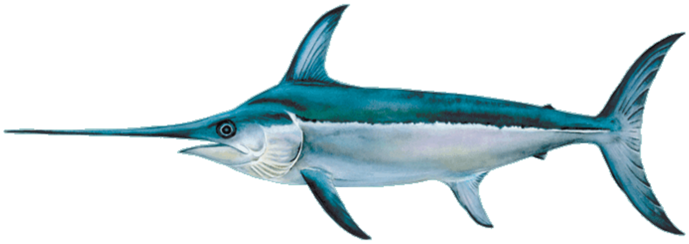

Optimizing Conservation Benefits of Pelagic Marine Protected Areas: Assessing Alternative Timing of the Charleston Bump Time-Area Closure

Sara M. Cleaver

Dr. Andre Boustany, Advisor

Dr. Patrick Halpin, Advisor

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EXECUTIVE SUMMARY

In the U.S. pelagic longline (PLL) fishery for highly migratory species, swordfish (*Xiphius gladius*), bigeye tuna (*Thunnus obesus*) yellowfin tuna (*Thunnus albacares*), and mahi-mahi (*Coryphaena hippurus*) or dolphinfish are the primary target species. These economically high-value fish migrate throughout the Atlantic Ocean, adding to the dynamic nature of this fishery. While fishing has direct ecological impacts on the stocks that are targeted, indirect impacts exist as well. The incidental catch, or "bycatch" of non-target species or undersized individuals has become a substantial ecological problem, and minimizing interactions with these species or size/age classes is a continuous management challenge. In particular, fisheries interactions with threatened species need to be prioritized so that managers can address these bycatch concerns. The reality that many target and non-target species overlap in both space and time creates further management challenges when trying to reduce these interactions.

Under the Magnuson-Stevens Fishery Conservation and Management Act ("the Act"), United States fisheries must be managed at optimum yield, which encompasses maximizing harvests while accounting for economic, social, and ecological factors. The Act also requires that conservation measures minimize bycatch and bycatch mortality. In addition, to optimize global conservation efforts, the U.S. should also consider the market forces and ecological consequences of domestic regulatory measures which may, on a global scale, render U.S. conservation efforts negligible.

In the 1990s, concern over the swordfish stock in the Northwest Atlantic led to a rebuilding program initiated by the National Marine Fisheries Service which included, amongst other measures, a series of nearshore marine protected areas in U.S. federal waters of the Atlantic. These areas excluded pelagic longlining either permanently or for certain times of the year. In 2001, the Charleston Bump Time-Area Closure was implemented primarily to reduce bycatch of undersized swordfish in the area.

The swordfish stock has since rebuilt, species' roles in the fishery have changed, and catch composition may now be different throughout the year than when the closure came into effect. The timing of, and need for this closure should be reevaluated. Thus, this project used historical catch records to examine catch composition and timing from 1986-2008. This catch data were used to predict expected catch (both of retained individuals and discarded bycatch) rates within the closed

area if it had not been closed for three months of each year. Accounting for new regulatory requirements for certain species, predicted rates for landings and discards were estimated for the future based on previous distributional shifts. Using predicted effort by month, I investigated closure timing scenarios to identify which consecutive three-month closure would maximize catch of target species and minimize interactions with protected species. Ultimately, this analysis provides a preliminary understanding of the catch and bycatch distribution of 31 species throughout the year. According to this study, the existing closure in February, March, and April does not optimize efficiency of the fishery, however a closure during January, February, and March may increase efficiency.

Additionally, the declining participation in this fishery has led to a reduction in domestic swordfish production, and managers must consider the global impacts of U.S. regulatory actions meant to protect bycatch species. Reduced U.S. production has led to increased importation of swordfish from less-regulated fisheries abroad. This merely transfers bycatch elsewhere; it does not eliminate it. The ecological damage generated by the U.S. pelagic longline fishery for one swordfish should be compared to that of other, ‘dirtier’ swordfish fisheries. There is much room for research beyond this preliminary study, and tradeoffs between species must be examined in further detail.

For future research, significant tradeoffs must continue to be evaluated. These tradeoffs include: the ecological impacts of protecting one species over another, domestic versus global species protection, and economic benefits to U.S. fishermen rather than loss of domestic products to cheaper and less regulated seafood production internationally. Because this fishery contributes to the bycatch of non-target and protected species as well as discard mortality, we need to consider how this fishery influences global overfishing of these species, and how our goals can be achieved through management decisions and policy change.

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LIST OF ACRONYMS

ABFT - Atlantic bluefin tuna (*Thunnus thynnus*)
ATCA - Atlantic Tunas Conservation Act
BPUE - Bycatch per unit effort; (for this project, # of discarded individuals per unit effort)
CPUE - Catch per unit effort; (for this project, # of retained individuals per unit effort)
DOM - Dynamic ocean management
ESA - Endangered Species Act
EEZ- Exclusive Economic Zone
FAO - Food and Agriculture Organization of the United Nations
FMP - Fishery management plan
HMS - Highly migratory species
ICCAT - International Commission for the Conservation of Atlantic Tunas
IUCN - International Union for Conservation of Nature and Natural Resources.
MMPA - Marine Mammal Protection Act
MSA - Magnuson-Stevens Fishery Conservation and Management Act
NMFS - National Marine Fisheries Service
PLL - Pelagic longline
RFMO(s) - Regional Fisheries Management Organization(s)
SAB - South Atlantic Bight
SCRS - Standing Committee on Research and Statistics
SEFSC - Southeast Fisheries Science Center
TAC - Total allowable catch
UNCLOS - United Nations Convention on the Law of the Sea

F_{MSY} - the maximum rate of fishing mortality (the proportion of a fish stock caught and removed by fishing) resulting eventually, usually a very long time frame, in a population size of B_{MSY}.

B_{MSY} - the biomass that enables a fish stock to deliver the maximum sustainable yield (MSY).

INTRODUCTION

I) Global marine capture fisheries: status and management strategies

In our oceans, overfishing threatens many fish species and the catch of unintended species is a critical resource management concern. According to an assessment of global marine fishery resources conducted by the Food and Agriculture Organization of the United Nations (FAO), the number of fish stocks within biologically sustainable levels (Biomass>B_{msy}) has declined from 90% in 1974 to 68.6% in 2013 (*Figure 1*); thus, 31.4% of fish stocks are estimated as overfished.[1] Large vertebrates such as tunas, billfishes, sharks, and sea turtles are of immediate conservation concern,[2] and removal of top predators and prey species at unsustainable rates can have ecosystem-wide impacts.[3’4’5’6] Nonselective fishing practices that catch non-target species or “bycatch” can have major impacts on fish populations worldwide.[7] While some non-target species may be sold, they may also be unsalable or unwanted due to regulatory or economic reasons and subsequently thrown back to sea (‘discarded), often dead or injured.[8’9’10] Discard mortality may occur shortly or immediately after release due to severe injury, but stress or injury sustained during capture or handling can also lead to delayed discard mortality if injury causes chronic conditions that increase vulnerability to predation or inability to capture prey after release.[11] Research shows that some fish are more physiologically fragile to capture and handling than others, and certain species may be more likely to suffer from high discard mortality than others.[12]

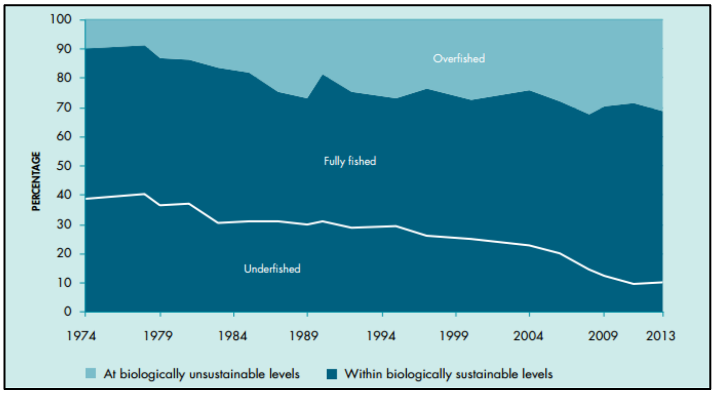


Figure 1. Global trends in the state of world marine fish stocks since 1974. Note: Dark shading= within biologically sustainable levels; light shading= at biological unsustainable levels. The light line divides the stocks within biologically sustainable levels into two subcategories: fully fished (above the line) and under-fished (below the line). Source: FAO, 2016.

Estimating bycatch is extremely difficult due to lack of data and misreporting, and mortality rates of bycatch species constitute a large source of uncertainty in estimates of overall fishing mortality and stock assessments.[13’14’15’16] While bycatch estimates vary based on the use of the term and on the specific fishery and the region where it operates, global bycatch rates have been estimated as high as roughly 40% of the world’s catch.[17’18] One estimate for global discards of all marine organisms was as low as 7.3 million U.S. tons (Mt),[19] while a different study estimated that 27 Mt of marine organisms are discarded each year (range = 17.9±39.5 Mt), with annual landings around 100 Mt.[20] While shrimp trawl fisheries generate approximately one-third of these discards, other gear types such as longlines also catch high numbers of non-target organisms, including endangered and threatened species.[21]

Management tools such as harvest restrictions, which attempt to address overfishing and bycatch issues, require discarding of fish or other animals that are prohibited or that are not within allowable size or catch limits. As regulations become more restrictive in response to overfishing, as they have in the United States, this can lead to higher rates of regulatory discards. The National Marine Fisheries Service (NMFS), which manages federal U.S. fisheries, claims that U.S. fisheries are among the world’s most sustainable.[22] However, research has demonstrated that over 1Mt (17-22%) of fish caught in U.S. fisheries every year are discarded before reaching port,[23] while the estimate for landings was 3.7 million tons, yielding a discard to landings ratio of 28%.[24] Discard mortality may be driving population declines of certain species on a global scale, however these population-level consequences are difficult to assess, particularly for highly migratory species with poorly understood life histories. Studies have shown discard mortality rates of large pelagic fishes approach 30% depending on hook type and the specific fishery.[25’26] The uncertainty of discard mortality rates for many species complicates attempts to quantify the true ecological cost of bycatch.[27]

Definitions of target and non-target catch also vary widely, which further confound interpretations of global bycatch estimates.[28] This is particularly true in multi-species fisheries, where market forces, other socioeconomic factors, and depletion of certain species lead to differing perceptions of what is considered target and non-target catch. Dr. Steven Murawski summarized these shifts in changing target species: “yesterday's bycatch may be tomorrow's target catch”.[29] What may have been considered bycatch species in the 1980s or a few years ago may no longer be considered “bycatch” by today’s standards, even within the same fishery,[30] and it is important that managers account for changes in catch composition to ensure that management measures are in compliance with international and national law.

II) International Policy: Managing Highly Migratory Species

Highly migratory species (HMS) such as Atlantic tunas, swordfish, sharks, and billfish must be managed both domestically and internationally due to their movements beyond regional boundaries. Concern over the state of some HMS stocks prompted international cooperation to attempt to reduce fishing mortality at the International Commission for the Conservation of Atlantic Tunas (ICCAT) in the 1960s. ICCAT, which was established in 1969, is the regional fisheries management organization (RFMO) responsible for the management and conservation of tuna and tuna-like species in the Atlantic Ocean.[31] ICCAT conducts negotiation of country-specific catch quotas for certain species, which are intended to be adopted by member countries.[32] ICCAT member countries have followed these recommendations to regulate their catches of HMS to varying degrees, contributing to ineffective conservation of certain species. ICCAT has been a target of criticism for making decisions based on politics rather than science,[33] and for its inability to make substantial progress in the conservation of HMS due to its failure to undertake difficult management actions. [34’35’36’37’38]

The majority of species assessed in this project are included in the 1982 Convention on Law of the Sea (UNCLOS) under Annex I, ‘highly migratory species’. UNCLOS, which came into force in 1994, established general requirements for protecting the marine environment, including the long-term conservation of fish stocks on the high seas.[39] The 1995 Straddling Fish Stocks Agreement (SFA) strengthened the role of existing regional fisheries management organizations, and decreed that commercial fishing fleets from member countries must abide by RFMO regulations.[40] RFMOs are currently the only legally-mandated fisheries management bodies on the high seas.[41] RFMOs face substantial challenges: decision-making and consensus in order to adopt regulations, uncertainty of the status of resources and limited data, lack of enforcement on the high seas, lack of political commitment and compliance by members, lack of control of non-member activities, limited funding and capacity, diverse national agendas and differing economic priorities.[42,43]

In 1995, the FAO adopted the Code of Conduct for Responsible Fisheries, a set of principles and international standards for responsible fishing practices to ensure the conservation, management, and development of living aquatic resources.[44] This Code, while not legally-binding, prescribed goals for managing fisheries resources for sustainability and economic viability. A 2009 study revealed that compliance with the Code was poor for the 53 countries assessed (which accounted for 96% of the global marine catch) *(Figure 2*). While improvements in compliance were low overall (no countries hit the “passing” threshold), the U.S. scored second highest of all countries assessed after Norway (both countries scores’ had confidence limits which overlapped with 60% compliance).[45] Unfortunately, over 80% of U.S. seafood is imported,[46,47] and the U.S. is increasingly reliant on fishing countries that score even lower on compliance with the Code of Conduct. According to the FAO, certain countries, particularly developing countries, “may have inadequate regulatory frameworks and institutional capacity for sustainable governance of the fishery sector”.[48]

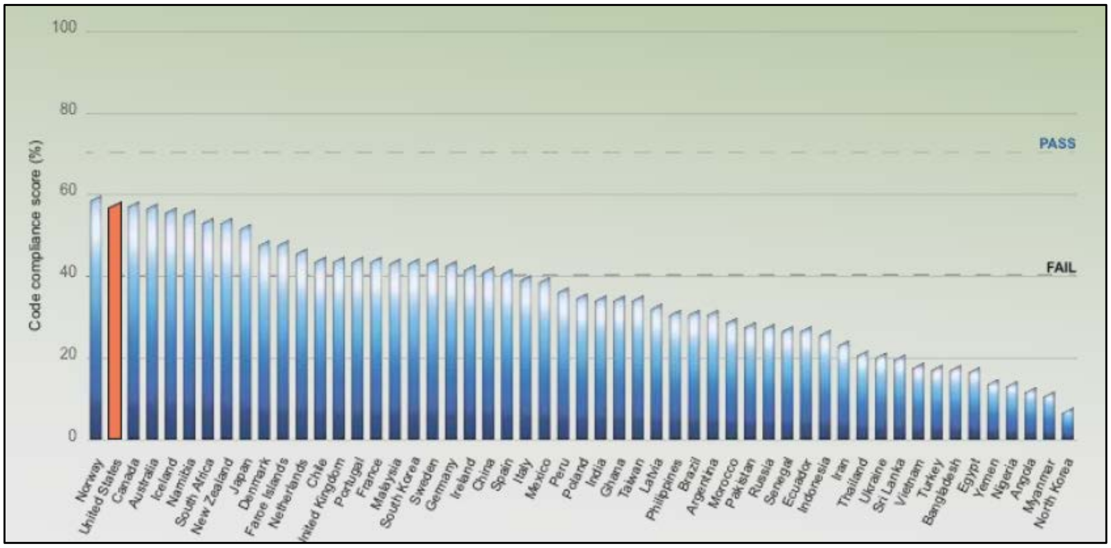


Figure 2. Overall Code of Conduct compliance. Source: Pitcher et al., 2009.

III) Fisheries Policy in the United States

a. *Magnuson-Stevens Fishery Conservation and Management Act*

The U.S. HMS fishery in the Atlantic is managed under the dual authority of the Magnuson-Stevens Fishery Conservation and Management Act (MSA) and the Atlantic Tunas Convention Act (ATCA). The ATCA authorizes NMFS to create regulations based on recommendations adopted by the ICCAT.[49] The primary goal of the Magnuson-Stevens Act (MSA) is to “foster long-term biological and economic sustainability of our nation’s marine fisheries out to 200 nautical miles”.[50] More specifically, the Act aims to “prevent overfishing, rebuild overfished stocks, increase long-term economic and social benefits, and ensure a safe and sustainable supply of seafood".[51] Under the Act, the NMFS must manage fisheries for optimum yield (OY).[52] As noted by Dr. Dunphy-Daly, the need for managers to adhere to conservation principles while also balancing optimization of yield leads to tensions between profit and conservation interests, creating challenges for fisheries managers.[53] The Magnuson-Stevens Act also established eight Regional Fishery Management Councils to oversee the development and implementation of Fishery Management Plans (FMPs) for species fished in U.S. federal waters.[54] All FMPs must follow ten National Standards as required by the MSA.[55] National Standards One and Nine are especially pertinent to the reasoning for this project:

National Standard 1: "*Conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery for the United States fishing industry".*

National Standard 9: "*Requires U.S. action to minimize bycatch and bycatch mortality to the extent practicable".*

b. The Endangered Species Act and the Marine Mammals Protection Act

Due to the strongly protective provisions of two federal statutes, the Marine Mammal Protection Act (MMPA) of 1972 and the Endangered Species Act (ESA) of 1973, U.S. fishery practices are subject to an additional degree of regulation. Many fisheries interact with species protected under one or both of these statutes, or other vulnerable overfished species. The NMFS has jurisdiction over 151 endangered and threated marine species.[56] The NMFS has authority, under both the ESA and the MMPA, to permit incidental takes of protected species to a certain limit, which they are responsible for setting. Additionally, the MMPA mandates that each U.S. commercial fishery must be classified into one of three categories by the level of incidental mortality or serious injury of marine mammals.[57] These categories are:

1. Frequent incidental mortality or serious injury of marine mammals.
2. Occasional incidental mortality or serious injury of marine mammals.
3. Remote likelihood of / no known incidental mortality or serious injury of marine mammals.

Due to the long history of interactions between pelagic longlines (PLL) and protected species, the Atlantic PLL fishery for HMS has been classified as a Category I fishery with respect to the MMPA.[58]

IV) The Atlantic Pelagic Longline Fishery for Highly Migratory Species

a. Longline gear and background

Pelagic longlines are the most widespread fishing gear used in the open ocean.[59] The United States pelagic longline (PLL) fishery for Atlantic Highly Migratory Species is a multispecies commercial fishery that primarily targets swordfish (*Xiphias gladius)*, bigeye tuna (*Thunnus obesus)*, yellowfin tuna (*Thunnus albacares)*, and more recently, dolphinfish (*Coryphaena hippurus)*. Secondary target species include albacore tuna (*Thunnus alalunga*), and certain species of sharks. This fishery extends from the Grand Banks in the North Atlantic to the waters off of South America, and is classified into geographic areas for management purposes *(Figure 3).* The U.S. Atlantic PLL fishery is currently comprised of fewer than 100 boats,[60] and most effort in the fishery is concentrated on the continental shelf.[61]

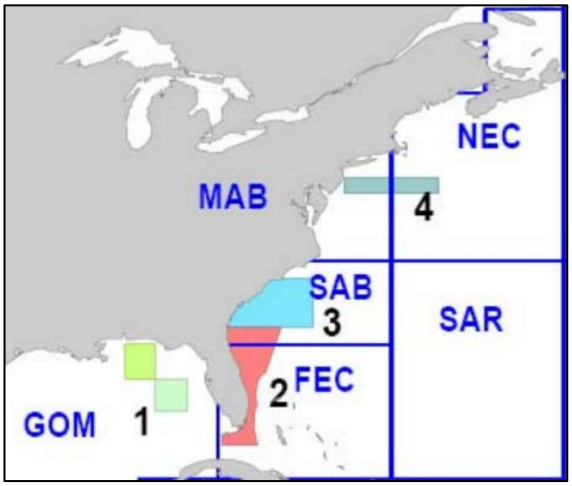


Figure 3. Geographical area distribution of some of the U.S. Pelagic longline fishery and closures: GOM Gulf of Mexico, FEC Florida east coast, SAB south Atlantic bight, MAB mid Atlantic bight, NEC north east coastal Atlantic, SAR Sargasso Sea. Shaded areas represent the time-area closures affecting the pelagic longline fishery. Permanent closures shown: 1) DeSoto Canyon in them U.S. Gulf of Mexico (2000), 2) Florida east coast (2001). Non-permanent closures: (3) the Charleston Bump area closed February 1-April 30 (2001), 4) the bluefin tuna protection area closed June (2000). Source: Ortiz, 2010.

Pelagic longline gear consists of a mainline suspended in the water column by floats. From the mainline, baited hooks are attached on leaders *(Figure 4)*.[62] This gear can be modified (e.g., type of bait, hook size, length of mainline, depth and timing of set) to target certain species, such as in *Figure* 5.[63] Specifically, longliners traditionally deploy gear at sunset to take advantage of swordfishes' nocturnal near-surface feeding habits, whereas those targeting tuna set in the morning.[64] Unfortunately, however, many non-target species are also caught on pelagic longlines.

The U.S. PLL fishery for HMS is subject to numerous management measures, which have been designed to meet specific conservation goals. Any species that cannot be legally landed due to fishery regulations (or undersized catch of permitted species) is required to be released, regardless of whether the catch is dead or alive.

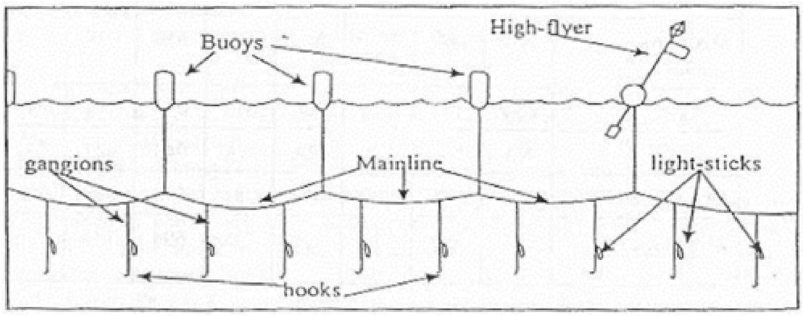


Figure 4. Pelagic longline gear. Source: Blue Water Fishermen's Association, 2016.

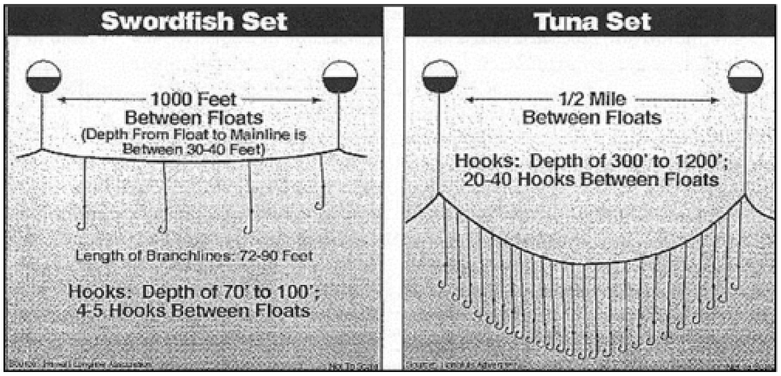


Figure 5. Differences between pelagic longline set targeting swordfish and a set targeting tuna. Source: NOAA Fisheries. (2014). 2014 Stock Assessment and Fishery Evaluation (SAFE) Report for Atlantic Highly Migratory Species.

U.S. pelagic longline fisheries have been subject to a complex series of regulations designed to ensure compliance with the MSA, MMPA, ESA, and ICCAT recommendations. Some of these measures include limits on fishing effort, modifications to gear and operations, requirements such as minimum swordfish sizes, and limits on incidental catch.[65] The NMFS has also restricted the allowable length of domestic longlines, and in the U.S., longlines can range from 20 to 40 miles in length depending on location.[66] Longliners must abide by reporting requirements, including the requirement that each vessel has a GPS monitoring system on board.[67] Beginning in 1986, all U.S. pelagic longline vessels that actively fished were required to self-report daily records by trip in logbooks, detailing where and when they fished, as well on details on gear used, species caught, and other fishing-related variables.[68] In 1992, the National Pelagic Observer Program was established, which mandated the presence of observers on selected longline trips to collect data on set location, species caught, their size and sex, environmental information, biological samples, and any fisheries violations which occurred.[69] The intent of this program is to better evaluate the harvest and status of pelagic fish stocks, and to assess how well management measures control harvests and reduce protected species interactions.[70] As of 2010, about 5-7% of the pelagic fleet trips were monitored by observers.[71] Longliners are also required to possess multiple permits, such as directed or incidental swordfish and shark permits, and an Atlantic Tunas longline category permit. Starting in 1999, the U.S. Atlantic PLL fishery functions under a limited access program, meaning that the number of permits is capped, and a new vessel wanting to obtain a permit can only obtain one by having one transferred from a permit holder who is leaving the fishery.[72]

b. Species Information

<u>Primary target species: Swordfish, dolphinfish, & tunas</u>

This fishery results in the catch of many target as well as non-target species. The primary target species in this fishery, swordfish, are large and fast pelagic predators found worldwide in temperate and tropical waters from about 50° North to 50° South in the Atlantic.[73] They are a highly valued commodity throughout their range, as they are an important food species worldwide.[74] Mixing among three populations (North Atlantic, South Atlantic, and Mediterranean) is likely to occur, however because genetic evidence points to these as distinct populations, they are managed as three separate units.[75] Spawning occurs in tropical and subtropical waters of the western Atlantic. They can reach a maximum size of nearly 1,200 pounds (over 500kg) and speeds up to 50 mph.[76] In general, swordfish mature early, at about five to six years,[77] and they have high individual growth rates. Females may spawn multiple times in a year, and it is both swordfish size and fecundity which contribute to their moderately high population growth rate. This makes swordfish a suitable species for fisheries to target because they are fairly resilient to fishing pressure.

According to Neilson et al.'s extensive research on swordfish migration patterns, the distribution of Northwest Atlantic mature and juvenile swordfish changes with their northerly migrations in the spring and southerly migrations in the fall along the Gulf Stream (*Appendix A*).[78]

Swordfish that were not in spawning condition appeared in February through March, while spawning individuals appeared largely from April through July.[79] Swordfish do not form schools,[80] one reason they are targeted by longline gear rather than purse seines. Similar to other pelagic species, swordfish have diel vertical migration patterns; they feed most often at night when they rise to surface and near-surface waters in search of smaller fish.[81] While swordfish typically remain near the surface, they occasionally make dives as deep as 2,100 feet.[82] Several studies noted a relationship among moon phase, swordfish behavior, and catch rates, noting that swordfish are in deeper waters during the full moon than during other lunar phases.[83]

Swordfish often loosely congregate around ocean current boundaries, convergence zones, and areas of upwelling, as large amounts of prey tend to exist in these places of increased productivity.[84] Swordfish frequently feed on squid, but small fish such as menhaden, mackerel, bluefish, silver hake, butterfish, and herring also contribute to their diet in the Northwest Atlantic.[85] Even juvenile swordfish are aggressive and feed on large prey.[86] Due to the potential for overlap of species and size/age classes in feeding areas, it is not uncommon for longliners to unintentionally catch undersized swordfish while targeting adults.[87]

In 1990, the ICCAT's Standing Committee on Research and Statistics (SCRS) determined that overfishing of north Atlantic swordfish was occurring, and that mortality rates of juvenile swordfish exceeded allowable levels.[88] While a Fishery Management Plan for Atlantic Swordfish was developed by the U.S. South Atlantic Fishery Management Council in 1985,[89] this alarm lead to ICCAT's active management of swordfish including restrictions on fishing effort, size limits, and allowable catches of the northwest Atlantic stock.[90] This concern also led to further domestic restrictions on PLL fishing effort, such as time-area closures.

Dolphinfish (or mahi-mahi), another large pelagic predator, has increasingly become a large proportion of the PLL catch in the Northwest Atlantic. Commercial landings in the Atlantic have increased significantly from approximately 20 metric tons to 620 metric tons from the 1980s to the 1990s.[91] Due to their fast growth rates and young age-at-maturity, dolphinfish are capable of withstanding high rates of fishing mortality.[92] Like swordfish, dolphinfish are generally found along temperature and current fronts in the open ocean,[93] and both species are often caught in similar areas in the U.S. Atlantic PLL fishery.

Members of the genus *Thunnus* are also frequently caught in this fishery. Bigeye and yellowfin tuna are other primary target species, while other tunas such as albacore and skipjack

(*Katsuwonus pelamis*) represent a smaller portion of secondary target catch. Unlike swordfish, tunas form schools near the surface, and tuna often school together by size rather than species.[94] The high market value of bluefin tunas for sushi and sashimi in Japan has led to high demand and severe overfishing of these species globally.

ABFT have in turn declined by an estimated 72% in spawning stock biomass (SSB) from 1970-2009.[95] In the most recent years (1988-2009), however, there has only been an estimate 1% decline in SSB.[96] To protect this species, NMFS trip limits in the 1980s, which requires longline vessels to account for incidental ABFT landings and dead discards. Vessels are restricted in the number of ABFT they can possess based proportionally on the weight of other retained species they have on-board. Low population levels continue today as the West Atlantic stock is at just 36% of its already overfished 1970 levels,[97] and ABFT is listed as "endangered" on the International Union for Conservation of Nature and Natural Resources (IUCN) Red List.[98]

Sharks

Since 1993, shark fisheries in the Atlantic and GOM waters in the U.S. have been managed under the Fishery Management Plan for Sharks of the Atlantic Ocean.[99] A comprehensive logbook was initiated for federally managed shark fisheries at this time. Depending on the permit (incidental or directed), PLL vessels may be limited to a retention limit for certain species per trip.[100] Within this fishery, interactions with both pelagic (oceanic whitetip, blue, porbeagle, mako, thresher, etc.) and coastal (sandbar, blacktip, hammerheads, etc.) sharks occur. Findings from fishery-independent data sources have shown that the blue shark (*Prionace glauca*) represents the most abundant pelagic shark in the Northwest Atlantic,[101’102] As such, the blue shark represents the most frequently captured shark in U.S. Atlantic PLL operations, constituting 17–32% of the overall catch reported in this fishery between 1987 and 1995.[103] The species reportedly comprises 50% of the Northwest Atlantic PLL bycatch, a group of species not comprised exclusively of sharks.[104] Due to their low commercial value, the majority of these blue sharks are discarded at sea.[105] One study on discard mortality of blue sharks in the Northwest Atlantic PLL fishery estimated a 35% mortality rate, however this study was completed at a time before the widespread introduction of the less-fatal circle hook.[106]

Many other shark species have low reproductive capacity, which make them vulnerable to overfishing and population depletion from discard mortality. Porbeagle sharks (*Lamna nasus*) have high commercial value and have been overexploited, but overfishing of the species is not currently occurring and the biomass of the stock is increasing.[107] The current porbeagle population is seriously depleted, and currently a small quota exists for porbeagle in the PLL fishery.[108] This species has a more northerly range, from New Jersey to Canada.[109] The oceanic whitetip shark (*Carcharhinus longimanus*) is of particular concern because it has been assessed by IUCN as a Critically Endangered species in the Northwest Atlantic based on estimated population declines of 70% from 1986 to 2000.[110] Baum et al. estimated that hammerhead sharks have declined in abundance by 89% also from 1986 to 2000.[111] Additionally, they estimated that scalloped hammerhead (*Sphyrna lewini*), white (*Carcharodon carcharias*), and thresher (*Alopias vulpinus*) sharks in the Northwest Atlantic have declined more than 75% over the same timeline.[112] The Great hammerhead (*Sphyrna mokarran*), listed as endangered in the Northwest Atlantic on the IUCN Red List, is suspected to have declined by over 50% from 1997-2007, however this species is very difficult to assess due to inaccurate reporting and poor species identification.[113] The Great hammerhead is vulnerable to overfishing because of its biennial reproductive cycle[114] and low survival at capture.[115] Physiologically, hammerheads are very fragile, and they suffer high mortality rates in longline fisheries.[116] Their late age at maturity renders many species vulnerable to overexploitation, and limits their potential to recover from threats.[117]

Data from surveys from 1972 to 2003 off the North Carolina coast showed significant declines in certain shark populations over those 32 years (*Table 1*).[118] A more recent survey (1989-2005) conducted by the same author also along the southeast U.S. showed a significant increase in juvenile scalloped hammerheads, possibly due to decreases in the population sizes of their predators, larger apex sharks.[119] Interestingly, in 2014, scalloped hammerheads became the only shark species listed on the Endangered Species List.[120]

Species	**Percent decline**
Sandbar (*Carcharhinus plumbeus*)	87%
Blacktip (*Carcharhinus limbatus*)	93%
Tiger (*Galeocerdo cuvier*)	97%
Scalloped hammerhead (*Sphyrna lewini*)	98%
Dusky (*Carcharhinus obscurus*)	99%
Smooth hammerhead (*Sphyrna zygaena*)	99%

Table 1. Estimated declines in shark populations off NC coast from 1972-2003. Data from: Myers, R.A., Baum, J.K., Shepherd, T.D., Powers, S.P. and Peterson, C.H., 2007. Cascading effects of the loss of apex predatory sharks from a coastal ocean. *Science*, *315*(5820), pp.1846-1850.

Billfish

In this fishery, types of billfish include blue marlin (*Makaira nigricans*), white marlin (*Kajikia albida*), longbill and roundscale spearfish (*Tetrapturus pfluegeri* and *Tetrapturus georgii*), and the sailfish (*Istiophorus albicans).* Some of these species are often misidentified and thus misclassified, confounding status estimates.[121] In general, these statuses of these species are fairly uncertain. Sailfish and marlin mature around two to four years, with longevity estimates from around 13 to over 20 years depending on the species, while spearfish may spawn after the first year, and may only live about four years.[122,123,124,125] White marlin stock estimates show population declines of 9-37%.[126] Current fishing mortality rates of blue marlin are above FMSY, with biomass either at or below BMSY.[127] Longbill spearfish are a “Least Concern” species according to the IUCN, with no evidence of decline and with moderate catch rates across time.[128] Additionally, they are not targeted in any fisheries.[129] Sailfish grow relatively fast, with an age of maturity at 2.5 years, and estimate longevity of 13 years.[130] Sailfish declined before 1990, and despite considerable uncertainty, there is evidence of overfishing of sailfish in the Atlantic.[131]

In 1988, the Billfish Conservation Act banned the retention of Atlantic billfishes on pelagic longline vessels in the U.S, and prohibited the sale of billfishes domestically.[132] This allowed fishing effort for billfish to be reserved for the recreational fishing sector.[133] Outside the U.S., few fisheries target these species, but they are caught as bycatch and then sold in global longline fisheries.[134,135,136,137]

Sea turtles

Beginning in 1992, sea turtle bycatch data were included in the logbook forms[138] Leatherback (*Dermochelys coriacea*) and loggerhead (*Caretta caretta*) sea turtles migrate between feeding and nesting areas. Despite being protected under a variety of national and international laws and agreements, both species are critically endangered in some parts of the world. However, the northwest Atlantic subpopulations for both leatherbacks and loggerheads are listed as "Least Concern" by the IUCN due to successful conservation and management efforts in this region.[139,140] It is important to note any changes in conservation status could lead to a shift in these subpopulations' health; they are conservation dependent. While subpopulation trends vary based on nesting sites, the northwest Atlantic subpopulation of leatherbacks has increased by 26% over the past three generations, and is projected to continue increasing over current management scenarios.[141] The overall trend for the loggerhead subpopulation is slightly positive in the northwest Atlantic.[142] Additionally, these sea turtles still face many non-fisheries related threats such coastal development, marine debris & pollution, and climate change.

V) Time-area closures & the Charleston Bump

Time-area closures are one management tool which fisheries managers have employed to restrict access of certain areas in order to reduce bycatch. This kind of marine protected areas prohibit certain activities within a defined geographic area either temporarily or permanently. This strategy focuses on changes in spatial and temporal overlap of target and bycatch species and attempts to minimize times when high rates of bycatch occur.[143] Additionally, nearshore time-area closures can be enforced better than many other types of regulations.[144] When designed appropriately, taking into account different spatial and temporal scales of the distribution of catch, time-area closures can be effective at mitigating bycatch.[145] These static management measures, however, have come under scrutiny as they do not always account for the dynamic nature of these ecological systems in the ways that dynamic ocean management (DOM) (grid-based closures and move-on rules using real-time data) attempts to.[146] Highly migratory species (such as those in the U.S. Atlantic PLL fishery) are especially difficult to manage due to their life-history strategies. Inter-annual variations in species' distribution can cause disparities in the timing or spatial extent of closed areas.[147,148] Fishing industries and their participants will respond to closures, often by redistributing fishing effort elsewhere.[149] In this way, closures may actually relocate rather than reduce bycatch to other regions outside of the closure.[150] Bycatch of finfish, sharks, and sea turtles in PLL fisheries has contributed to the decline of particular species worldwide, and there is a continued need to address this issue.[151],[152] While some time-area closures have been successful at reducing bycatch, it is important to reassess these closures and adapt management measures to account for changes in catch and bycatch composition as well as population-level changes over time.

In 1997, after many attempts at rebuilding swordfish biomass, ICCAT saw improvements in swordfish recruitment rates and catch rates, though it is possible that this was due to environmental and oceanographic conditions.[153] Around this time, ICCAT recommended a ten-year rebuilding program for swordfish. Concern about overfishing of juvenile swordfish and other bycatch species lead to the implementation of time-area restrictions in the U.S. Atlantic designed to reduce the frequency and severity of interactions with these species. These closures affect significant areas of the HMS pelagic longline fleet fishing grounds (Figure 3).[154] Included in these areas is a nearshore area in the South Atlantic Bight (SAB) named the Charleston Bump. The Charleston Bump is a deep-water bottom feature located southeast of Charleston, South Carolina.[155] An area of drastic depth change, it is made up of a of series rocky cliffs which deflect the flow of the Gulf Stream.[156] This deflection creates a series of persistent swirls and upwelling currents referred to as the "Charleston Gyre".[157] The upwelling created by this bottom feature brings nutrient-rich waters to the surface, bringing with it plankton and food for fishes. Increased concentrations of larvae and juvenile fishes attract large pelagic fishes, making this area a highly productive fishing ground.[158] This area is recognized as a persistent nursery area for juvenile swordfish, which are less migratory than adults and generally congregate in warm waters.[159]

The Charleston Bump time-area closure prohibited longline fishing on and surrounding the Charleston Bump over an area of approximately 124,400km^2.[160] Reasoning for this three-month closure was due to the NMFS' finding that "while pelagic longline activity in the Charleston Bump area results in bycatch of small swordfish throughout the year, over 70% of the swordfish bycatch takes place during February through April".[161] Additionally, bycatch of sharks, sea turtles, and other non-target species within the area is a conservation concern and a nuisance to fishers who are trying to maximize their efficiency and increase catch of target species. The closure extends from the northern boundary of the East Florida Coast Closed Area at 31°00' north to 34°00' north, and from the western (inner) boundary of the U.S. Exclusive Economic Zone (EEZ) seaward to 76°00' west.[162] Due to a mistake relating to the boundary of the area, there was a delay in its effective date for the first year, and the area was closed from March 1 to May 1 during 2001. After 2001, the closure was from February 1st to April 30th annually.

VI) Changes in the fishery

Since the Charleston Bump time-area closure was implemented in 2000, the U.S. PLL fishery for HMS has undergone many regulatory changes. For example, given existing concerns surrounding protected species, longline vessels are now required to have a valid Protected Species Safe Handling, Release, and Identification Workshop certificate.[163] Proper identification of shark species is crucial because some species of shark (silky, oceanic whitetip, great hammerhead, scalloped hammerhead, smooth hammerhead, bigeye thresher, dusky, bignose, longfin mako, night, and white) are now protected, meaning they are prohibited to retain, transship, land, store, or sell.[164] Additionally, there are commercial quotas for some species of shark, with retention limits based on permit type (directed or incidental).[165] Furthermore, shark finning was prohibited in 2000 with the passing of the Shark Finning Prohibition Act,[166] and all sharks must now have fins naturally attached through offloading.[167]

One of the changes within the HMS fishery that may significantly influence catch rates of protected species is the requirement to use circle hooks. J-hooks were predominantly used in this fishery until 2004, at which time NMFS mandated the use circle hooks for the U.S. PLL fleet.[168] The goal of this gear modification was to reduce catch rates of protected species and/or increase their post-release survival, and research findings demonstrate that circle hooks have differential effects on catchability and survivability depending on the species.[169],[170],[171]

Due to increased regulations and costs, including the closure of near-shore areas, restrictions on vessel upgrading, participation in the U.S. Atlantic PLL fishery has declined.[172] While the permit cap is set at 247 vessels, the fishery consists of fewer than 100 vessels actively fishing.[173] These boats that are actively fishing account for only five to eight percent of the total number of pelagic longline hooks fished in the entire Atlantic.[174]

As a result of several factors including U.S. management measures, ICCAT's adoption of a successful rebuilding plan, as well as certain biological traits of swordfish which contribute to their population resilience, the North Atlantic swordfish stock has recovered. [175] According to the 2009 stock assessment, swordfish biomass has consistently increased to just over B_{msy} since 2000; the stock is effectively rebuilt (*Figure 6*).[176] While U.S. landings have increased, the swordfish fishery is currently underutilized, and U.S. swordfish landings are not meeting domestic demand. This leads to increased importation of swordfish from less-regulated fisheries. [177'178] Re-opening nearshore closed areas would allow fishermen access to proximal coastal fishing grounds, potentially resulting in increased landings of targeted species and beneficial economic impacts such as the improved participation in the U.S. fishery.[179]

Due to the temporal and spatial variability of HMS fisheries, adapting closure boundaries or timing may be necessary over time. Adapting closures to reduce bycatch of current non-target species is crucial to effective management, especially in the face of climate change, where fish distributions are likely to change in response to ocean warming and its impacts on productivity.[180] In response to declining fishing effort and landings coupled with an under-utilized swordfish quota, NMFS considered a 2006 amendment to modify time-area closures in order to optimize the U.S. PLL fishery.[181] NMFS evaluated discard reductions for several species including white marlin, blue marlin, sailfish, spearfish, leatherback sea turtles, loggerhead sea turtles, other sea turtles, and BFT,[182] however this analysis excluded protected shark species, which have become an increasing conservation concern. Ultimately, several considerations including the need for further research led to the decision to make no modifications to the time-area closures.[183]

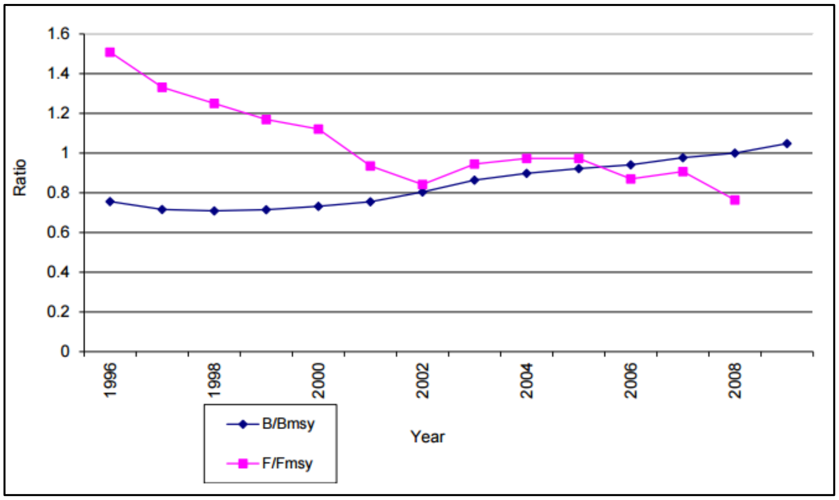


Figure 6. Rebuilding of North Atlantic swordfish. Data from: ICCAT 2014-2015. Retrieved from https://www.iccat.int/Documents/SCRS/ExecSum/SWO_ATL_ENG.pdf

VII) Project Objectives

While NMFS closed the Charleston Bump area for a three-month time frame with the purpose of decreasing bycatch of small swordfish and other non-target species, debate surrounds whether this timing of this closure is optimal in both ecological and economic terms (Andre Boustany, personal communication, 2016). The objective of this project is to investigate whether it would be appropriate to change the timing of the Charleston Bump time-area closure in order to increase the efficiency of this fishery by increasing retention of target species and decreasing bycatch of and interactions with non-target species. Due to technological constraints on implementing dynamic ocean management measures, managers must rely on existing management tools, including using the best-available scientific information. This project investigates whether it would be appropriate to update the timing of the Charleston Bump time-area closure to ensure it does in fact increase the efficiency of this fishery and decreases bycatch and interactions with non-target species. Since the establishment of the closure, the conservation statuses of many highly migratory species have changed, and, as a result, conservation priorities have also shifted. Species that were not a concern when the time-area closure was created now require more active management. Given the spatiotemporal overlap of some HMS target and non-target species (and size/age classes), different timings of the Charleston Bump time-area closure will lead to variations in retention and discard rates across taxa.

Research Questions:

- Is there a better time for the closure that is more beneficial for both the industry (the U.S. Atlantic pelagic longline fishery) and conservation of non-target species?
- Is it possible to find a closure period when retentions of target species would increase and interactions with discarded species decrease?

These questions were addressed by assessing the following:

1) The catch composition for retained and discarded species before the time-area closure was put in place (1986-2001)
2) The catch composition for retained and discarded species during the open period after the time-area closure was implemented (2001-2008)
3) The regulatory and conservation statuses for species in the fishery
4) Composition of the catch outside of the closure (within a specified distance, the study region) both when the area is open and closed.
5) Catch and discard rates for each species

METHODS

I. Data

a. Pelagic longline logbook data

The U.S. Atlantic PLL logbook data is collected and managed by the NOAA Southeast Fisheries Science Center (SEFSC), where it is entered into the fisheries logbook system and coded for each trip. The data comprise a total of 312,798 records-sets from 1986 to 2008, and has been available publicly online.[184] These self-reported data, despite quality control procedures at the SEFSC, can include errors such as misreporting, underreporting of effort, catch, and/or bycatch.[185,186] In both the Atlantic PLL as well as other fisheries, observer data have shown significantly higher bycatch rates than self-reported logbook data, particularly for sea turtles.[187] Despite differences in these rates, similar temporal patterns exist in the two datasets.[188] This logbook dataset is one of the largest and has been used in numerous studies.[189,190,191,192] It contains relevant information such as: date and geographic location of set, number of hooks deployed, sea surface temperature, numbers of individuals caught for finfishes, sharks, and sea turtles, including number of individuals kept, discarded, and their condition at release, among other variables.

b. Pelagic Observer Program data

Data from the Pelagic Observer's Program from 1992-2005 were obtained from the NMFS SEFSC. This dataset includes a comprehensive list of variables such as: location, date, and time of set, catch data, measurements of animals, gear configurations, safety requirements, and much more. For the purposes of this analysis, only set location, date, and catch data were necessary.

c. Geospatial Data

Shapefiles for the Charleston Bump closed area and East Florida Coast closed area were obtained from the NOAA Southeast Regional Office website. The South Atlantic Bight (SAB) shapefile was created for this project. The U.S. contiguous zone was used as the western boundary for both the Charleston Bump and entire SAB study area. This is essentially the end of the state's three nautical mile jurisdiction.

II. Data cleaning

Data were cleaned and organized in Microsoft Excel. Data from each year were located within its own file, and swordfish/tuna, sharks, sea turtles and other bycatch were separated across three sheets within each file. These data were compiled into one large sheet which included all information. I removed sets with non-PLL gear types. I also removed sets that did not include the following: set date, latitude and longitude coordinates, and number of hooks. Potentially erroneous records, such as sets with greater catch than the number of hooks set, or sets with less than 100 hooks, were deleted. Sets that were incorrectly recorded as on land or within closed areas that were in force on the set date were excluded. Sets that were outside of the study area (any sets east of 71.00° West, north of 36.55° North, south of 30.00° North, or within 3 miles of shore on the western border of the area) were removed. I defined the study area as the South Atlantic Bight and southern portion of the Mid Atlantic Bight, as it was considered that fishers displaced from the closed area would proceed to fish close to this area after the closure. While PLL sets are allowed in state waters (through provisions in the Atlantic Tunas Convention Act and the MSA which allow NOAA to apply federal regulations to state waters), it is unlikely that pelagic longlines are set in shallow waters, and those sets were excluded from the study due to the potential that the locations were incorrect.

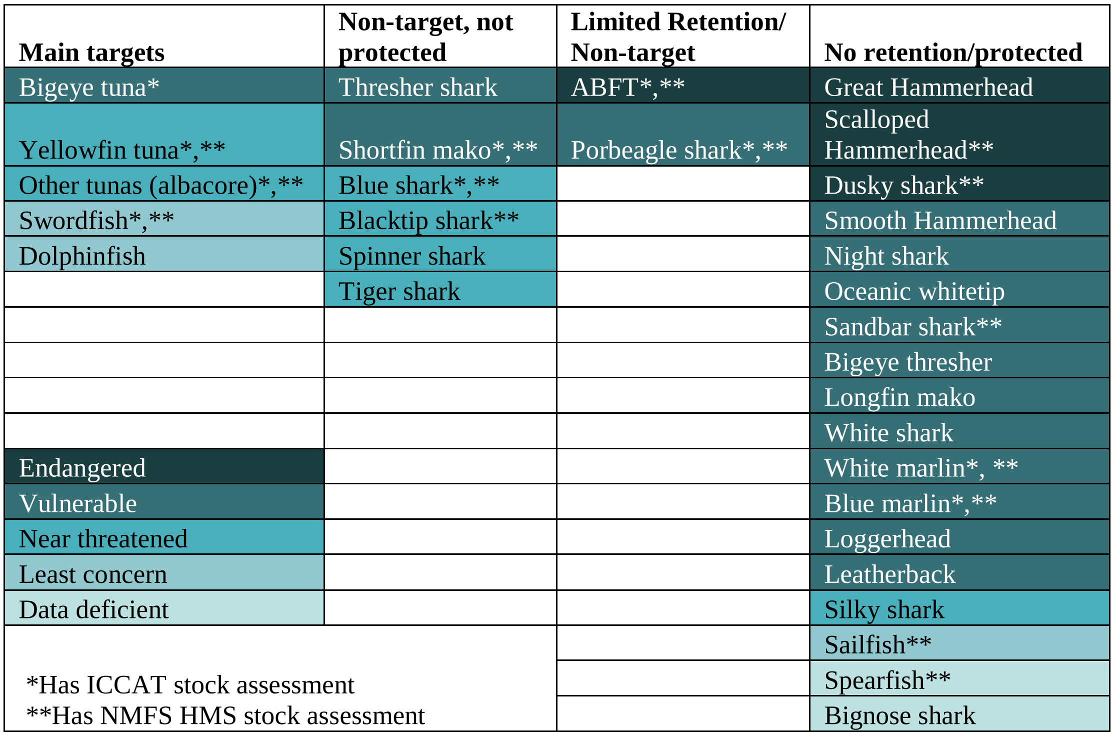
Sets within the Charleston Bump Time-Area Closure during March 1st to April 31st, 2001 and February 1st to April 30th from 2002-2008 were identified using a combination of querying latitude, longitude, and date in Excel and using ArcGIS to identify sets that were still remaining incorrectly in the closed area. Because the Florida East Closure is closed year-round, any sets found within that area after it was closed in 2001 were considered erroneous and were removed. A total of 43,718 records from between September 29th, 1986 to December 27th, 2008 within the study region were available for analysis.

Fishing effort was defined as number of hooks, which varied considerably by set (range = 100- 7500, mean hooks per set from 1986 to 2008 = 525). Although catchability of each hook can vary depending on a number of factors including time deployed, soak time, and location within the set,[193] hooks were assumed to be independent, similar in catchability, and equally accessible to finfish, sharks, and sea turtles. Additionally, sets with missing values could not be distinguished from true zeros; those cells were considered as zero catch but this does lead to potential for error.

Certain species were removed from the dataset for this analysis based on their lower economic importance to the fishery, low catch rates (each represented less than 0.5% of the total catch within the data), or a combination of both. These species included: skipjack tuna, blackfin tuna, 'other tunas', escolar, wahoo, bonito, greater amberjack, and king mackerel. The observer data were cleaned as mentioned above, using the same number of hooks as a minimum (100), and sets outside the study region (as defined above) were deleted.

III. Catch Composition

Thirty-one species *(Table 2)* were identified for analysis. Species were classified by their role in the fishery and IUCN status (*Table 2* and *Figure 7*). Of those 31 species, 61% are listed as either endangered or vulnerable by the IUCN and six percent are data deficient (*Figure 7*).



Main targets	**Non-target, not protected**	**Limited Retention/ Non-target**	**No retention/protected**
Bigeye tuna*	Thresher shark	ABFT*,**	Great Hammerhead
Yellowfin tuna*,**	Shortfin mako*,**	Porbeagle shark*,**	Scalloped Hammerhead**
Other tunas (albacore)*,**	Blue shark*,**		Dusky shark**
Swordfish*,**	Blacktip shark**		Smooth Hammerhead
Dolphinfish	Spinner shark		Night shark
	Tiger shark		Oceanic whitetip
			Sandbar shark**
			Bigeye thresher
			Longfin mako
			White shark
Endangered			White marlin*, **
Vulnerable			Blue marlin*,**
Near threatened			Loggerhead
Least concern			Leatherback
Data deficient			Silky shark
*Has ICCAT stock assessment **Has NMFS HMS stock assessment			Sailfish**
			Spearfish**
			Bignose shark

Table 2. All 31 species used in analysis, coded by IUCN status and their categorization in the fishery as target/non-target species.

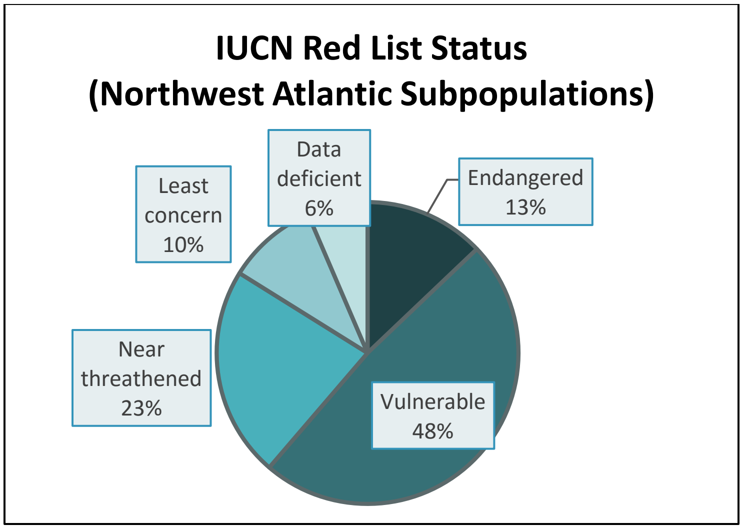


Figure 7. HMS species classified by IUCN Red List Status for the NW Atlantic subpopulations.

Because target catch and bycatch are often difficult to define in a multi-species fishery, I considered any retained species to be “target” and any discarded species to be “bycatch” to determine catch/bycatch composition and rates. Using retained and discarded species helps identify regulatory discards (e.g., undersized swordfish) that have no salable value. Total retained and discarded individuals for each species over the study region from 1986-2008 were summed and divided by the total number of interactions (retained + discarded) to determine the percentage of catch which was retained versus discarded for each species (*Figure 12*).

$$\textit{Retained} + \textit{Discarded} = \text{Total interactions}$$

$$\frac{\textit{Total retentions}}{\textit{Total interactions}} = \text{\% of catch retained} \qquad \frac{\textit{Total discards}}{\textit{Total interactions}} = \text{\% of catch discarded}$$

IV. Temporal Distribution of Catch in the Charleston Bump Area

Longline sets for both logbook and observer data were divided spatially based on latitude and longitude and classified as either inside or outside the closure area. They were also divided into two temporal classes: 1) “Before closure” (September 29th, 1986-February 27th, 2001), and 2) “After closure” (May 1st, 2001-2008). The time frames referred to as “during the closure” or “non-closure months” are those from February 1st- April 30th, 2002-2008. Any sets found to be on the border of the Charleston Bump were considered outside of the closed area, so that they were not falsely considered as illegally-set inside the area after 2001.

Effort by year (*Figure 9*) was graphed for each area (inside and outside the closed area), and average effort by month (*Figure 10*) was calculated by summing # of hooks in each month across years, and dividing by the number of years of data that were used for that specific month.

Catch rates, or catch per unit effort (CPUE) were calculated from Equation 1.

$$\textbf{\textit{Eq. 1}}\qquad \textbf{CPUE} = \frac{\textbf{\textit{\# of individuals caught}}}{\textbf{\textit{Hook}}} \qquad \text{or} \qquad \textbf{CPUE} = \frac{\textbf{\textit{Total \# of individuals}}}{\textbf{\textit{Total \# of hooks}}}$$

This results in a CPUE of less than one. In this case, CPUE represents # of individuals *retained* per unit effort (hook), and bycatch per unit effort (BPUE) represents number of individuals *discarded* per unit effort (hook). Similarly, when summing total interactions over a given timespan (e.g., month), the total number of interactions for a given species can be divided by the total number of hooks for retentions and discards.

These catch and bycatch rates were calculated for four time-space combinations: 1) pre-closure, inside closed area, 2) pre-closure, outside closed area, 3) post-closure, inside closed area (during open months, May-January), and 4) post-closure, outside closed area. Additionally, predicted values for February, March, and April post-closure, inside the closed area (during the closure) were calculated using Equation 2. This was necessary because there is no catch data for during the closure. Figures for each species with all four time-space combinations were created, and show the actual observed values (from the logbook data) as well as predicted values for inside the closure during February, March, and April (*Figures 13-18* and *Appendix B*). One of the principle assumptions of this analysis is that the ratio of CPUE or BPUE remained constant inside vs. outside of the closure across time.

$$\textbf{\textit{Eq. 2}}\qquad \frac{\textbf{\textit{CPUE post-closure outside}}}{\textbf{\textit{CPUE pre-closure outside}}} \quad \textbf{\textit{x}} \quad \textbf{\textit{CPUE pre-closure inside}} \;\; \mathbf{= Estimated\ CPUE\ post\text{-}closure\ inside}$$

Retentions of any species that became prohibited after 2001 were classified as discards to account for their updated protection statuses. This is not shown in the dark blue “retained” and maroon “discarded” values in the species subplots (*Figures 13-18*), because those are made up of actual observed data, which include retentions from any species that were prohibited after 2001. This correction is, however, accounted for in the predicted values for February, March, and April. When trying to estimate future catch rates for prohibited species, the predicted retention values for February, March, and April will be zero, since it is illegal to retain them. The originally-predicted retentions for prohibited species are still assumed to be caught (because we cannot eliminate these fisheries interactions from occurring) but they will subsequently be discarded. For this reason, originally predicted retentions for protected species were added to discards to obtain more accurate predictions for discards which align with current regulations.

In order to put these results into more comparable terms, I converted the retention (CPUE) and discard (BPUE) rates into the number of individuals retained and discarded. This was done by multiplying the rate of catch by the predicted number of hooks set in each month (Equation 3). The number of hooks predicted for February, March, and April (during the closure) was calculated using the same equation described in Equation 2, except instead of using CPUE, I used the average number of hooks for that month (see *Appendix C* for # of hooks for all four time-space combinations). The average number of hooks for the other nine months was obtained by calculating the sum of each month’s hooks, and divided by the number of years for which that month had available data. Numbers of individuals retained and discarded were then summed across 12 three-month combinations (Table 4).

Eq 3. ***CPUE x Effort (# hooks)*** **= # retained individuals**

BPUE x Effort (# hooks) **= # discarded individuals**

Observer data was used to calculate a more accurate catch rate for sea turtles that counts for underreporting. The BPUE was multiplied by the predicted number of hooks used from the logbook data, since the observer data is only a small sample of effort. However, due to this low sample size, sea turtle bycatch rates using the observer data were extremely high during January, during which there were only 13 observed sets, yet five leatherbacks and three loggerhead interactions. I calculated an average non-reporting rate for months where the number of sets was at least 3% of the total number of sets from all months. I then multiplied this rate by the reported catch from the logbook record for any months when months to get an "adjusted-observer" catch of turtles for January.

V. Determining a Better Time for the Closure: Making Species' Tradeoffs

Species and individuals were grouped into three categories based on whether they were: a) retained, b) prohibited species which are required to be discarded, or c) other species which were discarded but were not prohibited/protected species. They were classified in order to look at the expected number of interactions for each type of group if the closure were to occur at various times of the year. Number of interactions of each category were compared and contrasted to find three-month periods of low retention and high discards would be economically and ecologically beneficial to the fishery.

RESULTS

I. Catch Composition

Pelagic longline sets included in this study extend out to approximately 720 km (390 nm) from the coast. The area outside the closure boundaries covered over 247,840km^2 (154,000 square miles) and the area within the closure covered over 124,000km^2 (over 7,700 square miles). Of the 43,717 longline sets in the study region, 19,835 occurred within the closure area. Almost 23 million hooks (22,958,278) were set over the study region during this time, with a little less than half (9,998,345 hooks) set inside the closure area (*Figure 8*).

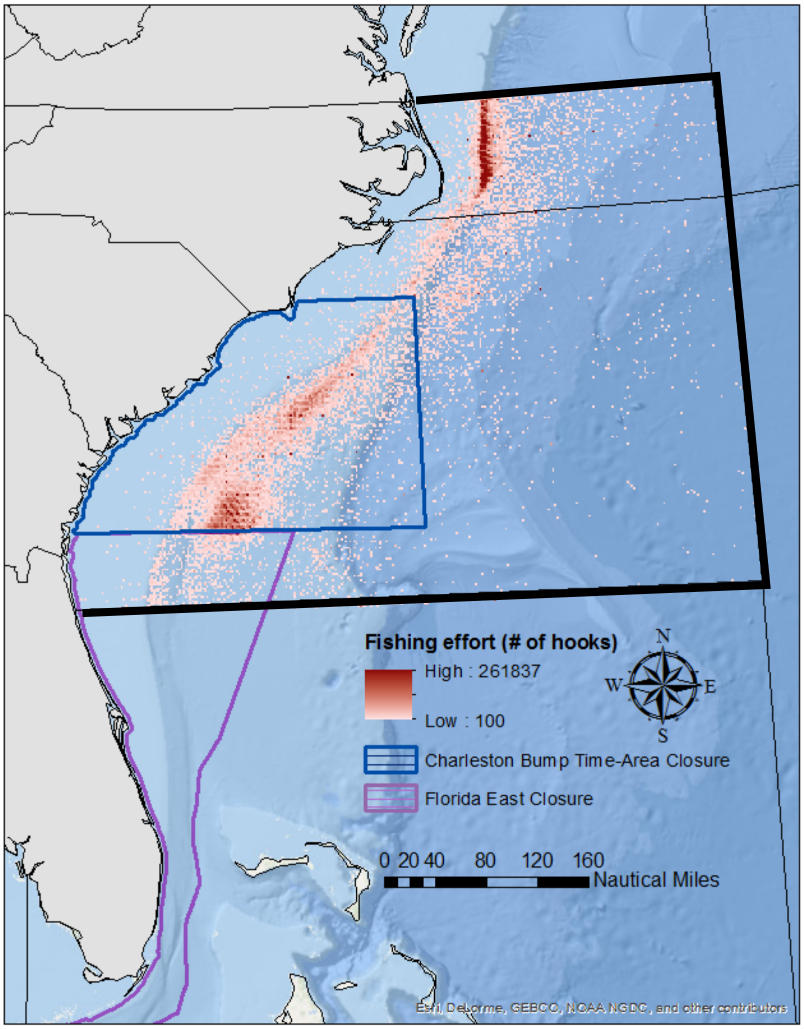


Figure 8. Distribution of pelagic longline fishing effort, study region, 1986-2008. Dark black line denotes entire study region.

Effort by year over the entire study region (*Figure 9*) shows a peak in 1996, followed by a steep decline until 1998, when effort briefly rebounds until the year 2000. After a small decline from 2000-2002, effort generally increases until 2007. There is a decline in effort inside the closure area, which appears unrelated to the closure in 2001 as this decline began between 1999 and 2000, before the closure was implemented. Effort throughout the year (

Figure 10) seems fairly constant, with a small decrease in January both inside and outside of the closure area. Lastly, the monthly effort in 2001-2008 (post-closure) decreased overall from monthly effort in 1986-2001 (pre-closure).

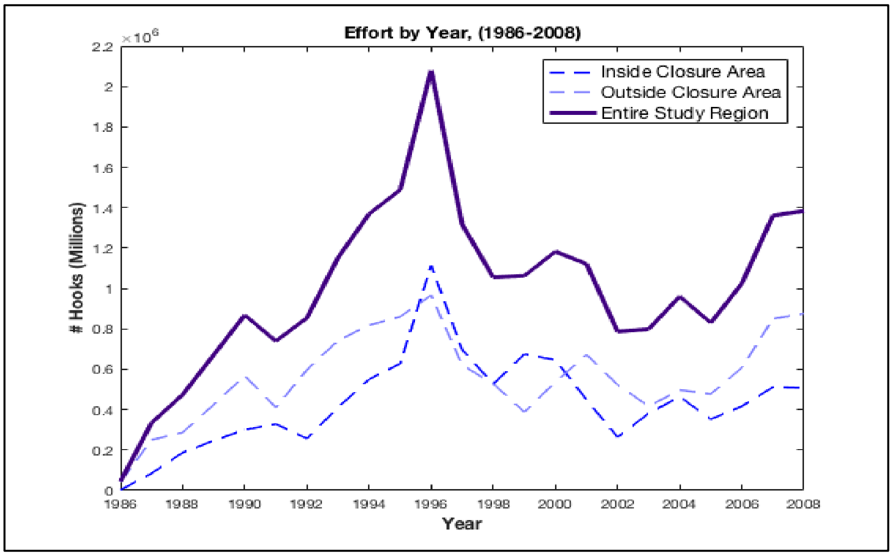


Figure 9. Effort by Year, study region, 1986-2008.

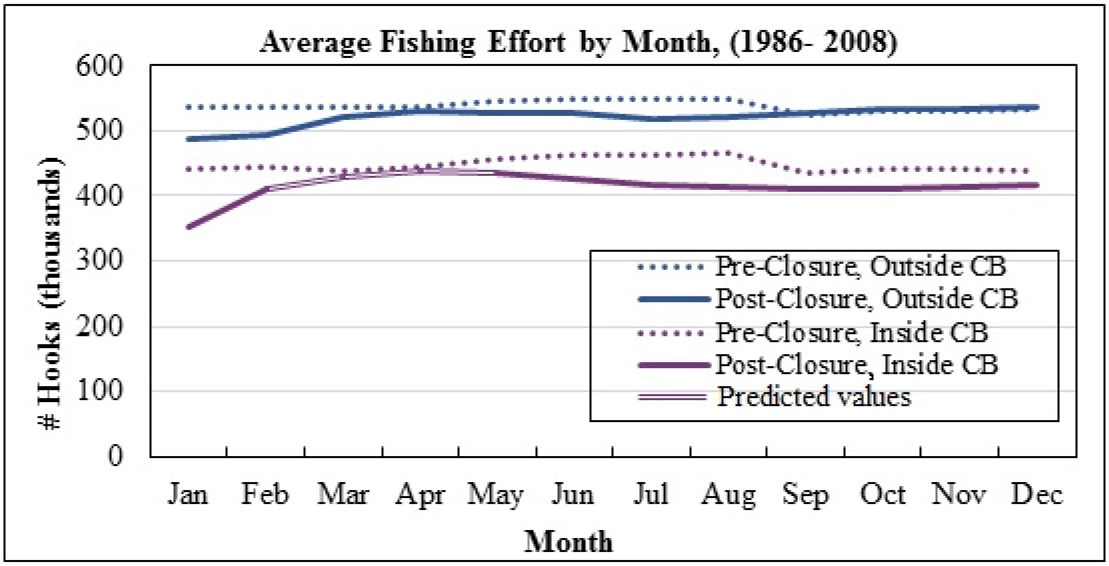


Figure 10. Average fishing effort by month.

Figure 11 shows a breakdown of all of the interactions by species within the study region from this time period. Notice that certain shark species which are now protected have made up ~11% of the catch. According to this data, sea turtles make up a very small percentage (0.02%) of the total catch, and billfish make up 0.92%.

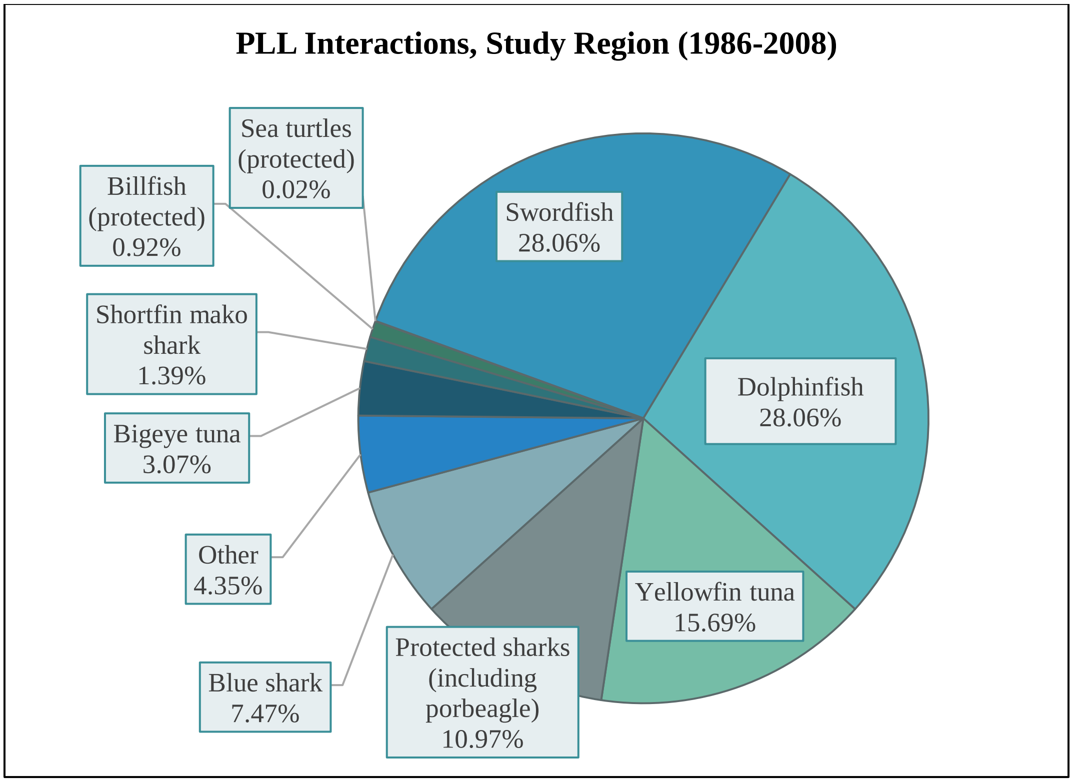


Figure 11. Pelagic longline interactions with specific species in the study region from 1986-2008.

Figure 12 includes only species which each made up greater than 0.5% of the total catch. Of these 15 species, six are now protected under U.S. longline regulations, therefore they are now illegal to retain. Over 70% of the catch throughout the study region over all 23 years is made up of three target species: swordfish, dolphinfish, and yellowfin tuna. Blue sharks follow in proportion of catch. The other primary target species, bigeye tuna, represents less than 3.1% of the total catch, just less than the catch rate of the currently-protected sandbar shark (*Carcharhinus plumbeus*).

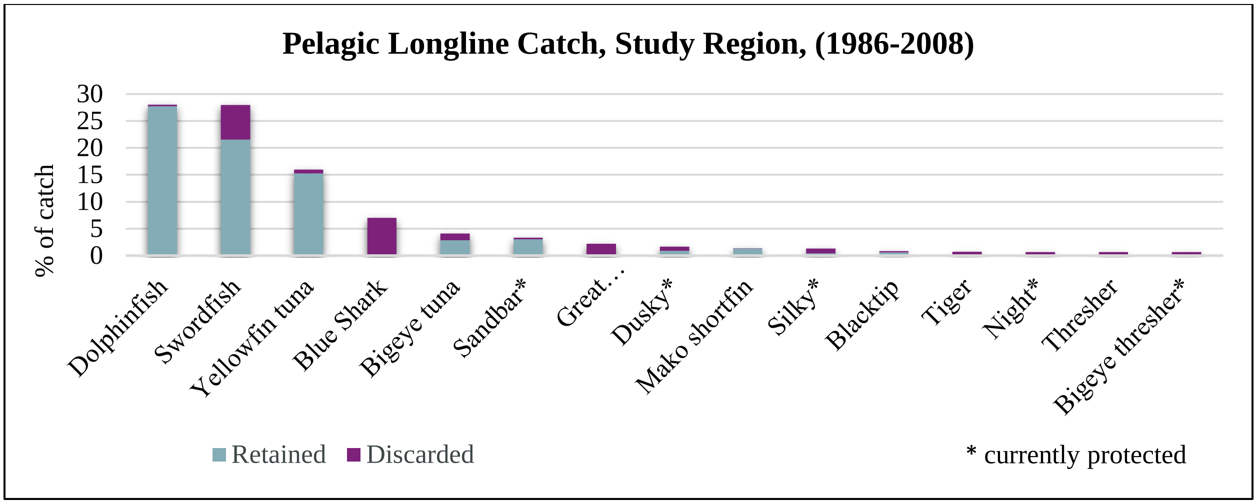


Figure 12. Catch by species, greater than 0.5% of total catch within the study region, 1986-2008

Twenty-five percent of the total catch across taxa within this study was discarded. Species with the highest proportions of discards over the study period (1986-2008) were blue sharks (~99% discarded), and sea turtles (100% discarded), and billfishes (~96-99% discarded). Table 3 illustrates species which have high discard rates and their corresponding discard mortality rates from the catch data. Note that the logbook data only account for individuals that were dead at the time of release; we cannot conclude anything about survival rates after release (post-release mortality).

Species	% Discarded	# Individuals discarded alive	# Individuals discarded dead	# Individuals kept	% of discards dead at release
Blue shark	99%	47504	48134	1315	50%
Thresher	84%	922	6107	1357	87%
Bluefin tuna	83%	2059	1258	695	38%
Hammerhead*	81%	10303	23456	5787	70%
Tiger shark	81%	6394	1160	1776	15%
Night shark	78%	4139	2655	1946	39%
Bigeye thresher	70%	4482	1321	2464	23%
Silky	68%	7176	4450	5359	38%
Oceanic whitetip	68%	650	98	365	13%
Sailfish	99%	1882	1086	42	37%
Spearfish	97%	187	131	9	41%
Blue marlin	97%	2800	1771	157	38%
White marlin	96%	2421	1327	128	35%

Table 3. Discard and discard mortality rates (at time of release) for selected species over the entire study region from 1986-2008. *Hammerhead includes great, scalloped, and smooth.

Leatherback and loggerhead sea turtles are the most commonly caught turtles in this region. 94% of leatherbacks, 88% of loggerheads, and 100% of green (*Chelonia mydas*), Kemp's ridley (*Lepidochelys kempii*), and hawksbill (*Eretmochelys imbricate*) sea turtles were reported injured at the time of released. Due to the infrequence of interactions with green, Kemp's ridley and hawksbill sea turtles, they were not included in further analyses. Based on the self-reported logbook data, of the 235 unidentified sea turtles 185 (68%) were killed, as well as and two loggerheads.

II. Temporal Distribution of Catch

Figures 13-18 illustrate catch per unit effort (i.e. retained) and bycatch per unit effort (i.e. discarded) for selected species across each month. Dark blue lines represent CPUE for retentions, maroon represents BPUE for discards, light blue represents predicted CPUE for retentions, and light purple represents predicted BPUE for discards. Upper left subplots depict these rates before the closure inside the closed area, upper right subplots show before the closure outside the closed area, lower left subplots display rates for after the closure inside the closed area, and subplots on the lower right are rates for after the closure outside the closed area.

The CPUE and BPUE values help to deduce the spatial and temporal distribution of certain species, as we assume that catch data provides a sample of the distribution of animals in the water at a certain place during a certain time. The catch and bycatch rates in *Figures 13-18*, as well as those in *Appendix B*, illustrate that while some species show fluctuating year-round distributions (e.g., dusky shark (*Carcharhinus obscurus*), *Figure 19,*) the presence of other species (e.g., mahi-mahi, *Figure 15*) is restricted to narrow temporal windows of just a couple of months when a species appears quickly and in high densities in the area. Similarly, plots for sailfish and marlins depict their gradual migrations into the Charleston Bump area by showing more normal distributions centered around the summer months. For swordfish (*Figure 13*), retention rates are higher inside the Charleston Bump closure area (~0.01- 0.05) than outside (< 0.02). Highest catches per unit effort are during the fall months, while the lowest are mid-summer. Discards remain well-below retentions, and we see that discard rates are highest in the fall and winter. Predicted rates for February, March, and April are lower than during the fall, and have a slight secondary peak around April. The swordfish discards in the top left subplot of Figure 13 do not correspond with the NMFS finding that over 70% of the swordfish bycatch takes place during February through April, which was the initial reasoning to close the area.

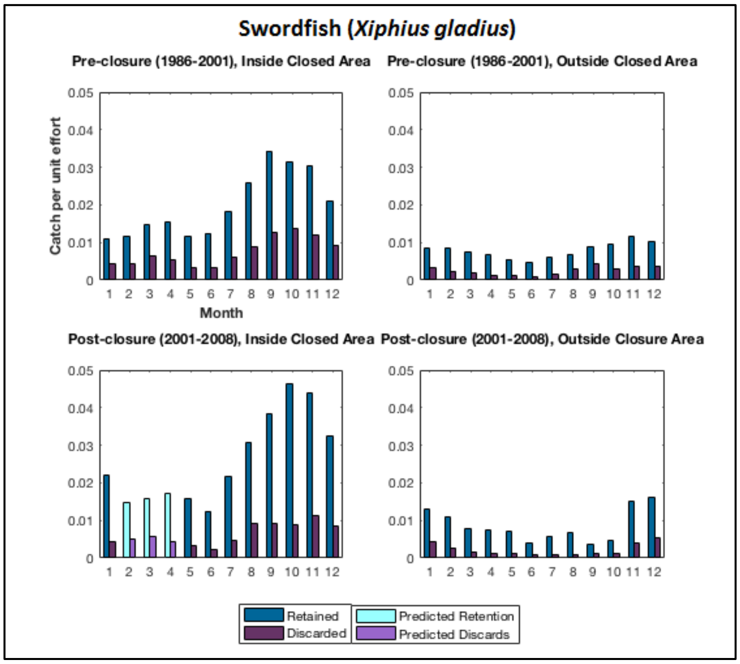


Figure 13. CPUE and BPUE for *Xiphius gladius* for the four time-area combinations.
Average % error (SwoRetained) = 24%, range: 3-67%
Average % error (SwoDiscarded) = 38%, range: 8-67%

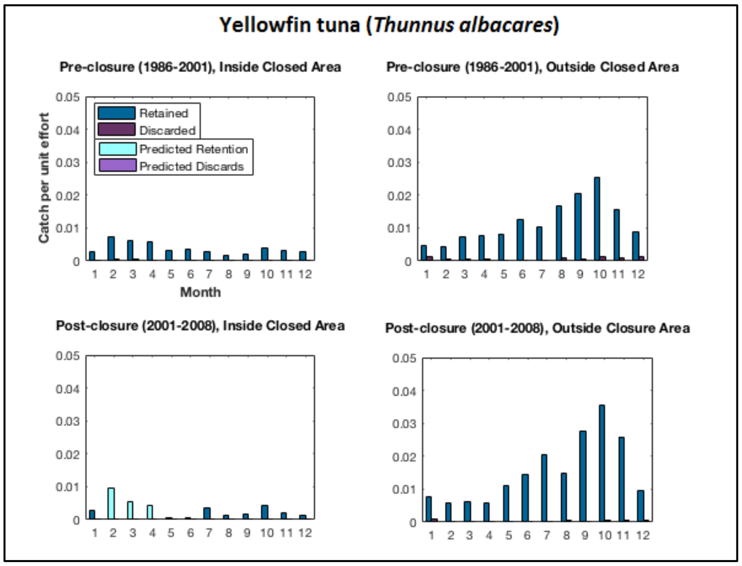


Figure 14. CPUE and BPUE for *Thunnus albacares* for the four time-area combinations.

These results show that catch of yellowfin tuna, another target species, would increase during February-March-April than during other parts of the year if the closed area was opened during those months (*Figure 14*). Mahi-mahi (*Figure 15*) have high retention rates during the summer months, with dramatic declines in catch from July to April. Catch rates for mahi-mahi are also higher in the closure area. Blue sharks (*Figure 16*) are predominantly discarded, with catch rates higher outside the closed area, and higher before the closure. It appears that BPUE in the closure area is distributed fairly evenly throughout the year, with a predicted peak in February. ABFT (*Figure 17*) had the highest CPUEs and BPUEs after the closure, outside the closure area, particularly from December – April. Inside the closed area, retention and discard rates are predicted to be highest in April, but less than one fish per 10,000 hooks. The ABFT season is currently only open during the first half of the year, which explains the zero catch after June for the post-closure, inside closure area (bottom left subplot). Note: the figures for protected species do not account for newer regulations prohibiting retention of those species. For these species, the predicted retention values for February, March, and April will equal zero, and those values were be added to the discard values. Oceanic whitetip (*Figure 18*) and dusky sharks (*Figure 19*), demonstrate this calculation in February, March, and April in the bottom left subplots, where predicted retentions are nonexistent (zero), and predicted discards (BPUE) are higher.

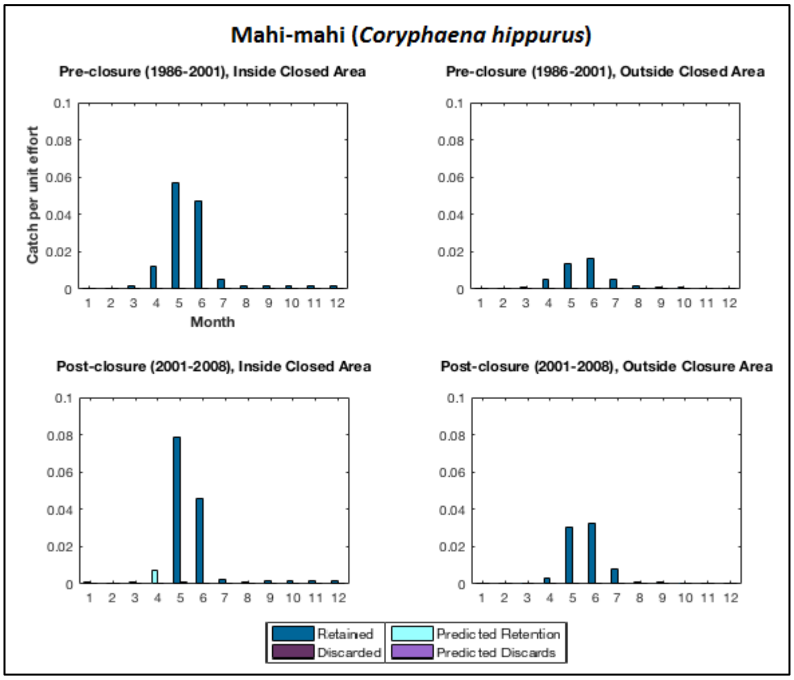


Figure 15. CPUE and BPUE for *Coryphaena hippurus* for the four time-area combinations.

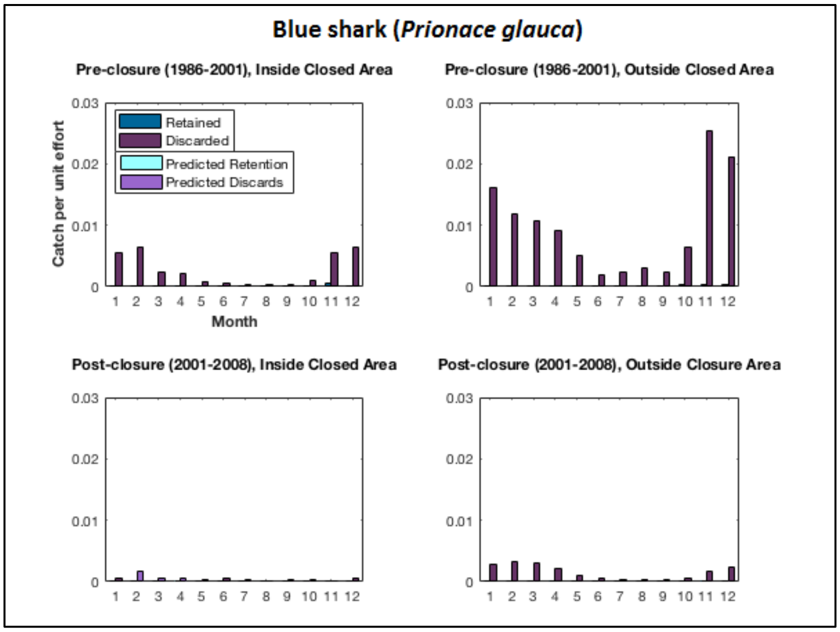


Figure 16. CPUE and BPUE for *Prionace glauca* for the four time-area combinations.

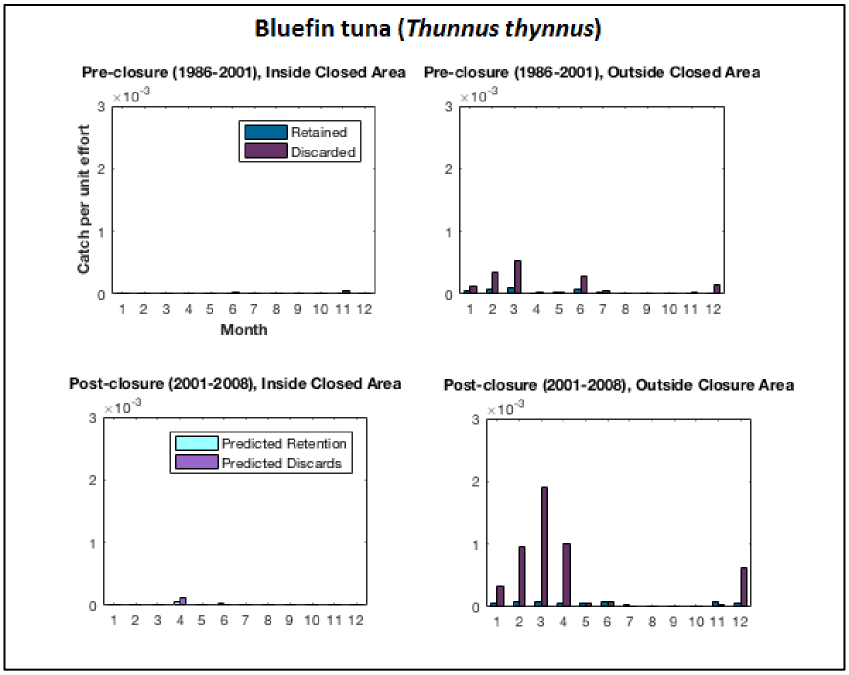


Figure 17. CPUE and BPUE for *Thunnus thynnus* for the four time-area combinations.

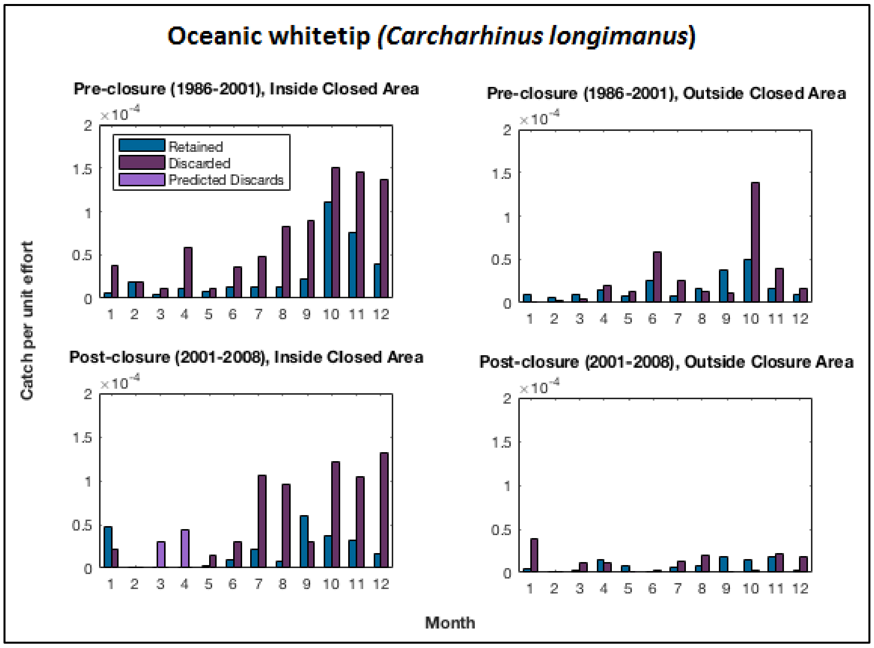


Figure 18. CPUE and BPUE for *Carcharhinus longimanus* for the four time-area combinations.

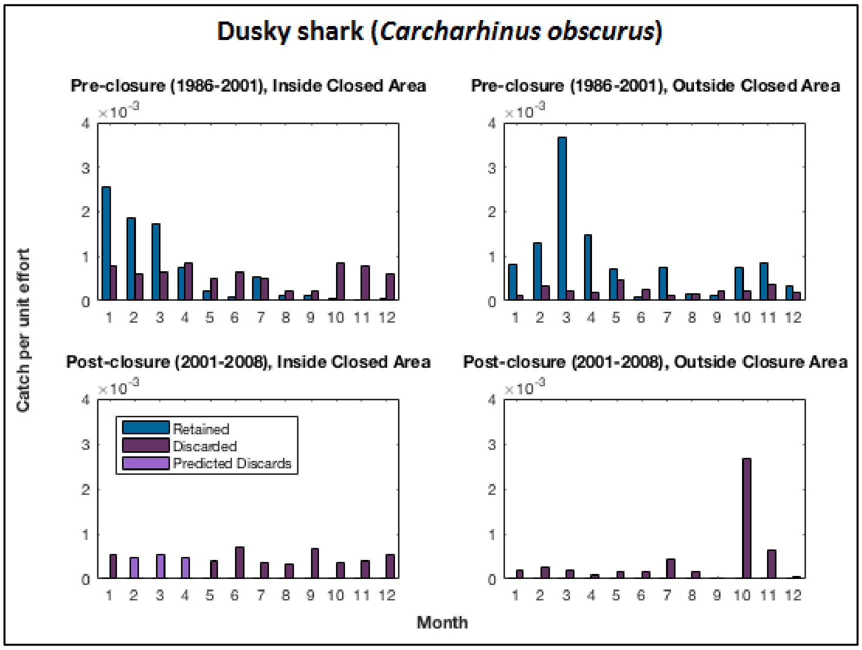


Figure 19. CPUE and BPUE for *Carcharhinus obscurus* for the four time-area combinations.

The distributional patterns across species will lead to unique combinations of overlap for the different time periods. In *Table 4*, the left column shows 12 consecutive three-month possibilities for the Charleston Bump time-area closure. The “Total retentions” column includes retained catch for swordfish, yellowfin, albacore, bigeye, and mahi-mahi (the main target species), plus any retentions of ABFT, porbeagle, blue shark, thresher shark, blacktip shark, spinner shark, tiger shark, and shortfin mako. Porbeagle sharks and ABFT were not considered "protected", because they have small quotas in place in the fishery and therefore a certain number (with size restrictions) are allowed to be retained. "Non-protected discards" are discarded individuals for all those same species. "Protected sharks" include: Great hammerhead, smooth hammerhead, scalloped hammerhead, bignose, dusky, night, oceanic whitetip, silky, bigeye thresher, white, sandbar, longfin mako, and white sharks. "Protected billfishes" include: white marlin, blue marlin, sailfish, and spearfish, while "protected sea turtles" include leatherbacks and loggerheads [Note: all species of sea turtle are protected in the U.S.].

III. Identifying Tradeoffs

Closure period (months)			**PROTECTED SPECIES INTERACTIONS**			
	Total retentions	**Non-protected discards**	**Protected sharks**	**Protected billfishes**	**Protected sea turtles**	**# Hooks set**
Jan, Feb, Mar	29941	7979	2661	304	18	1,189,326
<u>Feb, Mar, Apr</u>	**33137**	**8430**	**1749**	**333**	**11**	1,276,553
Mar, Apr, May	63779	7718	1270	362	11	1,301,358
Apr, May, Jun	79447	6325	1865	456	9	1,299,078
May, Jun, Jul	78828	6305	2834	593	8	1,276,839
Jun, Jul, Aug	51243	8277	3373	832	9	1,254,785
Jul, Aug, Sep	43091	10874	2962	758	9	1,239,969
Aug, Sep, Oct	52750	12757	2071	598	12	1,234,346
Sep, Oct, Nov	58631	13701	1806	360	8	1,234,237
Oct, Nov, Dec	56406	13711	1855	355	15	1,240,186
Nov, Dec, Jan	44171	11397	2687	348	22	1,180,820
Dec, Jan, Feb	34828	9193	3938	317	23	1,178,179

Table 4. Predicted # of individuals retained and discarded for possible consecutive three-month closure timings. Moving across each row, number of individuals represents the number of retentions, discards of non-protected species, and interactions with protected species (which by law must all be discarded). 'Non-protected discards' are a combination of regulatory discards and non-salable species. Optimizing the closure timing would mean finding a row in which we have light green and dark shades of orange and red.

As aforementioned, the number of individuals were estimated by multiplying CPUE or BPUE by the predicted average # of hooks for each month. Current closure timing (February-April) is underlined & bolded. Moving across that row, the number of individuals in each of these columns represents the predicted number of interactions within the Charleston Bump area if the closure was removed, and the area were opened up to pelagic longlining. All other rows represented the other possible eleven 3-month time-area closure periods and the interactions which would be avoided if the closure were implemented during those three-month combinations. These three-month closure scenarios are broken down by month for discards and retentions in *Appendix D* and *Appendix E.*

The highest effort is during March, April, and May, while the lowest is during December, January, and February. The two periods with the highest retentions occur during the April- May-June and the May-June-July combinations. The lowest occurred during the January-February-March, and February-March- April combinations. The highest discards of non-protected species occur during the September-October-November and October-November-December combinations. The periods with the lowest discards of these species are April-May-June and May-June-July. Protected shark interactions were highest during June-July-August and December-January-February, however January-February-March, May-June-July, July-August-September, and November-December-January all have protected shark discard numbers over 2,600 individuals. Billfish interactions were highest during the summer months of June-July-August and July-August-September. Sea turtle interactions were highest during the winter, November-December-January and December-January-February.

Observer data shows that over the same area but using a sample size of n= 641 sets, sea turtle interactions increase. After adjusting these discard rates due to the small sample size, sea turtle interactions (discards) are as shown in Table 5. These values are drastically greater than those for the logbook data. While the datasets show extreme differences in the magnitude of sea turtle interactions, they are not as temporally different from one another. The largest differences in temporal variation between the two datasets exist in the summer months, where sea turtle interactions are around eight to nine during the three-month time periods in the self-reported data and 80-107 in the observer data. Other species were not investigated using observer data, though this will be important in future research.

Month	
	Sea turtle interactions
Jan, Feb, Mar	164
Feb, Mar, Apr	58
Mar, Apr, May	52
Apr, May, Jun	52
May, Jun, Jul	80
Jun, Jul, Aug	107
Jul, Aug, Sep	107
Aug, Sep, Oct	80
Sep, Oct, Nov	0
Oct, Nov, Dec	59
Nov, Dec, Jan	166
Dec, Jan, Feb	223

Table 5. Predicted # of sea turtle interactions for possible consecutive three-month closure timings, adjusted by incorporating observer data.

DISCUSSION

I. Tradeoffs

The results of this analysis indicate that the current timing of the Charleston Bump time-area closure (February-March-April) does not optimize conservation benefits of this marine protected area for target and non-target highly migratory species. Current regulations that require the discarding of certain species do not ensure their survival. Reducing fisheries interactions with protected species and non-target fishes, while maximizing retention of responsibly-managed target species, is an optimal conservation and management strategy. These results show that any three-month combination will require management and conservation tradeoffs among species groups.

Based on the predicted number of interactions with target and non-target species throughout the year (*Table 4*), the current timing of the Charleston Bump time-area closure has the second lowest impact on the productivity of the fishery out of all 12 three-month combinations; during this time expected retentions would be 33,137 individuals of target species. While the closure is also potentially avoiding the discards of 8,430 non-protected specimens during February-March-April, selecting a different three-month combination for the closure (such as September-October-November with 13,701 discards or October-November-December with 13,711 discards) could reduce discards by up to 38.5%. However, changing the closure to one of these times would require foregoing either 58,631 or 56,406 retentions of target species, which would affect the production of the fishery.

Another possibility for closure timing would be a three-month combination which decreases protected shark interactions as much as possible. December-January-February and June-July-August have the highest protected shark interactions, at 3,939 and 3,373, therefore a closure during either of these periods could provide potential conservation benefits on the populations of these ecologically important species. Retention of target species is high during June-July-August, at 51,243 individuals, but in December-January-February target retention (34,828 individuals) is only slightly higher than the 33,137 target individuals that are forgone during the current closure period. If billfishes become the conservation priority, summer months are most beneficial for the closure, with a high of 832 interactions in June-July-August and 758 interactions during July-August-September, as compared to the 333 billfish interactions during the current closure period. Lastly, a closure during November-December-January, December-January-February, or January-February-March would minimize fishery interactions with loggerhead and leatherback sea turtles

(*Table 5*). Another consideration, though likely not feasible due to economic and social restraints, may be thinking about three, non-consecutive one-month closures. This would require further examination.

A more balanced approach would be one in which the timing of the closure does not preclude the retention of large numbers of target species and which, in turn, reduces a higher number of longline interactions with sharks and sea turtles. Only one three-month combination satisfies these requisites, and as such it is the closure timing which I would recommend based on these results: January-February-March.

The effect of discard mortality on regulatory discards of the target species should also be taken into account, so that populations of economically valuable species do not experience unaccounted impacts. Looking at Table 3, it is important to compare discard rates and discard mortality rates with the CPUE (or BPUE) of each species. For example, billfish and sea turtles have very low catch rates (billfish < 0.001 per hook = 1/1000 hooks; sea turtles < 0.00002 per hook = 2/100,000 hooks), so despite their high discard rates and discard mortality rates, their populations may not be as affected as a species with a higher CPUE estimates, higher discard rates, and lower discard mortality rates, such as blue sharks. There is evidence that the decline of large predatory shark species along the U.S. East Coast can lead to ecosystem-level impacts across trophic-levels,[194] however, the existence and extent of this has been called into question.[195]

These tradeoff scenarios generate multiple questions on how existing management schemes should weigh the allocation of conservation benefits across species: *Is one sailfish worth one dusky shark*? *How many of a certain shark species are we, or managers, willing to give up as discards in order to protect a smaller number of sea turtles*? The number of potential combinations is extensive. Given that the categorizations in Table 4 include several species, answering these questions on tradeoffs will require determining the ecosystem-level impacts of protecting one species over another, which requires further research. Managers must also consider how to weight the prioritization of species of high social or economic value versus those of high ecological value.

Considering these tradeoffs, current conservation measures for certain species which are less threatened should not necessarily be diminished for the health of another species. While some species may be classified as “least concern”, they are listed as such due to the strict management measures in place to protect that species. Certain species in this fishery have been identified as having greater threat levels than others according to their IUCN statuses. While it can be argued that management decisions should be prioritized with more severely threatened species in mind, we should also not compromise current conservation measures for the less-threatened species according to IUCN status, particularly because the status of certain species, leatherbacks for example, are as such due to the current management measures in place. They are at less risk of becoming endangered in the future because IUCN has taken into account the current conservation measures. The principle objective of the time-area closure, in my opinion, should be to have the biggest conservation impact as possible in the most efficient manner.

II. The Transfer (or Spillover) Effect

Global swordfish landings have increased steadily since the 1950s from approximately 30,000 metric tons to roughly 115,000 metric tons in 2012,[196] The U.S. consumes approximately 25% of these landings. [197,198] Since 1997, the proportion of imported swordfish to all swordfish consumed has increased, with U.S. importing on average 75% of the swordfish consumed. Importing such a large proportion of swordfish to meet the high U.S. demand is partially a result of a decline in domestic swordfish fishing effort,[199] considering that in 2016 only 20-30% of the total allowable catch (TAC) for swordfish in the U.S. Atlantic PLL fishery was utilized.[200]

U.S. fishermen must comply with multiple laws and types of management to ensure their fishing practices sustain diverse and productive marine ecosystems.[201] This guides the development of fisheries which are responsibly managed when compared to non-domestic fisheries. Swordfish imported to the U.S. come from countries that generally have a higher rates of fisheries bycatch, as other countries often place a lower priority on conservation.[202,203] Decreased participation in the U.S. PLL fishery transfers environmental impacts elsewhere, because it induces greater effort in foreign fleets to meet demand. Many have hypothesized that filling the consumption gap with imported swordfish increases the overall amount of bycatch caught on a global scale.[204] The unilateral conservation of these highly migratory species may reduce benefits from U.S. regulations if bycatch reduction in the U.S. is offset by an increase in bycatch in foreign fishing fleets.[205] Research has shown that per pound of swordfish, fewer longline interactions with leatherback sea turtles occurred within the U.S. EEZ as compared to outside of the U.S. EEZ.[206] This is referred to as the “transfer” or “spillover” effect. The resulting increases in foreign fleet fishing activity not only result in lower profits to U.S. fishers, but may also have unintended consequences for marine ecosystems and sensitive species on a global scale.[207,208] For this reason, increasing our domestic production of swordfish to the extent possible may actually be the most ecologically beneficial option, as we must consider global-scale impacts. While any proposal to re-open the Charleston Bump time-area closure may be faced with criticism, U.S. fishermen could further utilize our TAC and increase U.S. landings of swordfish, reducing our dependence on fisheries with higher bycatch rates. To what extent this management scenario would fulfill U.S. consumption and decrease the need for swordfish imports would need to be determined.

III. Recommendation

The consideration of the transfer effects solidifies my recommendation for adjusting the timing of the Charleston Bump time-area closure to January, February, and March. This timing would allow for maximum retention of target species, while attempting to lessen the consumption gap and not exacerbate the ecological impacts of bycatch in foreign longline fleets. This timing would also reduce protected shark and sea turtle interactions, while discards of non-protected species and billfishes would not be substantially different from those with current timing of the closure. The main limitation of this choice is the uncertainty in the outcome of not prioritizing protection for any species, but rather thinly spreading mediocre conservation benefits across many species. While it has its own tradeoffs, in comparison to the current timing, January-February-March nears the optimization of conservation benefits for both the closure as well as on a global scale.

IV. Limitations & Further Research

There are multiple ways to improve this analysis and many avenues for further research on this topic. Beginning with the logbook dataset itself, while it is comprehensive and has a large sample size, misreporting is a problem. Non-reporting rates for species other than sea turtles should be calculated, and catch rates should be adjusted. Another limitation of this dataset is the inability to distinguish true zeros from missing values, because zeros are not recorded.[209] Other studies have addressed this problem by modeling the positive catches or using specific binomial models which assume that if a positive number of interactions is recorded for a set, then it is approximately correct.[210] Of course, these methods have their own limitations. Lastly, these data cannot account for post-release mortality rates, which could have dramatic effects on populations of teleosts and elasmobranchs. Numbers of individuals recorded as “discarded alive” or “injured” may in fact be higher than reported due to varying if animals proceeded to die after release.

Further datasets could be utilized to gain a more accurate understanding of current catch rates. The first priority should be supplementing the current 1986-2008 dataset with the 2008-present logbook data. This would help account not only for any environmental changes which may have affected distribution of species, but would also allow for analyses to be conducted using > 12 years of catch data after the use of circle hooks was mandated (2004). Additionally, few exploratory sets have occurred inside the Charleston Bump, and more sets during February, March, and April could be beneficial to determine catch rates and composition during those months. Additionally, the observer data could be used to identify whether underreporting is occurring for other species in addition to sea turtles. Lastly, determining any spatiotemporal patterns of longline interactions with other bycatch species such as marine mammals and sea birds would guide further recommendations.

Changes in the environment as well as gear configuration should be corrected for. Multivariate analyses could be done using sea surface temperatures, moon phase, use of light sticks, depth of set, and bait type. This is particularly important because gear type and deployment depth have been shown to be essential factors in explaining variation of swordfish catch rates,[211] and hooking mortality has been shown to double for certain bycatch species when sets targeted tuna rather than swordfish.[212] Indices of population abundance should also be accounted for in this project by standardizing the time-series data for area, season, and year, amongst other variables, as has been done in other studies.[213] A more detailed understanding of how CPUE is changing for each species over time could have a significant impact on catch rates.

More areas for future research also include identifying the social and economic barriers to temporal change of the closure such as: other fisheries occurring during certain times of the year (fishers’ lifestyles and personal needs), weather patterns and safety at sea, and fluctuations in the market price of economically valuable species, which could influence fishing effort and numbers of individuals retained and discarded. Moreover, the opening of nearshore fishing grounds may increase conflict of recreational and commercial fishermen. The results of this analysis are also somewhat dependent on predictions of the behavior of fishermen in the PLL fleet, which could be assessed by gaining input from the fishers themselves. If the predicted average effort rates do not reflect actual future effort, then the number of retained and discarded species will be inaccurate.

V. General Implications for Management

While more research should be conducted based on updated logbook and observer data, socioeconomic considerations highlighted above, and global bycatch rates for PLL fisheries, the timing of the Charleston Bump should be reevaluated and if necessary, modified to January-February-March to address modern conservation concerns rather than conservation concerns of 20-30 years ago. While it is unlikely the closure could be entirely eliminated due to political restraints, a closure during January-February-March would be a step forward in optimizing conservation benefits of the Charleston Bump time-area closure. Management measures exist for many of the species addressed in this study, however a proportion remain unprotected by current management structures, and continued research into shifting distributions of highly migratory species based on most recent data is essential. Continuing to implement regulations which require discards of certain species does not seem to be the most effective form of management, particularly for species with high post-release mortality rates. It will be crucial to manage fisheries in a way that attempts to prevent fisheries and bycatch interactions, such as shifting towards dynamic ocean management tools (e.g., move on rules and fine scale closures based on the spatiotemporal distributions of species we want to avoid). Maintaining a balance between global-scale impacts and protection of species which migrate throughout our EEZ will be a continued challenge, one which will require domestic and international cooperation to ensure sustainable management of the world’s fisheries, and optimizing conservation benefits of time-area closures will depend on the scale at which decide to manage.

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Each cast, a quest for nature ***undefiled.***

CNC

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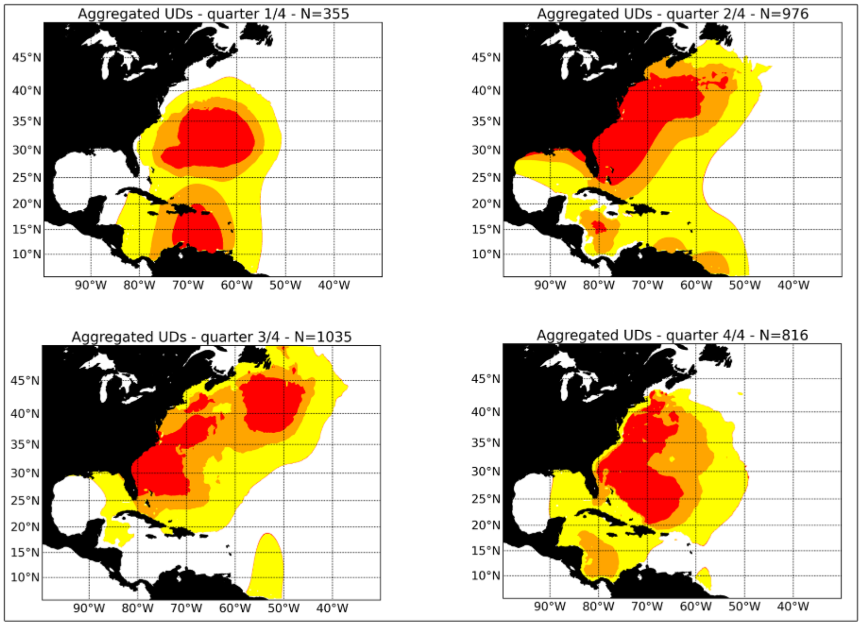
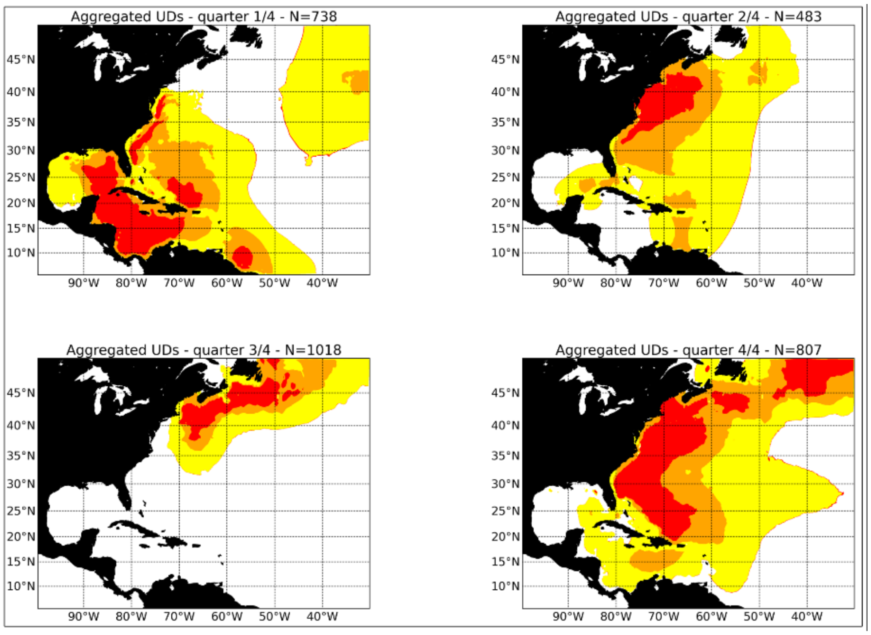
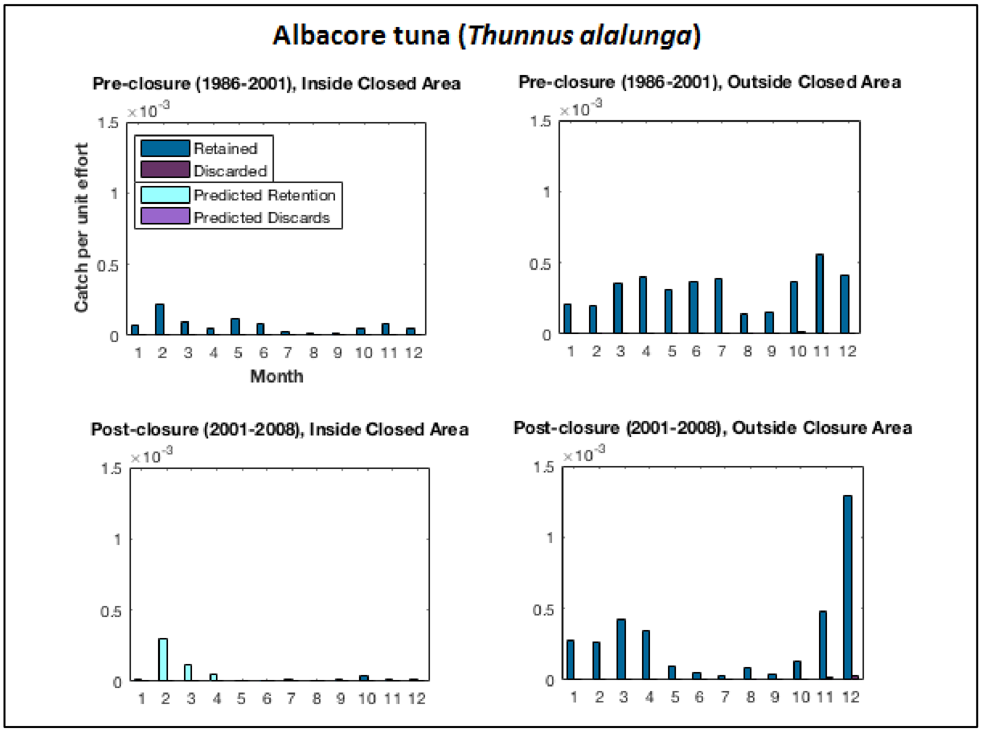
APPENDICES

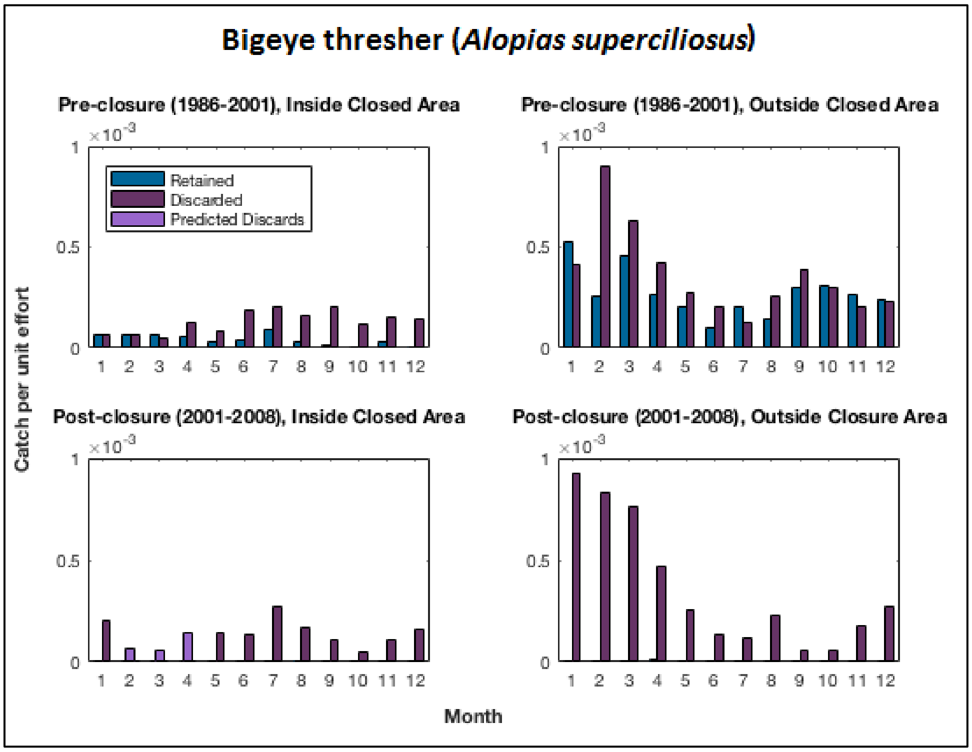
Appendix A. Neilson et al. 2014. The seasonal distribution of immature swordfish (<179 cm) (top) and mature swordfish (=>179 cm) (bottom) based on information from pop-up archival satellite results obtained by the National Marine Fisheries Service (NMFS), South Carolina Department of Natural Resources (DNR) and Fisheries and Oceans Canada (DFO).

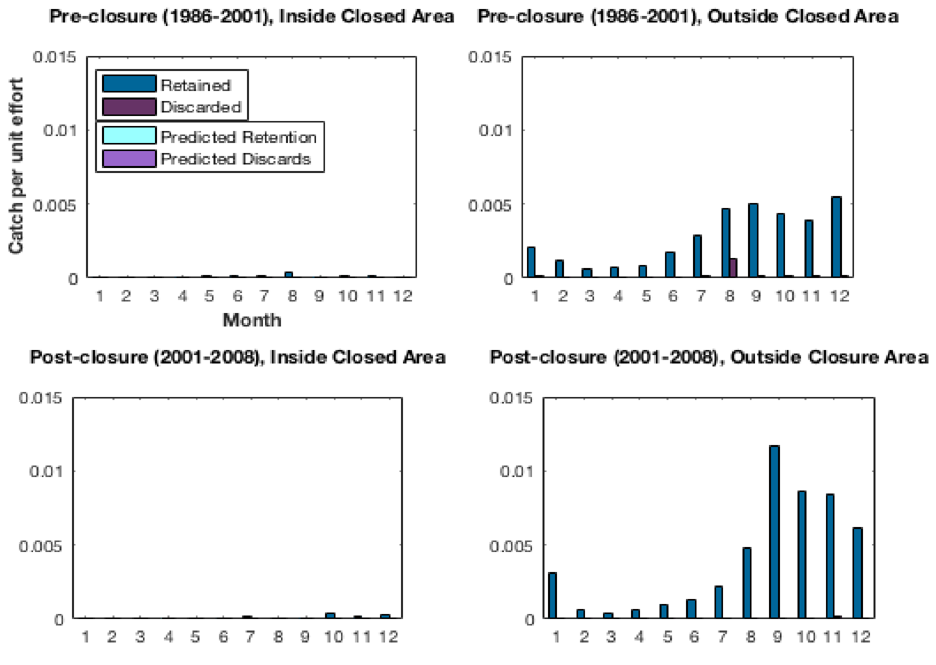


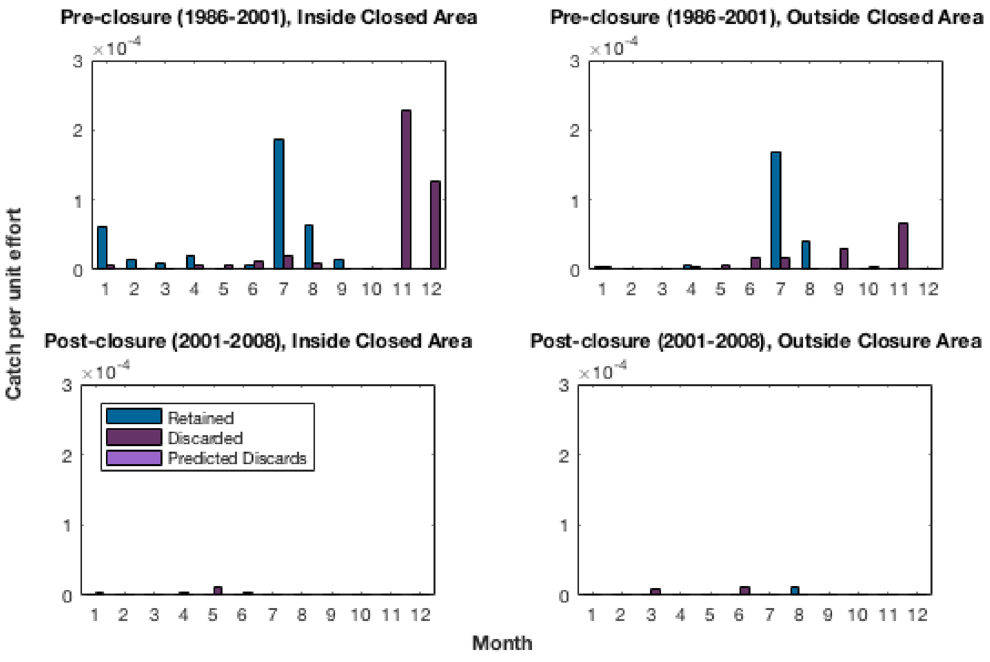


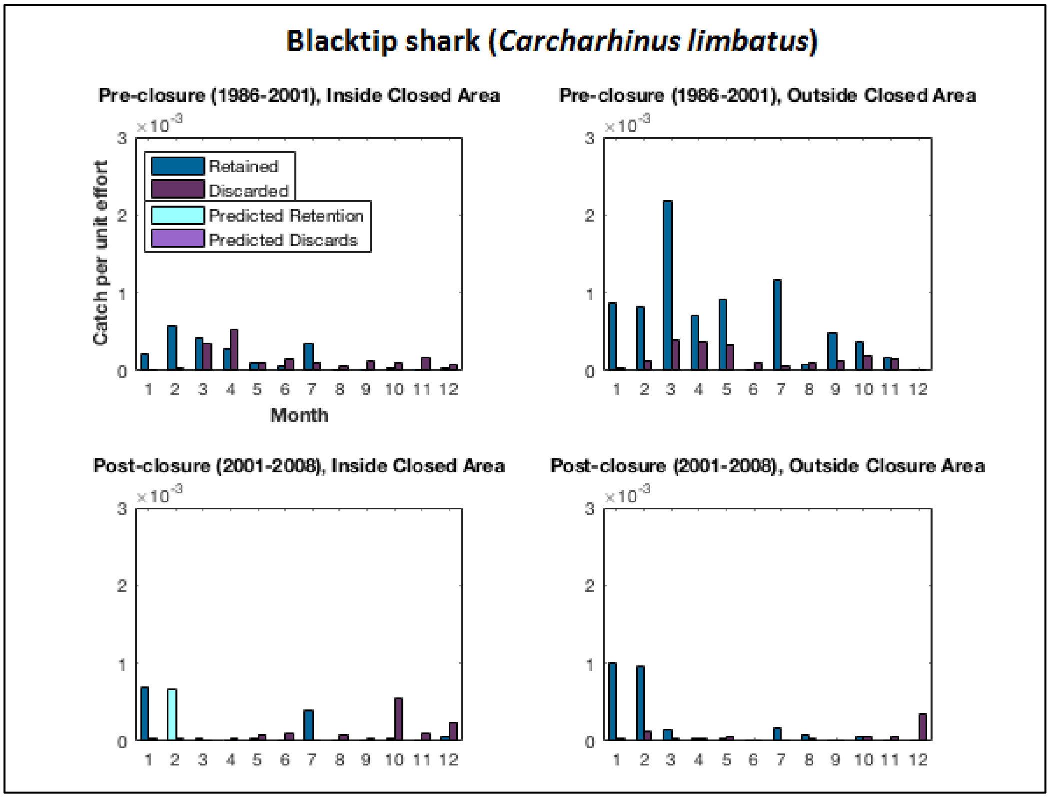
Appendix B. Catch per unit effort (i.e. retained) and bycatch per unit effort (i.e. discarded) for selected species across each month for the four time-space combinations.



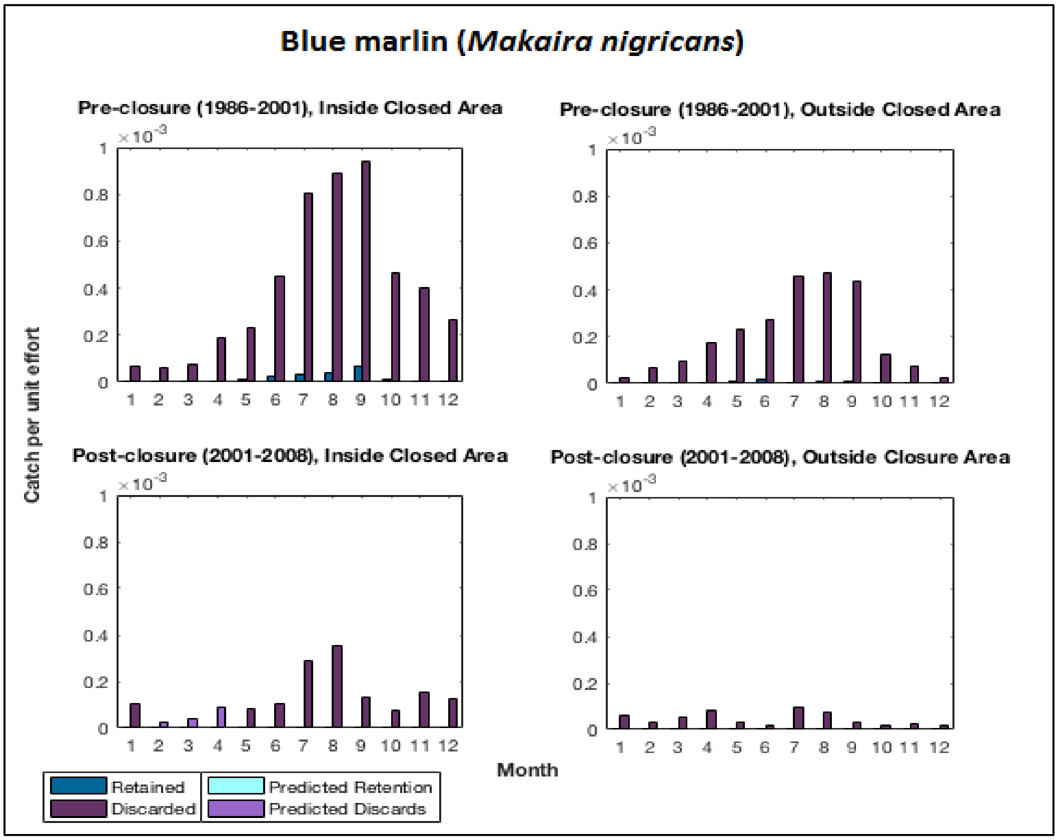



Bigeye tuna (*Thunnus obesus*)

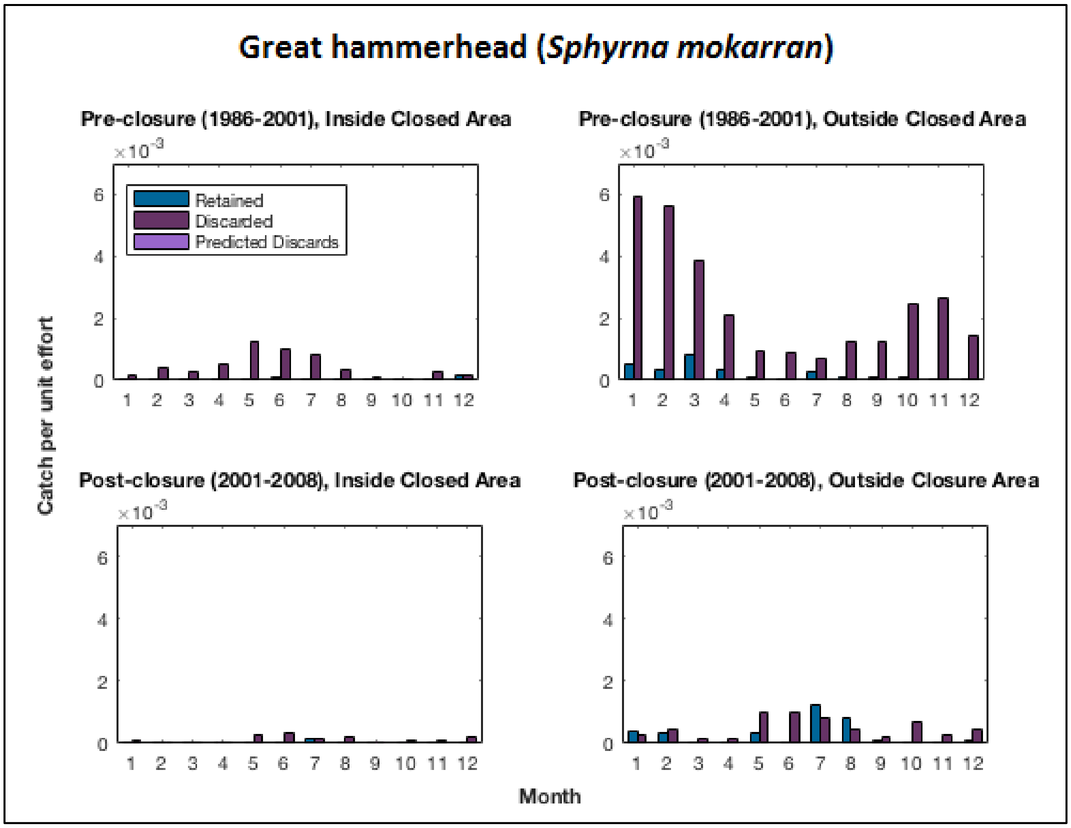

Bignose shark (*Carcharhinus altimus*)



Blacktip shark (*Carcharhinus limbatus*)



Blue marlin (*Makaira nigricans*)



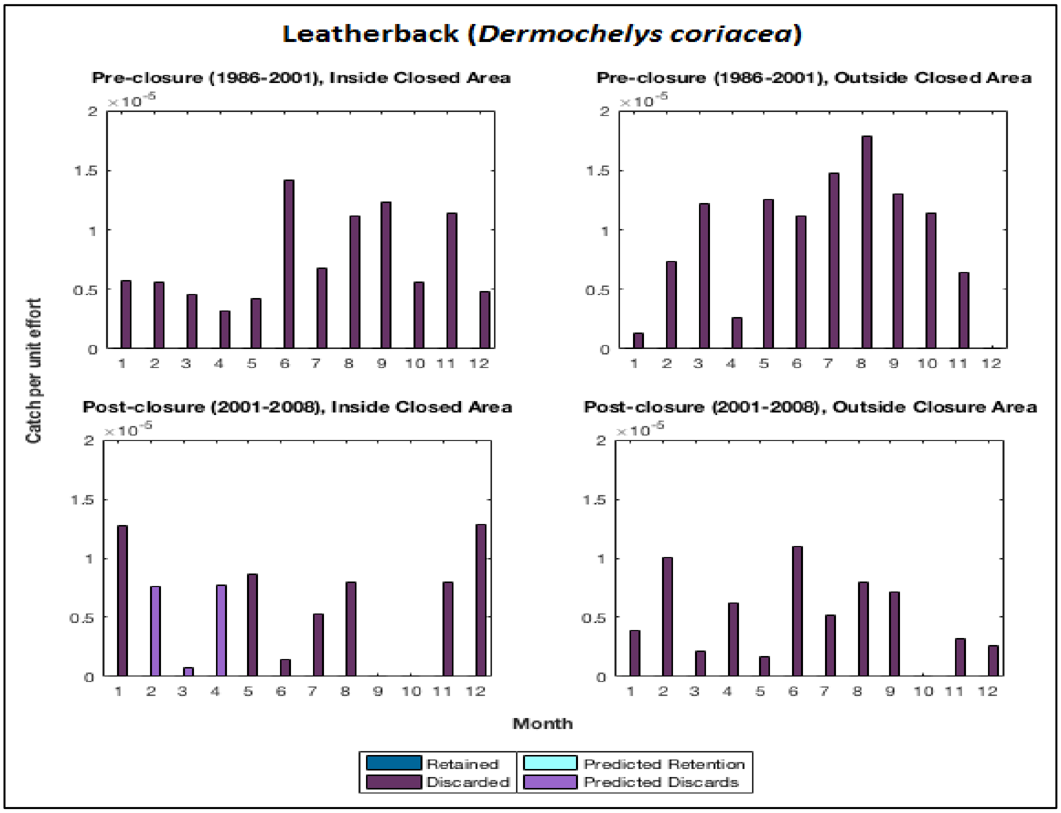
Great hammerhead (*Sphyrna mokarran*)

Pre-closure (1986-2001), Inside Closed Area

Pre-closure (1986-2001), Outside Closed Area

Post-closure (2001-2008), Inside Closed Area

Post-closure (2001-2008), Outside Closure Area



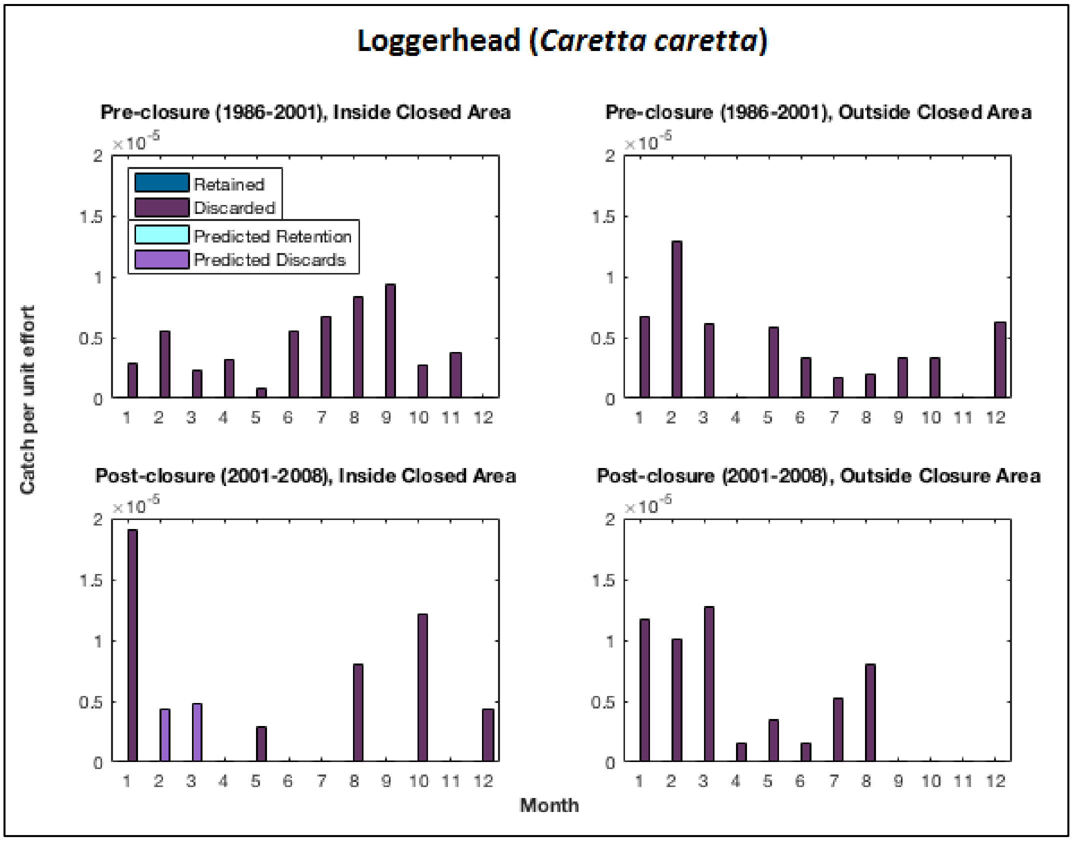
Leatherback (*Dermochelys coriacea*)

Pre-closure (1986-2001), Inside Closed Area

Pre-closure (1986-2001), Outside Closed Area

Post-closure (2001-2008), Inside Closed Area

Post-closure (2001-2008), Outside Closure Area



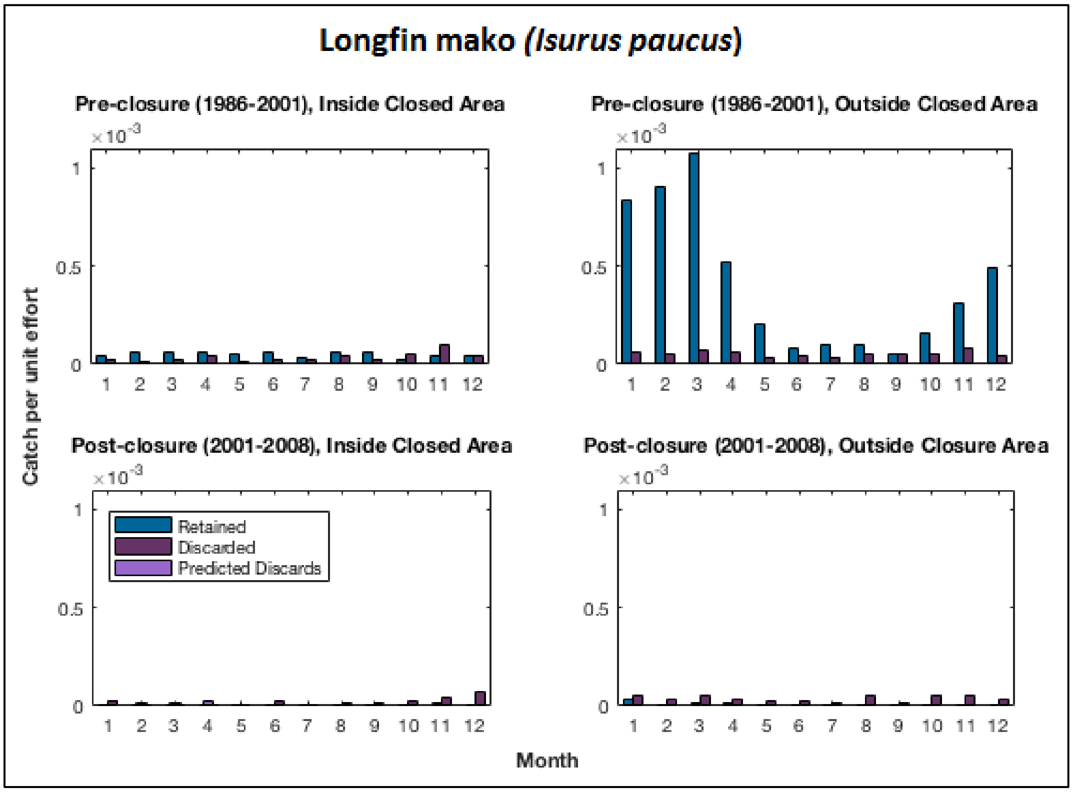
Loggerhead (*Caretta caretta*)

Pre-closure (1986-2001), Inside Closed Area

Pre-closure (1986-2001), Outside Closed Area

Post-closure (2001-2008), Inside Closed Area

Post-closure (2001-2008), Outside Closure Area



Longfin mako *(Isurus paucus)*

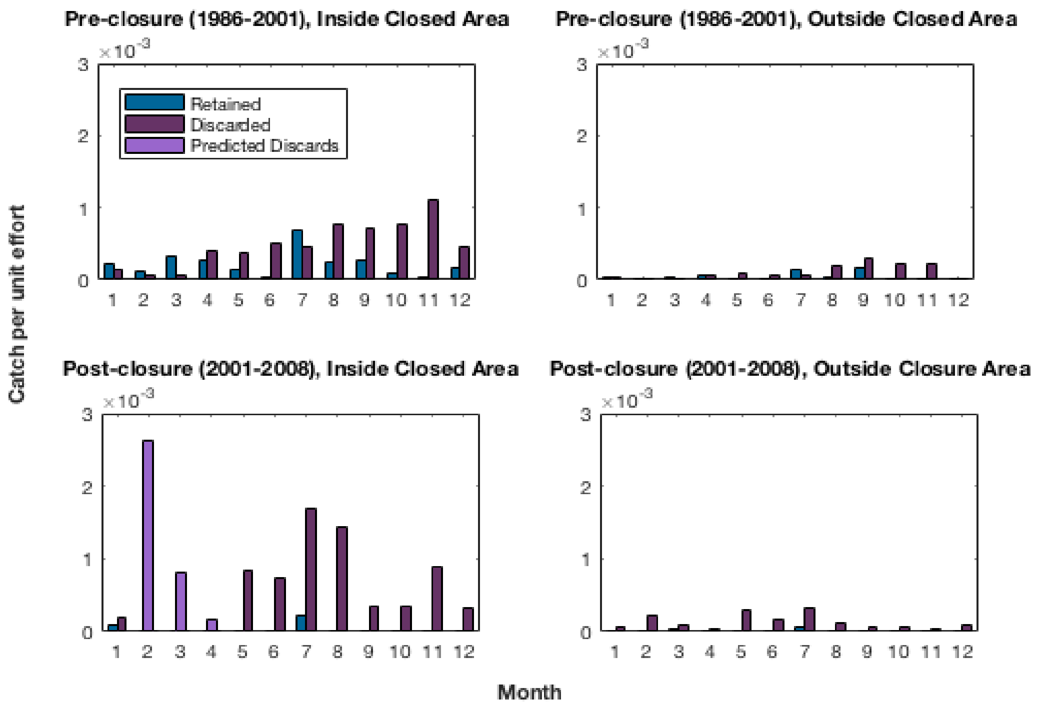
Pre-closure (1986-2001), Inside Closed Area

Pre-closure (1986-2001), Outside Closed Area

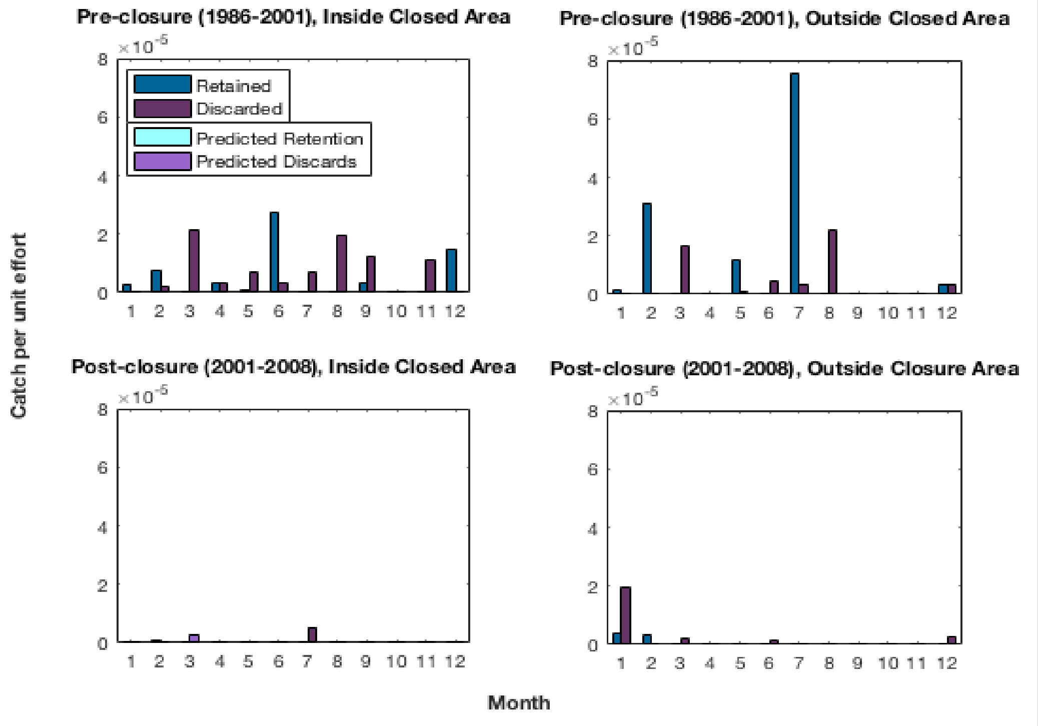
Post-closure (2001-2008), Inside Closed Area

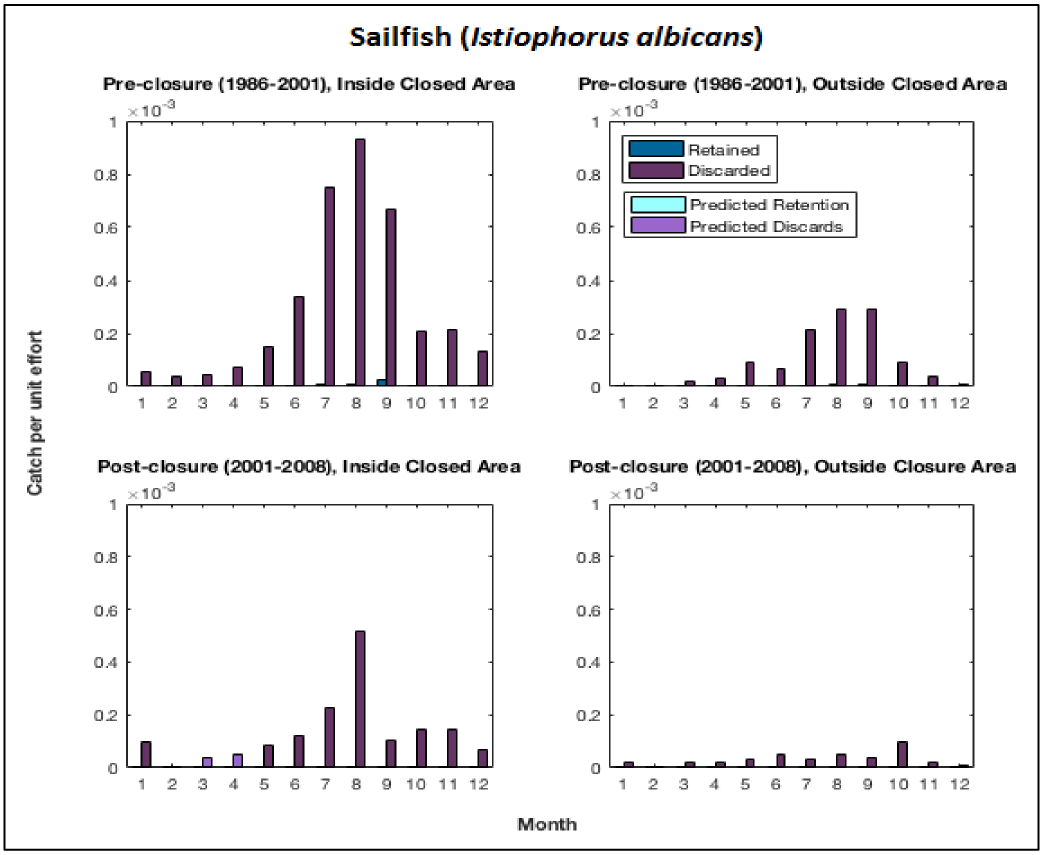
Post-closure (2001-2008), Outside Closure Area

Night shark (*Carcharhinus signatus*)

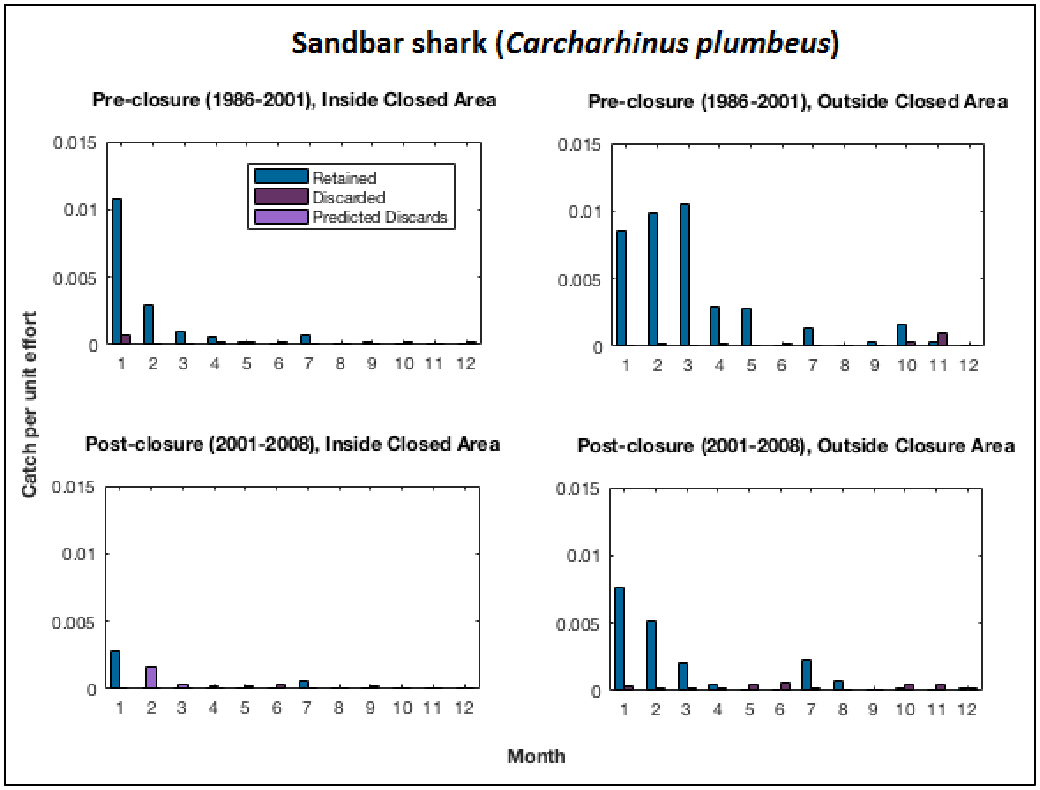


Porbeagle (*Lamna nasus)*

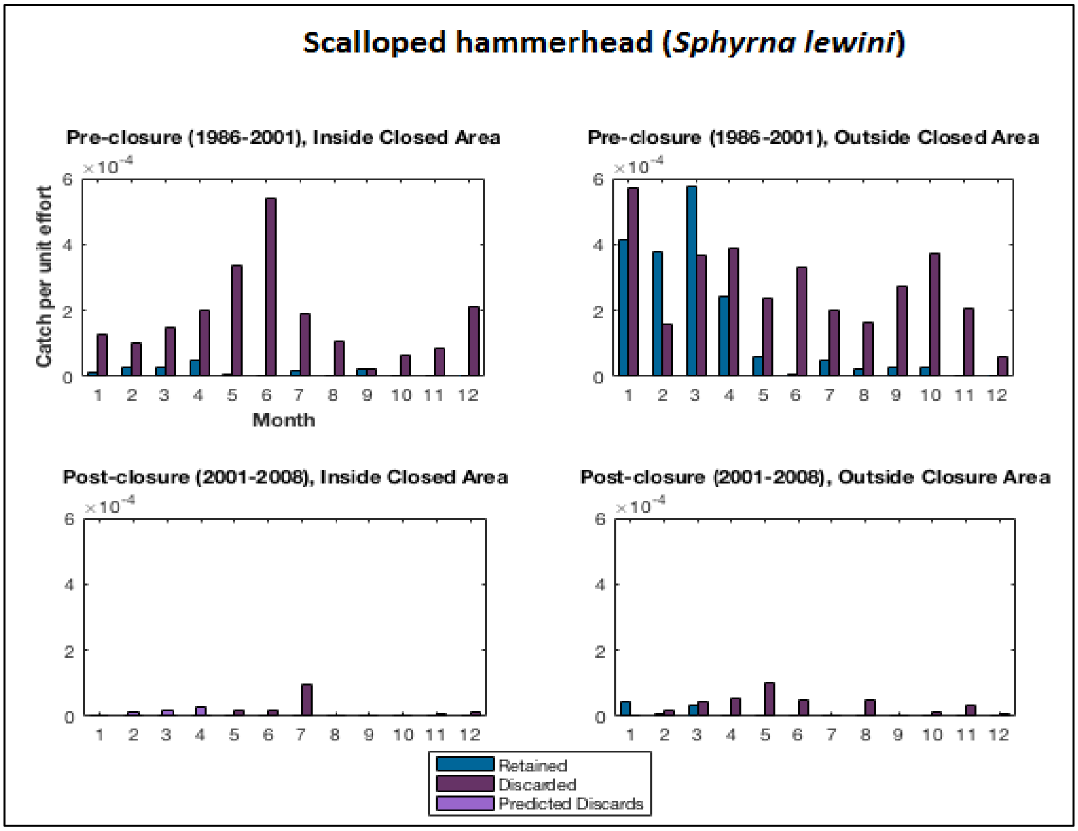




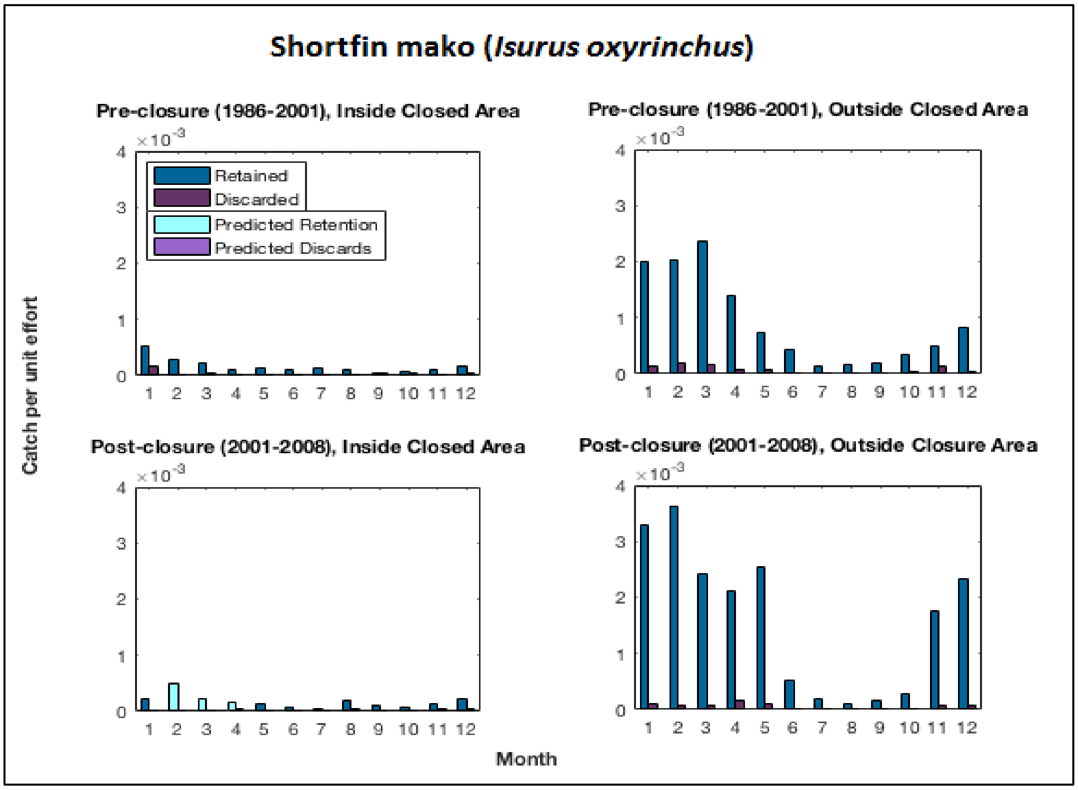
Sailfish (*Istiophorus albicans*)



Sandbar shark (*Carcharhinus plumbeus*)

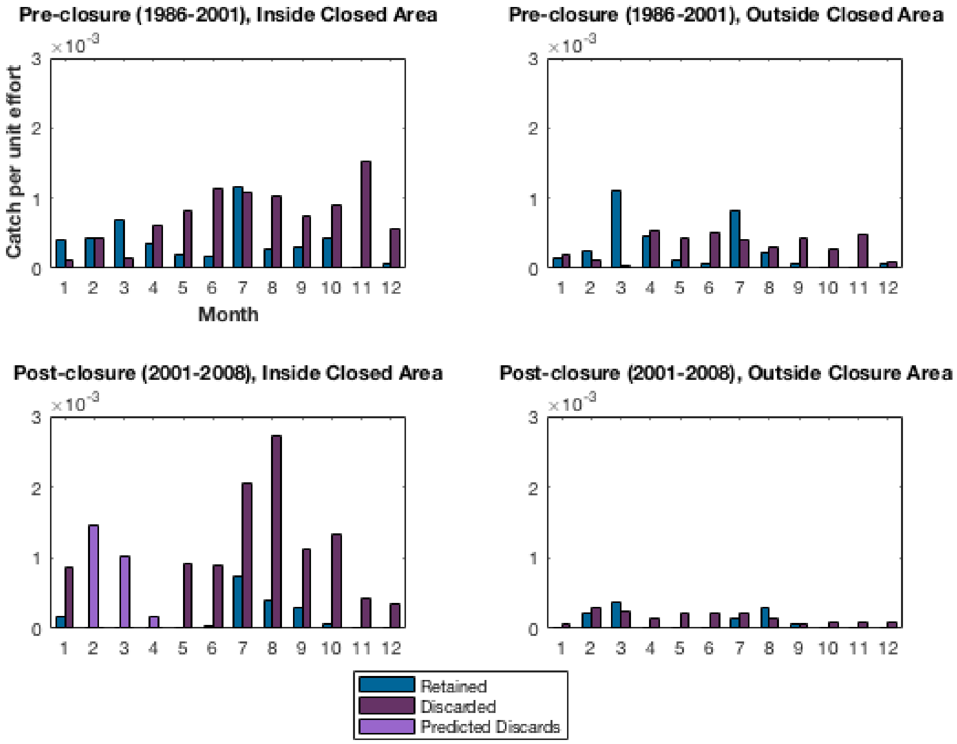


Scalloped hammerhead (*Sphyrna lewini*)

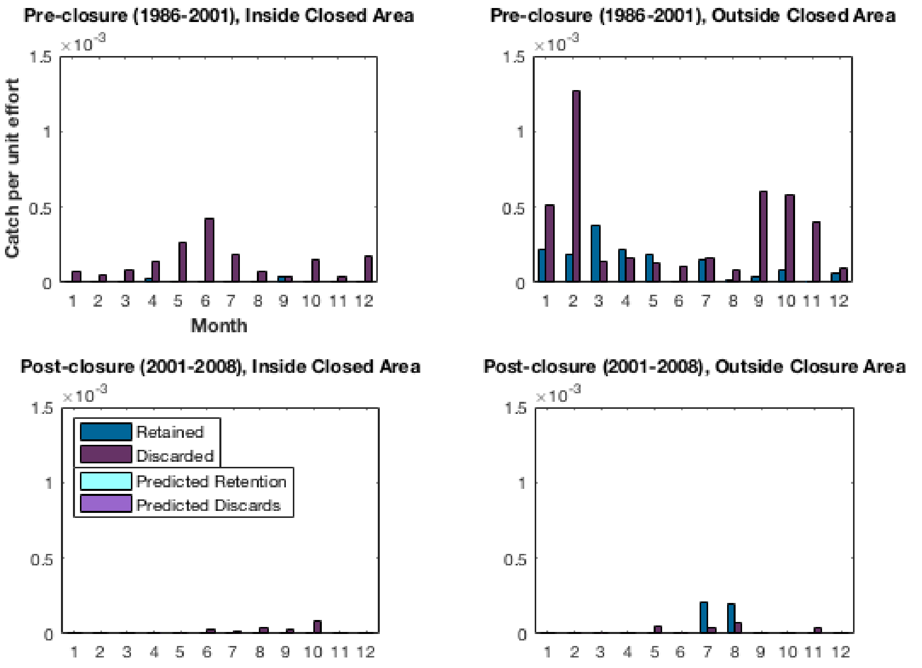


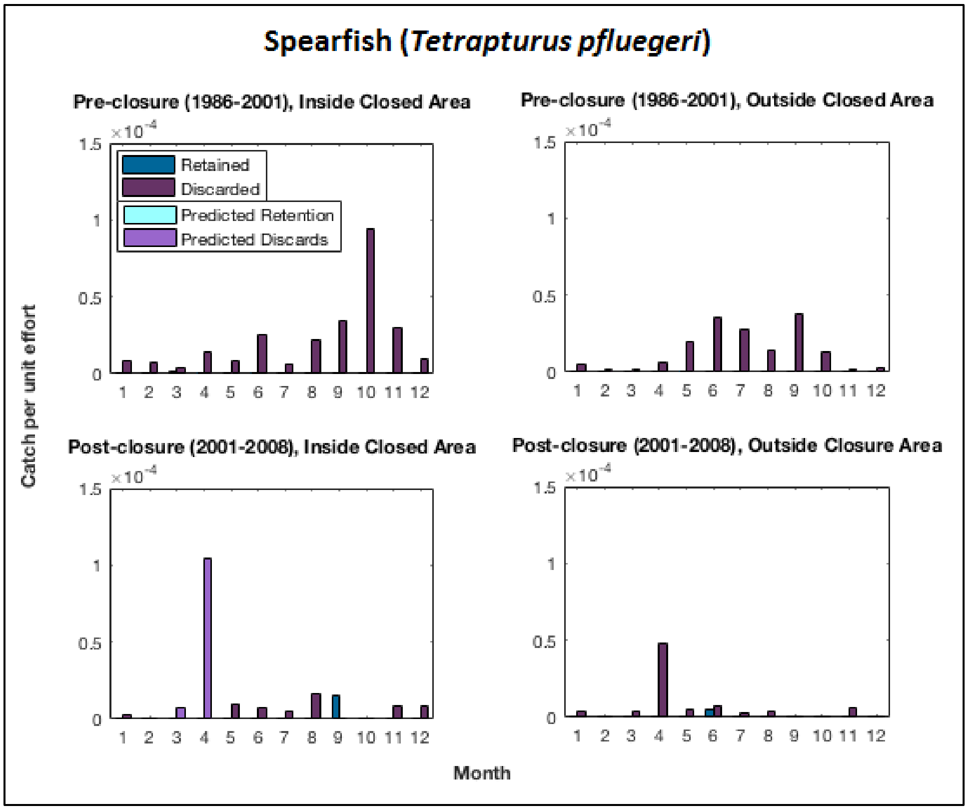
Shortfin mako (*Isurus oxyrinchus*)

Silky shark (*Carcharhinus falciformis*)

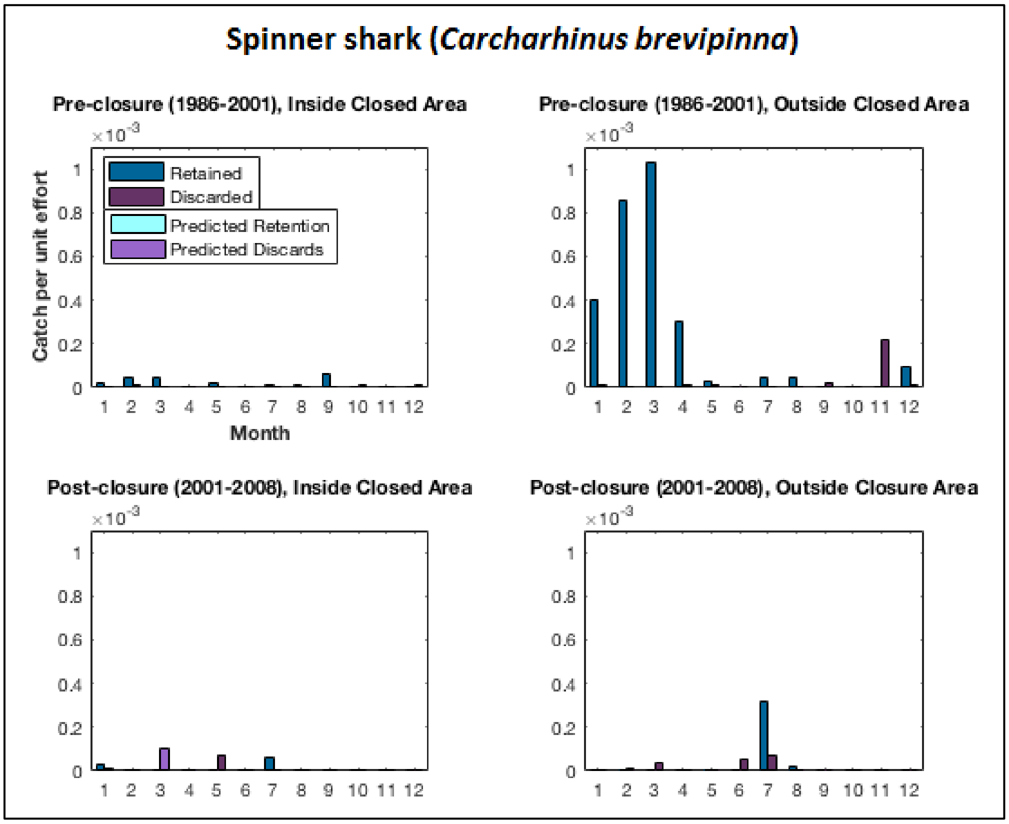


Smooth hammerhead (*Sphyrna zygaena*)

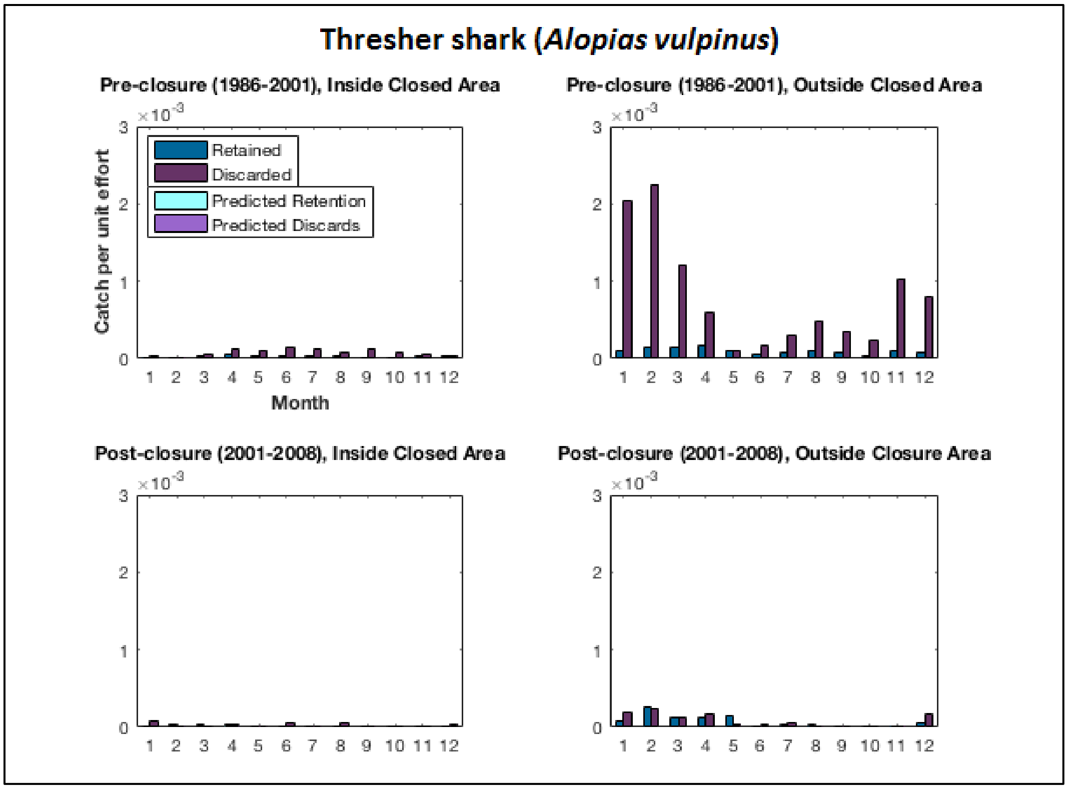


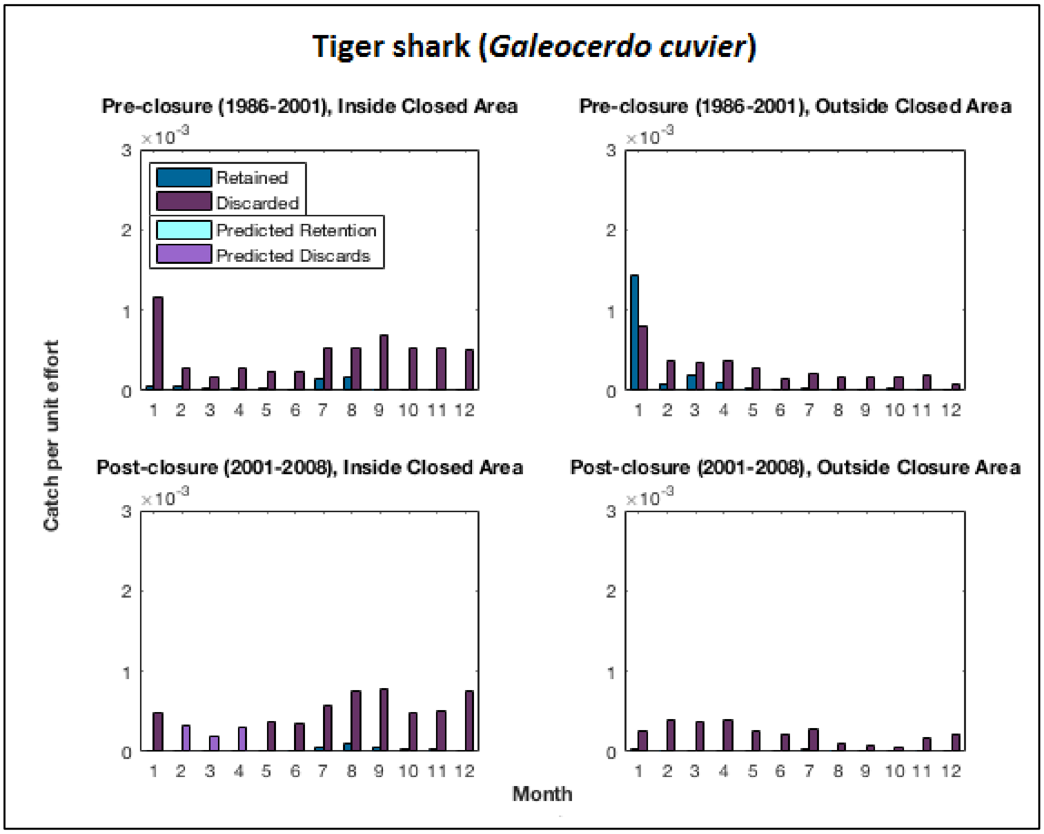


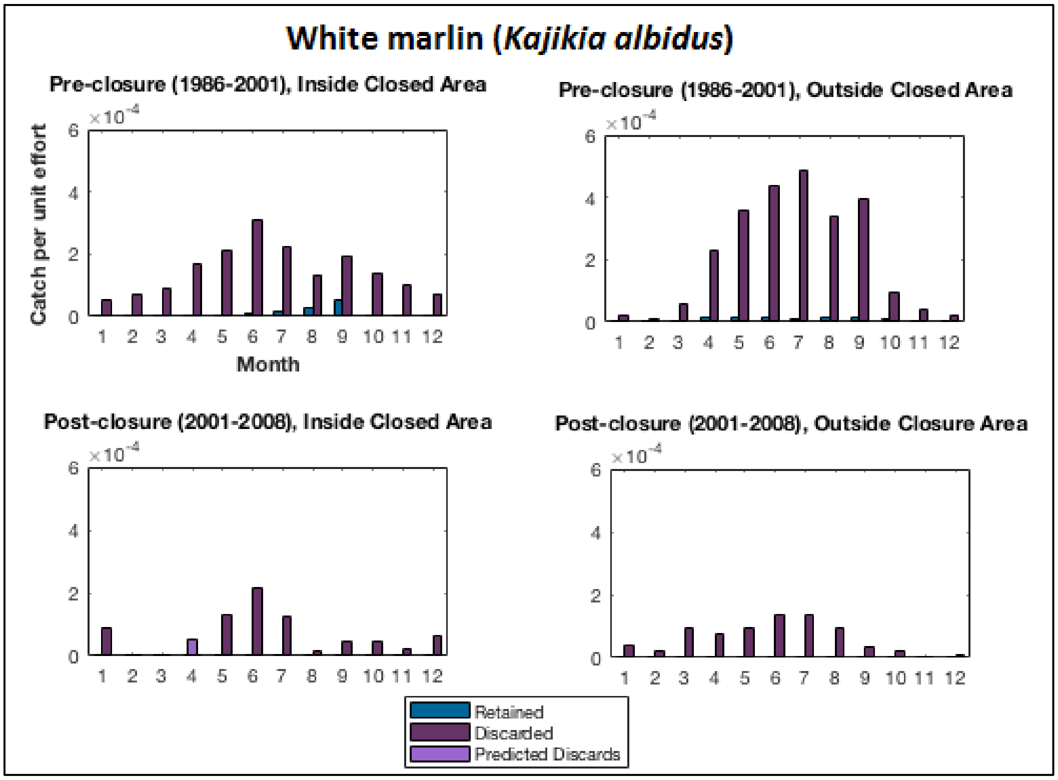
Spearfish (*Tetrapturus pfluegeri*)

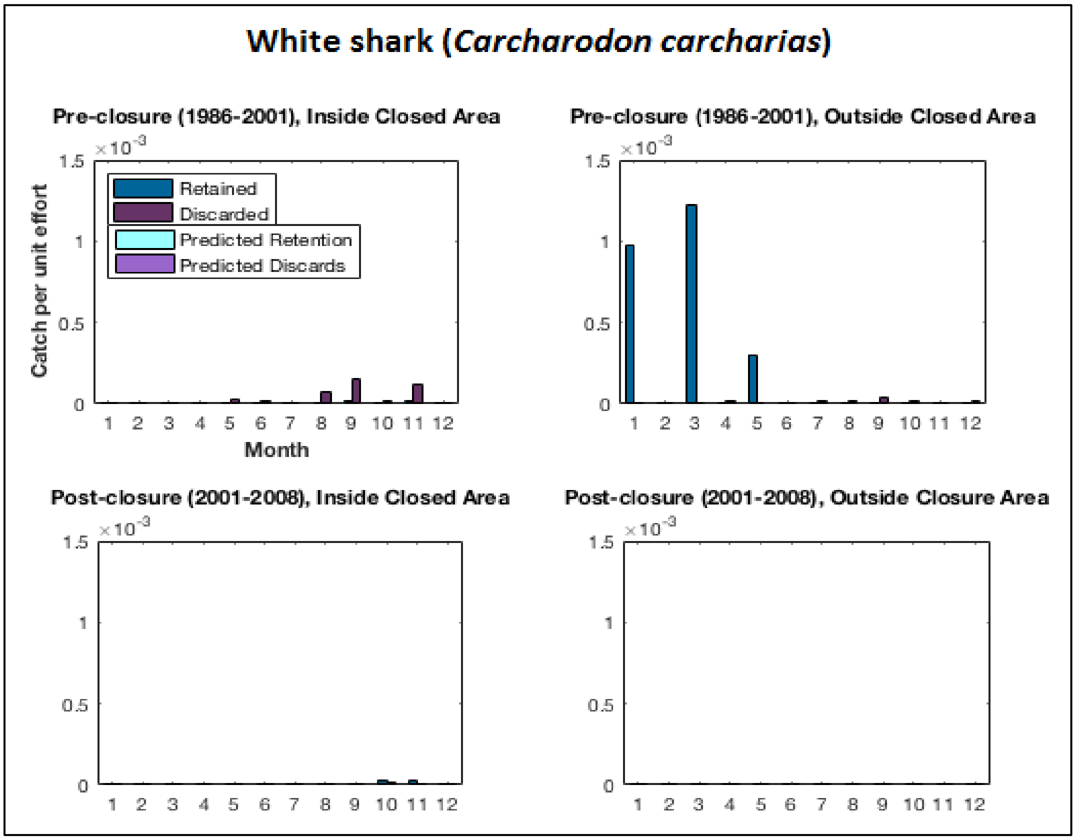


Spinner shark (*Carcharhinus brevipinna*)


Thresher shark (*Alopias vulpinus*)
Pre-closure (1986-2001), Inside Closed Area
Pre-closure (1986-2001), Outside Closed Area
Post-closure (2001-2008), Inside Closed Area
Post-closure (2001-2008), Outside Closure Area
Catch per unit effort
×10^-3
0
1
2
3
Retained
Discarded
Predicted Retention
Predicted Discards
1 2 3 4 5 6 7 8 9 10 11 12
Month


Tiger shark (*Galeocerdo cuvier*)
Pre-closure (1986-2001), Inside Closed Area
Pre-closure (1986-2001), Outside Closed Area
Post-closure (2001-2008), Inside Closed Area
Post-closure (2001-2008), Outside Closure Area
Catch per unit effort
×10^-3
0
1
2
3
Retained
Discarded
Predicted Retention
Predicted Discards
1 2 3 4 5 6 7 8 9 10 11 12
Month


White marlin (*Kajikia albidus*)
Pre-closure (1986-2001), Inside Closed Area
Pre-closure (1986-2001), Outside Closed Area
Post-closure (2001-2008), Inside Closed Area
Post-closure (2001-2008), Outside Closure Area
Catch per unit effort
×10^-4
0
2
4
6
1 2 3 4 5 6 7 8 9 10 11 12
Month
Retained
Discarded
Predicted Discards


White shark (*Carcharodon carcharias*)
Pre-closure (1986-2001), Inside Closed Area
Pre-closure (1986-2001), Outside Closed Area
Post-closure (2001-2008), Inside Closed Area
Post-closure (2001-2008), Outside Closure Area
Catch per unit effort
×10^-3
0
0.5
1
1.5
1 2 3 4 5 6 7 8 9 10 11 12
Month
Retained
Discarded
Predicted Retention
Predicted Discards

Appendix C. Number of hooks for all four time-space combinations using observer data and logbook data

# of Hooks (logbook data)				
	Pre-Closure, Outside CB	**Post-Closure, Outside CB**	**Pre-Closure, Inside CB**	**Post-Closure, Inside CB**
Jan	535486	486603	440862	351526
Feb	536425	494715	444353	409802
Mar	535550	522348	438814	427997
Apr	537325	529082	445590	438754
May	544426	527204	455198	434607
Jun	548899	526391	462865	425718
Jul	547538	518607	463574	416514
Aug	547224	521852	465293	412553
Sep	525406	527293	434622	410902
Oct	528860	533762	440339	410891
Nov	531027	533917	441663	412444
Dec	533845	536785	437718	416850

Values in red are predicted values based on Equation 2.

# of Hooks (observer data)				
	Pre-Closure, Outside CB	**Post-Closure, Outside CB**	**Pre-Closure, Inside CB**	**Post-Closure, Inside CB**
Jan	37163	11751	1328	5201
Feb	28062	16173	21170	12201
Mar	9115	10623	40708	47443
Apr	19537	26071	37726	50343
May	31028	12459	30622	53992
Jun	22345	12459	47609	16571
Jul	9700	20540	9727	12685
Aug	8619	0	11929	8823
Sep	865	5827	8863	1215
Oct	14722	1182	13132	0
Nov	9873	8037	9511	2180
Dec	19873	10644	9358	5415

Appendix D. Individuals discarded per month using average hooks per month. Note: adjusted observer data for leatherback and loggerhead sea turtles are bottom two rows.

Individuals discarded per month using average hooks per month												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Effort (avg # hooks)	351526	409802	427997	438754	434607	425718	416514	412553	410902	410891	412444	416850
Swordfish	1518	2046	2523	1879	1407	972	1882	3749	3757	3671	4647	3511
Bigeye tuna	0	0	1	1	0	1	13	0	0	5	13	0
Bluefin tuna	1	0	0	52	0	0	0	0	0	0	0	0
Yellowfin	36	26	109	38	9	9	45	23	37	45	30	16
Albacore	0	0	0	0	0	0	0	3	0	0	0	0
Dolphinfish	6	0	0	49	376	251	109	3	12	45	118	27
Blue sharks	203	718	287	223	187	215	109	40	98	99	69	272
Great hammerhead	37	17	5	16	128	141	56	76	24	45	33	82
Thresher	26	1	2	15	8	21	9	20	6	0	7	18
Bignose shark	1	0	0	1	5	2	0	0	0	0	0	0
Blacktip	12	13	9	16	38	41	0	33	18	229	39	103
Dusky	185	188	232	197	166	297	156	142	275	154	164	219
Scalloped hh	1	5	9	13	8	8	40	0	0	0	3	5
Smooth hh	0	0	0	0	0	12	9	17	12	35	3	0
Night	0	0	0	0	0	310	701	587	147	139	365	0
Oceanic whitetip	8	0	13	20	6	13	45	40	12	50	43	55
Porbeagle	0	0	0	0	0	0	2	0	0	0	0	0
Silky	300	595	434	78	400	384	854	1131	458	542	178	149
Spinner	3	0	43	0	32	2	0	0	0	0	0	2
Bigeye thresher	70	25	23	62	60	57	113	73	43	20	43	66
White	1	0	0	0	1	2	0	3	0	15	13	2
Tiger	172	132	78	136	164	148	240	313	324	199	207	311
Sandbar	1020	683	114	103	63	142	269	40	67	35	26	39
Longfin mako	11	4	8	11	6	13	4	7	6	10	23	30
Shortfin mako	2	4	8	20	6	8	0	17	12	0	13	14
White marlin	30	93	60	24	57	91	51	7	18	20	10	27
Blue marlin	37	11	18	41	35	45	120	145	55	30	62	52
Sailfish	35	0	16	22	37	51	96	214	43	60	59	28
Spearfish	1	0	3	46	4	3	2	7	0	0	3	4
Leatherback	4	3	0	3	4	1	2	3	0	0	3	5
Loggerhead	7	2	2	0	1	0	0	3	0	5	0	2
Leatherback (obs)	33	0	0	0	26	0	28	40	0	0	0	39
Loggerhead (obs)	74	58	0	0	26	0	0	40	0	0	0	20

Appendix E. Individuals discarded per month using average hooks per month

Individuals retained with avg hooks per month												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Effort (# hooks)	351526	409802	427997	438754	434607	425718	416514	412553	410902	410891	412444	416850
Swordfish	7690	6077	6732	7542	6829	5304	9060	12706	15785	19048	18080	13572
Bigeye tuna	8	10	10	29	3	18	78	7	24	184	79	101
Bluefin tuna	4	2	1	26	2	11	0	0	0	0	0	0
Yellowfin tuna	1004	3932	2310	1773	250	301	1517	617	678	1796	862	516
Albacore	6	124	51	20	0	5	9	0	6	15	7	7
Dolphinfish	395	196	383	3116	34330	19616	1146	448	580	587	694	609
Blue sharks	0	18	18	46	1	0	0	0	0	0	0	0
Thresher	2	12	12	16	0	0	0	0	0	0	0	0
Blacktip	246	274	12	6	17	6	160	3	0	10	0	23
Porbeagle	0	0	0	0	0	0	0	0	0	0	0	0
Spinner	11	0	0	0	0	0	24	0	0	0	0	0
Tiger	7	2	1	1	0	4	20	46	24	15	16	5
Shortfin mako	81	208	102	76	65	35	16	86	49	35	56	89