets of each fishery (NMFS, 1998; Orphanides, 2010). Incidental capture of
345 seabirds in gillnet fisheries have been correlated with sea surface temperature and water depth
346 (Northridge et al, 2017). Common loons were noted to have higher capture rates in U.S. Atlantic
347 coast gillnet fisheries in low sea surface temperatures and in mid-water depths whereas other
348 species of seabird are often reported as bycatch in shallow water areas (ICES, 2008; Warden,
349 2010). Additionally, behavioral characteristics such as feeding behaviors of pursuit diving
350 piscivorous seabirds and aggregations of birds in breeding colonies may make some species
351 more susceptible to incidental capture (Norman, 2000; Dagys and Zydellis, 2002; Northridge et
352 al., 2017). Similarly, bycatch of porpoises have been attributed to foraging near or out of gillnets
353 (Northridge et al., 2017).

354 Consolidated information of the bycatch of protected species in the U.S. east coast
355 commercial fisheries indicated that the Mid-Atlantic and Northeast gillnet fisheries had some of
356 the largest numbers of documented species that were incidentally captured (Zollet, 2009). For
357 example, Atlantic sturgeon have been incidentally captured in seven of 12 gillnet fisheries on the
358 U.S. east coast, including sink nets, drift nets, and inshore gillnets (Zollet, 2009). Sink gillnets
359 have been identified as a source of high mortality for Atlantic sturgeon (Stein et al., 2004), and
360 the majority of incidental captures in our study occurred in sink gillnets. Atlantic sturgeon are
361 benthic feeders (ASMFC 2017) and thus makes them highly susceptible to capture in sink
362 gillnets. Out of the 12 gillnet fisheries analyzed in the meta-analysis by Zollet (2009), smalltooth
363 sawfish were found to have been incidentally captured only in the southeastern U.S. Atlantic
364 shark gillnet fishery. Similarly, one smalltooth sawfish was captured in shark-targeted gillnet sets

365 within our study. Smalltooth sawfish are generally a benthic, shallow water (<10m) species
366 though they have been found to occur in approximately 100m depth (NMFS, 2009; Dulvy et al.,
367 2016; Carlson et al., 2014). Though they spend time resting on the benthos, large sawfish have
368 been documented to swim mid-water column (D. Grubbs, personal communication), which can
369 make them more susceptible to capture in both sink and drift gillnets. Identification of factors
370 that may be associated with the probability of incidental capture of marine fishes is scarce, and it
371 is largely unknown which factors may influence smalltooth sawfish and Atlantic sturgeon
372 bycatch in the U.S. Both of these species are listed as *Critically Endangered* on the International
373 Union for Conservation of Nature (IUCN) Red List throughout their range and thus bycatch
374 potentially leading to mortality can have large impacts on dwindling populations of threatened
375 and endangered species (Zollet, 2009).

376 5. Conclusion

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

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399 and Technology-National Observer Program. We thank R. Coelho for discussions about the
400 gillnet fishery and data analysis.

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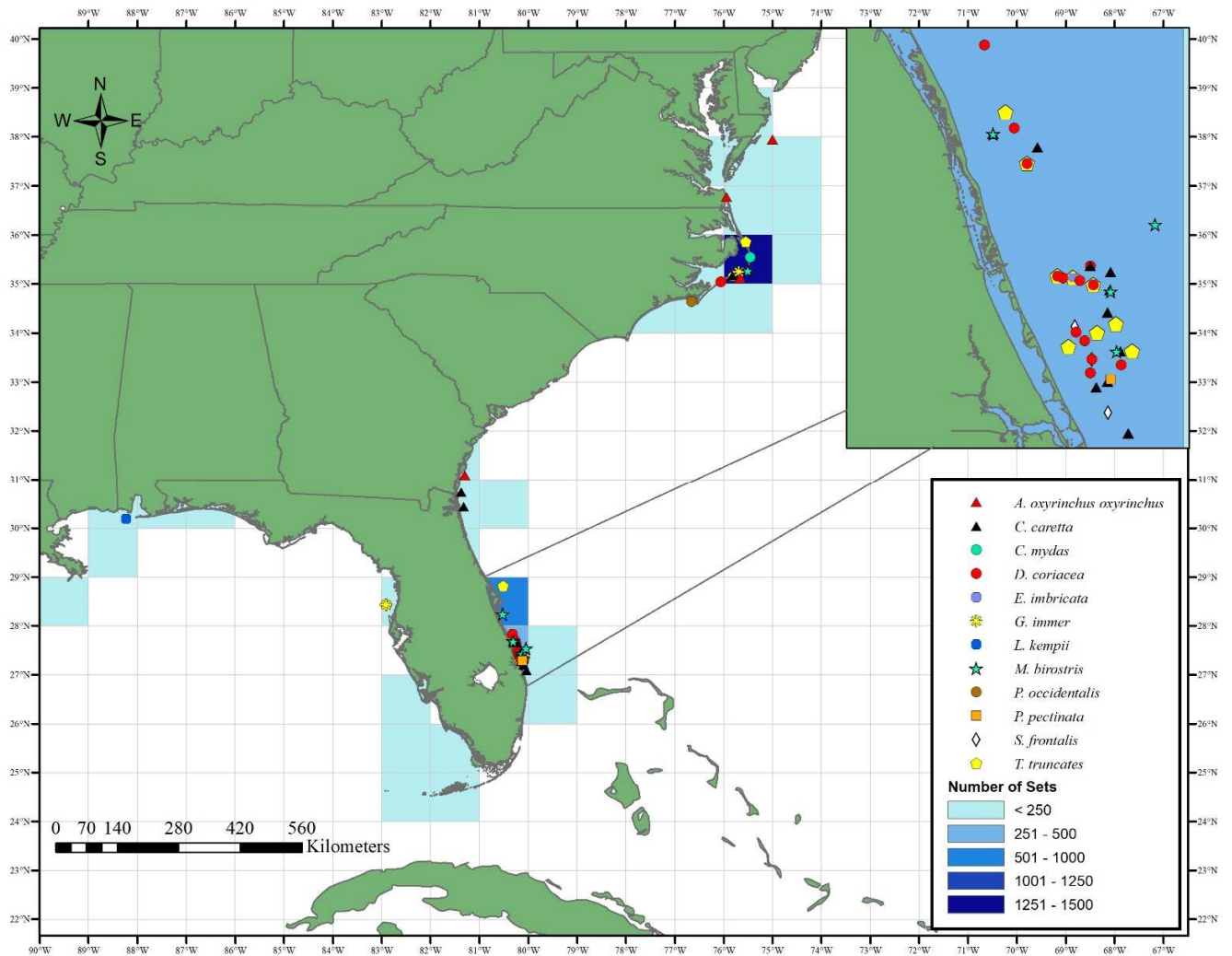
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569 *Figure 1.* Distribution of observed gillnet fishing effort and locations of protected species
 570 interactions (1998-2017).

571 **note Figure 1 should be used in color

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

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

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

Variable	Type	Description	Biological interpretation
<i>Space</i>			
Region	Categorical	Gulf of Mexico, US south Atlantic	Some areas are more likely to have encounters due to high animal density or unmeasured characteristics
Latitude	Categorical	24°N to 36°N	
<i>Time</i>			
Season	Categorical	Summer = April-September Winter = October-March	Seasonal migration patterns, distribution, or behavior of species may differ over time increasing susceptibility to capture
<i>Environment</i>			
Sea Surface Temperature	Continuous	20.5 to 24.4 °C	Ocean characteristics may affect the dispersal and movements of species
Depth	Continuous	1.2 to 110.0 meters Mean depth of set	
<i>Fishery</i>			
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	

590 Table 3 Results of the model selection for the zero-inflated negative binomial for *Dermochelys*
 591 *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)

592 SST= Sea surface temperature

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

Factor	df	AIC	Δ AIC	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)

609 SST = Sea surface temperature

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

Factor	df	AIC	Δ AIC	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	$X^2 = 20.2$	(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	$X^2 = 32.4$	(df = 4, p < 0.001)

626 SST= Sea surface temperature

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

Factor	df	AIC	Δ AIC	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	$X^2 = 16.4$	(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	$X^2 = 22.0$	(df = 4, p = 0.0002)

641 SST= Sea surface temperature

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