Investigating single and multiple species fisheries management: stock status evaluation of hammerhead (*Sphyrna* spp.) sharks in the western North Atlantic Ocean and Gulf of Mexico.

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Thesis Abstract

Three hammerhead sharks (*Sphyrna* spp.) are currently managed as part of the large coastal shark complex in the United States. Including multiple species in an assessment ignores the different stock dynamics of each individual species within the complex due to different life histories. This study completed individual assessments of scalloped (*S. lewini*), great (*S. mokarran*), and smooth (*S. zygaena*) hammerhead sharks in the U.S. Atlantic Ocean and Gulf of Mexico. Combined data for all three species and unclassified hammerhead sharks were also used to produce a stock assessment of the hammerhead shark complex. Depletions of 83%, 96%, and 91% were estimated for scalloped, great, and smooth hammerhead sharks, respectively, between 1981 and 2005. When modeled as a single stock, the hammerhead shark complex experienced a 90% decline over the same time period. All three stocks, and the complex were overfished (below population size associated with maximum sustainable yield (MSY)), and overfishing (fishing level above that associated with MSY) occurred in 2005. We found that scalloped hammerhead shark population recovery is likely to occur within 10 years if catch remains at or below 2005 levels. Great and smooth hammerhead sharks will likely still be overfished in 30 years unless catches are reduced.

It appears that the species composition could be changing in this hammerhead shark complex. The faster-growing scalloped hammerhead sharks are able to withstand fishing pressure better than great or smooth hammerhead sharks. However, it is difficult to target any single large coastal shark species while fishing; hence they are subject to similar fishing pressure. The result is a greater decline in great and smooth hammerhead sharks than experienced by scalloped hammerhead sharks. Therefore, the proportion of scalloped hammerhead sharks increased between 1981 and 2005. Species-specific stock assessments, such as those presented here, allow managers to more closely monitor populations of slower-growing species and reduce the risk of overexploitation of those species.

Keywords: hammerhead sharks, *Sphyrna*, multi-species, stock assessment, population dynamics, production model

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List of Abbreviations Used

B – Biomass

B_{MSY} – Biomass at Maximum Sustainable Yield

CSFOP – Commercial Shark Fishery Observer Program

EEZ – Exclusive Economic Zone

ENP – Everglades National Park

FMP – Fishery Management Plan

F_{MSY} – Fishing mortality at Maximum Sustainable Yield

GACP – Georgia Coastspan Project

GNOP – Gillnet Oberver Program

HMS – Highly Migratory Species

IUCN – World Conservation Union’s International Union for the Conservation of Nature

Kg - Kilograms

LCS – Large Coastal Sharks

m - meters

MSY – Maximum Sustainable Yield

mt – metric tons

NCLL – North Carolina Longline index

NMFS – National Marine Fisheries Service

NMFS LL – National Marine Fisheries Service Longline index

N – Abundance in Numbers

N_{MSY} – Abundance at Maximum Sustainable Yield

OY – Optimum Yield

PCGN – NMFS Panama City Laboratory Gillnet survey

PLL – Pelagic Longline Logbooks

PLLOP – Pelagic Longline Observer Program

SCS – Small Coastal Sharks

SEDAR – Southeast Data Assessment and Review

Chapter 1 – Introduction

Summary

Large coastal sharks are at high risk of overexploitation due to late age at maturity, slow growth, and low fecundity. A decline in shark abundance, first observed in the late 1980s, lead to National Marine Fisheries Service (NMFS) management of sharks. The decline is due to the slow growth rate of shark populations, the high occurrence of shark bycatch (incidental catch) in many fisheries, and the capitalization of a directed-shark fishery in response to the rising value of shark fins. There are no independent assessments of the status of hammerhead shark populations, with two exceptions: based only on trends in relative abundance indices, Baum et al. (2003) showed an 89% decline in scalloped hammerhead sharks (*Sphyrna lewini*), and Myers et al. (2007) suggested 98% and 99% declines in scalloped and smooth (*S. zygaena*) hammerhead sharks, respectively, in the western North Atlantic Ocean. These and additional internal assessments have lead the World Conservation Union (IUCN) to list scalloped hammerhead and smooth hammerhead sharks as Near Threatened and great hammerhead sharks (*S. mokarran*) as Endangered.

Hammerhead sharks are included in the large coastal shark complex, presently composed of 11 species, for assessment and management purposes (NMFS, 2006). It is important to investigate the possible uncertainty caused by assessing multiple species as part of a complex, compared to individual, single-species assessments. The NMFS recognizes the need for more species-specific assessments and is interested in knowing the status of hammerhead sharks (*Sphyrna* spp.). This study provided full stock assessments of scalloped, great and smooth hammerhead sharks, individually and as a complex.

Review of life history of sharks with emphasis on hammerhead sharks

Sharks (*Selachii*) have survived as predators for over 400 million years. Today they are a diverse group of over 400 known species ranging from over twelve meters in length to only a few centimeters (Manire et al., 1990). Many sharks are characterized by slow growth, late age at maturity (some commercially exploited species are not mature until 18 years old), and low reproductive potential when compared to bony fishes. Internal fertilization and viviparity (embryos develop inside the mother) are the predominant reproductive strategies of sharks and result in reduced fecundity compared to most other reproductive strategies used in the marine world (Bonfil, 1997). Adults are believed to typically congregate to mate and choose discrete pupping sites. These 'slow' life history parameters follow a pattern known as a K-selective life history strategy; the 'slower' a species, the more vulnerable it is to overexploitation because population growth rates are relatively low and cannot compensate for high fishing pressure (Cortés, 2004). Many studies have cited these life history strategies to explain why some species can withstand fishing pressure while others collapse (Bonfil, 1997; Musick et al., 2000; Cortés, 2004).

Hammerhead sharks are viviparous, with a yolk-sac placenta. They give birth to two to forty pups every other year (Compagno, 1984; see Appendix I). There is a strong positive relationship between body size, litter size, and offspring size (Cortés, 2000). Females attain maturity at a larger size and older age than males. Both sexes mature at roughly 70% of their maximum length and 50% of their lifespan (Compagno, 1984; Branstetter, 1987; Chen et al., 1990; Liu et al., 1999; Cortés, 2000).

There have been few studies on the life history of hammerhead sharks (Appendix I). Studies from different areas of the world have different parameter estimates. Cortés (2000) explains that those differences may often be more methodological than real. For example, sample sizes in the studies listed varied over an order of magnitude (<30 to >300). Most studies to date have focused on the more common scalloped hammerhead shark (*S. lewini*).

Through predation, hammerhead sharks potentially have a strong influence on ecosystem dynamics. They eat invertebrates and a wide variety of teleosts, feeding primarily at night (Branstetter, 1987). Hammerhead sharks are also known to favor stingrays and other batoids as prey and have been observed using their 'hammer' to pin the ray while the shark bites the wing (Strong et al., 1990; Klimley et al., 1993; Bush, 2003). The expanded shape of the head does not seem to confer greater electroreception (common among sharks, the sense of detecting small charges emitted by muscle contractions of potential prey), but it provides a wider lateral search area and improves maneuverability, which may help locate and capture prey (Martin, 1993; Kajiura et al., 2002).

Review of history of shark fisheries and management

Sparked by demand for vitamin A, industrial shark fisheries developed in the 1930s; within a decade, many of these collapsed due to the commercial synthesis of vitamin A and shark population declines (Holden, 1974; Manire et al., 1990). Most shark fisheries disappeared by the 1950s. Even in the late 1970s, Holden (1977) noted that there were "no major fisheries directed specifically for elasmobranchs," illustrating the youth of the current directed-shark fishery. By the 1980s, however, a fishery developed as the shark fins became increasingly valuable. Catch of sharks increased from 5500t in 1980 to 18000t in 1989 in the Gulf of Mexico: a three-fold increase (Bonfil, 1997). This increase was in response to a growing demand for shark fins; the shark fin market pays over $30/lb for some species' fins (Musick et al., 2000). Many species could not withstand such an increase in fishing rates. Populations of many shark species have declined significantly, e.g., the oceanic whitetip shark in the Gulf of Mexico was estimated to have declined by 99% in a study by Baum et al. (2004). Scalloped hammerhead and smooth hammerhead sharks have also reportedly declined 89% and 99%, respectively (Baum et al. 2003; Myers et al. 2007). Other collapsed shark fisheries include those for porbeagle, soupfin shark, basking shark, and spiny dogfish (Musick et al., 2000).

There is evidence that fishing targets juvenile hammerhead sharks in the southern Gulf of Mexico (Bonfil, 1997). When individuals are fished before their growth potential is realized, yield is lost through a process called growth overfishing (Campana et al., 2002). Moreover, many juvenile hammerhead sharks are caught in the swordfish fishery before they have an opportunity to reproduce (Buencuerpo et al., 1998). In a study on shark bycatch of the swordfish longline fishery, 94% of male and 96% of female scalloped hammerhead sharks were not mature (Buencuerpo et al., 1998), which could compromise future recruitment.

In 1989, the National Marine Fisheries Service (NMFS) began managing sharks within the U.S. Exclusive Economic Zone (the EEZ extends 200 miles from the coast) at the request of the five eastern U.S. councils (NMFS, 2006). Thirty-nine of the sharks most frequently caught in United States waters were assigned to three groups (Table 1.1): pelagic sharks (five species), small coastal sharks (SCS) (four species), and large coastal sharks (LCS) (30 species, including hammerhead sharks). The first LCS assessment was completed in 1992 and resulted in the first shark Fisheries Management Plan (FMP) in 1993. It established recreational catch limits and commercial quotas by group (i.e., LCS, SCS, and pelagic). The FMP instituted both a calendar year quota and two equal half-year quotas. The 1996 LCS assessment concluded that the population was overfished because the biomass (B) of LCS was below the size that would maintain maximum sustainable yield (B_{MSY}) (NMFS, 2006). Overfishing was occurring because fishing mortality (F) was estimated to exceed the level that would maintain the population at maximum sustainable yield (F_{MSY}) (NMFS, 2006).

In 1998, the stock biomass (B) of the large coastal complex, sandbar sharks (*Carcharhinus plumbeus*), and blacktip sharks (*C. limbatus*) were estimated to be below B_{MSY} (30-36%, 58-70%, and 44-50% of B_{MSY}, respectively). The 2002 assessment estimated that B/B_{MSY} for the LCS complex had more than doubled since the 1998 assessment, but the complex was still overfished and experiencing overfishing (Cortés et al., 2002). However, within the complex, the blacktip shark stock was healthy (not overfished and no overfishing occurring) and the sandbar shark stock was near the threshold (Cortés et al., 2002). The 2006 assessment estimated that the LCS complex and the blacktip shark stock in the Gulf of Mexico were not overfished nor experiencing overfishing, although overfishing was occurring in the overfished sandbar shark fishery (NMFS, 2006).

The 2006 assessment utilized the Southeast Data, Assessment, and Review (SEDAR) process. SEDAR is a relatively new assessment process that includes stock-assessment analysts, biologists, fishermen, policy makers, and sometimes social scientists with the aim of synthesizing data and assessing the stocks of commercially exploited species (NMFS, 2006). This inclusive process is considered an improvement over past stock assessments, which were much more condensed that SEDAR. SEDAR consists of three workshops: the data workshop, the assessment workshop, and the review workshop. The participants at the Data Workshop (DW) synthesize all available data and determine which information should be used in the assessment. All data are included unless specific problems can be identified but not rectified. The Assessment Workshop (AW) contributors choose the model that will best describe the data. This group also decides how abundance indices will be weighted and what sensitivity analyses will be most informative. The most recent SEDAR Assessment Workshop for Large Coastal Sharks used Bayesian surplus production models and age-structured production models in the assessments (NMFS, 1998; Babcock et al., 2001; Cortés et al. 2002; NMFS 2006). Finally, the Review Workshop (RW) provides independent feedback, in the form of a peer review, about the assessment before management utilizes it in decision making.

Review of the study area of hammerhead sharks

The study area includes the range of distribution of hammerhead sharks in the U.S. east coast. Hammerhead sharks range from New Jersey to the southern tip of Florida, including the Gulf of Mexico and the Caribbean Sea (Compagno, 1984). They visit warmer waters of the Gulf of Mexico during winter and migrate up the U.S. east coast during the summer (Wakabayashi et al., 1981).

Hammerhead sharks are coastal-pelagic sharks. As semi-oceanic species, they can be found from continental and insular shelves to deeper water just beyond the shelves, but avoid open-ocean and transoceanic movements (Compagno, 1984). In the U.S. catch, scalloped hammerhead, great hammerhead, and smooth hammerhead sharks compose roughly 2%, 1%, and <1% of the total LCS landings, respectively (Cortés et al., 2002). Although these seem small proportions of the catch, scalloped hammerhead and great hammerhead sharks are among the ten-most commonly caught species in surveys (Grace et al., 1997).

Materials and methods

Relative abundance indices can be categorized based on their dependence to fisheries, i.e., as fishery-dependent or fishery-independent indices. Fishery-dependent data include landings, sea sampling, catch, and port samples collected while harvesting. These data are dependent on where and how fishers work. Fish availability or abundance is only one of many variables that influence fishery-dependent data. Technology, gear, skill level, and fishing intensity are others (Haddon, 2001). Survey, or fishery-independent, data are designed to decrease the influence of harvest activities on the abundance index. They depend on random or systematic sampling with a consistent methodology to portray population abundance over time.

Review of stock assessment methods used in shark fisheries

Various stock assessment models have been used for the Large Coastal Shark complex. Included among those are surplus production models; non-equilibrium state-space production models; age-structured models; and lagged recruitment, survival, and growth models (Cortés et al., 2002). The choice of the model depends on the quantity, quality, and type of data available. As is the case with many fisheries, age-structured data were unavailable for hammerhead sharks, hence surplus production models were utilized in the present study.

Surplus production models are among the simplest models and have few data requirements relative to other population dynamics models. They are simple because they pool the changes in the population into one variable: either biomass (B) or population size (N). All recruitment, growth, and mortality are grouped into a single function: production (r). Age structure, size structure, and sex ratios, e.g., are ignored. These characteristics make these models useful when detailed age, size, or sex data are not available. The minimum data necessary include only a relative abundance index and associated catch data (Schaefer, 1954). The data necessary for surplus production models are less expensive to collect than those needed for age-structured models, but surplus production models can be similarly relevant to management in many cases (Haddon, 2001). In fact, Ludwig et al. (1988) and Prager (1994) argue that surplus production models outperform models with more parameters, each containing associated error.

Uncertainty was estimated by using the bootstrap method, which involves random sampling of residuals (the numerical difference between observed and expected values) with replacement, adding those residuals to the original data, and re-fitting the model to establish new parameter estimates. Monte Carlo simulation, a process of repeatedly and randomly selecting model input parameters (Hilborn and Walters, 1992), was used to incorporate the uncertainty of parameter estimates into population projections. This process is necessary to assess the risk of overfishing in population projections due to uncertainty in the parameter estimates.

Review of biological reference points used in current shark management

The minimum population size necessary to sustain maximum harvest (N_{MSY}) or fishing levels that would sustain maximum yield (F_{MSY}) are examples of Biological Reference Points (BRPs, management benchmarks for sustainable harvest (Mace, 1994)). In Chapters 2-4, I estimate the following BRPs:

MSY – Maximum sustainable yield

F_{MSY} - Fishing level associated with MSY,

N_{MSY} - Population size that will produce MSY,

These BRPs will be used to estimate the current stock status based on the following values when t is the last year of data in the assessment:

F_t/F_{MSY} – If greater than 1, overfishing is occurring, and

B_t/B_{MSY} – If less than one, the population is overfished.

Maximum sustainable yield estimates should be seen as upper limits, and associated risk should be assessed; a conservative management approach uses targets that are more cautious than these limits because of the inherent uncertainty in the estimates (Sissenwine, 1978; Mace, 1994; Richards et al., 1998). Enforcement, recording, and verifying data, are among many problems that can result in uncertainty in population estimates. Sharks assessments in particular suffer from data deficiency and unreliable identification. Conservative targets would not be based on the maximum yield, but a smaller Optimum Yield (OY) (Sissenwine, 1978; Mace, 1994; Roughgarden et al., 1996). A control rule, or an ongoing procedure of adjusting catch to maintain OY, is used to manage the LCS complex. The NMFS-HMS control rule establishes optimum fishing pressure (F_{OY}) as 75% of the F_{MSY} estimate and optimum biomass (B_{OY}) as 125% of the B_{MSY} estimate (K. Brewster-Geisz, NMFS Highly Migratory Species Office, personal communication).

Overview of uncertainties associated with the hammerhead shark stock assessments

There are several data insufficiencies that could have biased the results of the stock assessments. The status of the populations in 1981 is unknown, so we set initial biomass to 100% and 75% of virgin stock size, though the exact magnitude of initial depletion is unknown. Longer time series would make the model more informative. The relative abundance indices start in the early 1990s, with NMFS regulation, and catch records begin in 1981. Identification at the species level is another major problem with shark fisheries data. Early catches, in particular, were considered problematic by the SEDAR (NMFS, 2006) data workshop. In some cases, the recorded catches were over 2 orders of magnitude larger than recent catches. Finally, many relative abundance indices covered small geographic areas, and not all areas are represented. Hammerhead sharks are known to have a wide distribution and be highly migratory. Therefore, not all changes in abundance may be represented in the data. The results of these assessments are presented with certain caveats, but are still important for the conservation of hammerhead sharks.

Species identification problems exist across the shark industry; the hammerhead complex is no exception. The differences in morphology between hammerhead sharks are much less apparent than those between hammerhead and other carchariniform sharks. Therefore, many landing or catch records often lump scalloped, great, and smooth hammerheads together (Cortés, 2000), leading to several key assumptions. Scientific observer data, when available, were thus used to determine species composition in the present study. Although changes in recreational catch composition were thought to be associated with problems in identification, there was no concrete basis to alter the recorded numbers. Several sensitivity analyses dealt with exploring the influence of catch and relative abundance data.

Sensitivity analyses were used to test the influence of various assumptions in the model. For example, assumptions about initial population size relative to K can be tested by setting N_0 equal to and proportional to K. Also, various combinations of abundance indices were used to test the impact of those indices on results (NMFS, 2006). Relative abundance indices showing contradictory tendencies are a problem common in stock assessments and were also present in these studies of hammerhead sharks. However, selection of indices for the hammerhead shark assessments was based on recommendations from the recent LCS shark stock assessment (NMFS, 2006).

Research goals and objectives

We aimed to use production models to provide complete stock assessments of scalloped, great, and smooth hammerhead sharks. Each assessment included all available data; appropriate relative abundance indices were used in the base model and others were considered in sensitivity analyses. In addition to testing the effects of relative abundance indices, we explored how initial population depletion and uncertain catch records affected the results. We also provided an assessment of the hammerhead shark complex using similar methods. The bootstrap method was used to estimate confidence intervals of key parameters (Hilborn and Walters, 1992).

We compared the management of hammerhead sharks as a complex to managing each species individually. With very different life-history characteristics, some shark species are inevitably more productive than others. In mixed-stock fisheries, the populations of more productive species can often withstand moderate fishing pressure while populations of less productive species cannot, and as a result, decline (Adams 1980; Musick et al. 2000; Parkinson et al. 2004). The decline of the less productive species may be masked by the perceived healthy status of the aggregated mixed-stock fishery. The hammerhead shark complex (or species within) could decline unnoticed under the current multi-species system of monitoring an aggregated large coastal shark complex.

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Tables

Table 1.1. National Marine Fisheries Service shark management units (NMFS, 2006).

Management Unit	Shark Species Included
Large Coastal Sharks (11)	sandbar, silky, tiger, blacktip, bull, spinner, lemon, nurse, **smooth hammerhead, scalloped hammerhead, and great hammerhead sharks**
Small Coastal Sharks (4)	Atlantic sharpnose, blacknose, finetooth, and bonnethead sharks
Pelagic Sharks (5)	shortfin mako, thresher, oceanic whitetip, porbeagle, and blue sharks
Prohibited Species (19)	whale, basking, sandtiger, bigeye sandtiger, white, dusky, night, bignose, Galapagos, Caribbean reef, narrowtooth, longfin mako, bigeye thresher, sevengill, sixgill, bigeye sixgill, Caribbean sharpnose, smalltail, and Atlantic angel sharks

Appendix 1. Life History parameter estimates from previous studies.

	S.lewini				*S. mokarran*		*S. zygaena*
Parameter:	Gulf of Mexico	Western Pacific	Eastern Indian	Gulf of Mexico	Eastern Indian	Southwestern Indian	Eastern Indian
Max size (F) (cm TL)		324	346	233.1		459	
Max size (M) (cm TL)		305	301	214.8		374	
Max size (All) (cm TL)	329				550-610		370-400
K (F) (year $^{-1}$)		0.249		.09			
K (M) (year $^{-1}$)		0.222		.13			
K (All) (year $^{-1}$)	0.073						
t_0 F/M (years)	-2.2	-0.0413/-0.746					
Size at maturity (F) (cm TL)	250	210	212		250-300	337	210-240
Size at maturity (M) (cm TL)	180	198	140-165		234-269	309	210-240
Longevity (F) (years)		14		38.5			
Longevity (M) (years)		11		26.6			
Mean litter (individuals) (range)	>30	26 (12-38)	(15-31)				
Pup size (cm TL)	49	45	42-55				
Reference	Branstetter	Chen et al.	Compagno	Piercy et al	Compagno	Cortés	Compagno
	1987	1990	1984	2007	1984	2000	1984

Chapter 2 – Stock assessment of scalloped hammerhead sharks (*Sphyrna lewini*) in the western North Atlantic Ocean and Gulf of Mexico

Abstract

The status of the western North Atlantic Ocean population of scalloped hammerhead sharks (*Sphyrna lewini*) was assessed from 1981 through 2005 using logistic and Fox surplus-production models. The population declined rapidly prior to 1996, but it began rebuilding in the late 1990s as fishing pressure decreased. Currently, scalloped hammerhead sharks are overfished; the population is 47% of the size that would produce maximum sustainable yield (MSY). In 2005, fishing mortality was 114% of that associated with MSY, thus overfishing was occurring. This population is 17% of the population size prior to fishing or virgin stock size; depletion was estimated to be 83%. A Monte Carlo simulation showed that the population had a 64% probability to rebuild in 10 years when the 2005 catch level (3,704 individuals) was maintained and an 87% probability of rebuilding if the 2005 total catch is halved. The sensitivity analyses showed that the stock assessment results were most sensitive to scenarios when only fishery-independent relative abundance indices were used and when data sets were weighted by the inverse of the variance.

Introduction

Scalloped hammerhead sharks (*Sphyrna lewini*) are globally distributed and occur in coastal and adjacent pelagic waters (Compagno, 1984). Hammerhead shark fins are among the most highly valued in the Asian shark fin trade for shark fin soup, making them highly targeted species (IUCN, 2006). Like many shark species, *S. lewini* has a high potential for overexploitation due to late age at maturity, relatively small reproductive output, and long lifespan (Piercy et al., 2007). Estimates vary by location, but males are sexually mature at 1.5-2m and females mature at 2-2.5m (Compagno, 1984; Branstetter, 1987; Chen et al., 1990). Following a 9-10 month gestation period, *S. lewini* give birth to 10-40 live pups every other year (Branstetter, 1987; Liu and Chen, 1999). In the northwest Atlantic Ocean and Gulf of Mexico, Piercy et al. (2007) estimated longevities of 26.6 and 38.5 years for males and females, respectively. Unlike most other sharks, *S. lewini* also exhibit schooling behavior, which makes them vulnerable to being caught in large numbers.

As of 2007, the National Marine Fisheries Service (NMFS) has managed large coastal sharks as an aggregate including eleven species. This approach is potentially risky as the decline of one species can be masked by the increase of more productive species. NMFS recently completed an assessment of large coastal sharks, the Southeastern Data Assessment and Review (SEDAR) 11. The eleven-species (including *S. lewini*) aggregate was determined not to be overfished (i.e., the population was larger than the size needed to produce maximum sustainable yield; NMFS, 2006). Only the two most common species in the catch, sandbar sharks (*Carcharhinus plumbeus*) and blacktip sharks (*Carcharhinus limbatus*), were assessed individually using age-structured models because the data available for less common sharks were not sufficient for similar assessments in most cases. The review panel recommended that NMFS conduct species-specific assessments of all large coastal sharks.

To date, there has been no comprehensive assessment of stock status for *S. lewini*. Baum et al. (2003) estimated an 89% decline in stocks of *S. lewini* in the western North Atlantic Ocean. Conclusions derived from this study were contentious because the authors used a single relative abundance index, the pelagic longline logbook data set (Baum et al., 2003; Burgess et al., 2005). Largely based on the Baum et al. (2003) paper, the World Conservation Union (IUCN) recently changed the global status of *S. lewini* from "Near Threatened" to "Endangered" (IUCN, 2002; 2006). This study is a formal stock assessment that incorporates all the data available into a synthesis model.

Materials and methods

Surplus-production or age-aggregated models are commonly used when only catch and relative abundance data are available, as is the case with *S. lewini*. We investigated the goodness of fit of surplus-production models with three productivity curves: Schaefer (1954), Fox (1970), and Pella-Tomlinson (1969), using the Akaike Information Criterion for small sample size (AICc; Akaike, 1974; Bedrick et al., 1994). Virgin population size or carrying capacity, K, and intrinsic population growth rate, r, were estimated. Initial population size was set equal to K or a proportion of K (Punt, 1990). The parameters q_i, or catchability coefficients, were estimated within the model (Jiao and Chen, 2004). By eliminating the need to estimate these parameters, the error of the model was drastically reduced. Surplus-production models may outperform more complex models by estimating fewer parameters, thus minimizing uncertainty associated with each parameter (Ludwig and Walters, 1985; Prager, 1994). Multiple scenarios were constructed to test the influence of abundance indices, weighting scheme, initial population size, and catch composition uncertainty.

Catch data

Annual catch data were recorded by NMFS starting in 1981 (Table 2.1). Recreational catches dominated the early fishery (Fig. 2.1), largely in response to the release of the movie "Jaws." Recreational catch data were collected through three surveys: the NMFS Marine Recreational Fishery Statistics Survey (MRFSS), the NMFS Headboat Survey, and the Texas Parks and Wildlife Department Marine Sport-Harvest Monitoring Program. These data were available only in numbers, and no reliable average weight information was available. With no way to estimate recreational catch in biomass, this assessment was conducted in numbers.

Commercial catch data in weight were collected by the NMFS Southeast Fisheries Science Center and Northeast Regional Office from the Pelagic Dealer Compliance program (formerly known as Quota Monitoring System) and canvass data from the states. The annual catch was converted to numbers by dividing the weight by an average weight of individual animals measured in the Commercial Shark Fishery Observer Program (CSFOP). Discard statistics were obtained from the pelagic longline observer program (PLLOP) and dealer weighout data.

The fishery also provides catch and effort data through logbooks and observer programs (Table 2.2). This study followed the SEDAR 11 recommendations to use observer data when available. There are also fishery-independent surveys, which are often considered less biased indices of abundance than fishery-dependent data because samples are taken from randomly selected stations and they do not target concentrated areas of fish, in contrast to fishing vessels.

The more statistically rigorous methods of fishery-independent surveys infer closer relationships to population abundance.

Fishery-dependent indices

In 1994, NMFS began a voluntary observer program for the directed bottom-longline shark fishery, the commercial shark fishery observer program (CSFOP). In 2002, the program became mandatory for vessels with a directed shark fishing permit (Cortés et al., 2005). This fishery is currently responsible for the greatest proportion of the *Sphyrna lewini* catch, which are present in about 21% of the hauls (NMFS, 2006). This abundance index is included in the BASE scenario.

The shark drift-gillnet fishery is a relatively small fishery with six to twelve boats, depending on the market and other fisheries (Carlson et al., 2005). Data from the drift-gillnet observer program (GNOP) are available from 1994 through 2005, excluding 1996 and 1997. *Sphyrna lewini* are present in 39% of the hauls. This index was included in the SEDAR 11 base model (NMFS, 2006) and is also included in the BASE scenario of this assessment.

Five percent observer coverage of pelagic longline vessels was mandated in 1992, and eight percent was mandated in 2002 (Beerkircher et al., 2002) as part of the pelagic longline observer program (PLLOP). Using surface longlines, this fishery primarily targets swordfishes and tunas. Sharks represent about a quarter of the catch. This index covers the largest geographical area, so though *S. lewini*, specifically, appear in only about 5% of the hauls, it is included in the BASE scenario.

Fishery-independent surveys

To monitor the distribution and abundance of coastal sharks, the NMFS Pascagoula Laboratory started a stratified random sampling survey in 1995 using bottom longline gear (NMFS LL SE). It is conducted annually throughout the Gulf of Mexico, Caribbean, and western North Atlantic Ocean (Ingram et al., 2005). On average, 9% of the sets catch at least one *S. lewini*. This survey has the greatest geographical coverage of any fishery-independent index of abundance available for *S. lewini*.

From 1996 through 2005, the NMFS Panama City Laboratory conducted a fishery-independent survey (PCGN) to estimate the change in relative abundance of sharks over time. They used a gillnet consisting of several panels of varying mesh size. Gillnets are highly size-selective and the nets used were intended to capture a representative sample of all size classes (Carlson and Bethea, 2005). On average, 23% of the hauls between 1996 and 2005 included at least one *S. lewini*.

The longest time series of relative abundance available is that from the University of North Carolina longline survey (NCLL), which started in 1972. *Sphyrna lewini* represent an average of 6% of the total sample. While the area covered by the survey was limited to a bay, the survey was consistent in terms of stations and gear used (Schwartz et al., 2007).

In 2000, the Georgia Department of Natural Resources and the University of Georgia started a survey of coastal sharks to contribute to the COASTSPAN program (GACP) started by the NMFS Apex Predator Program (McCandless and Belcher, 2007). Using longline and trawl surveys, the program recorded annual relative abundance of sharks. Given the short time series and large variance, we followed the recommendations of SEDAR 13 (stock assessment for small coastal sharks; NMFS, 2007) and excluded this survey from the final model, but included it in a sensitivity scenario.

The NMFS Narragansett Laboratory conducts a standardized survey of coastal and pelagic sharks (NMFS LL NE) from Delaware to the southern tip of Florida. It started in 1986, but changed methodology in 1996 to better follow the directed shark fishery. Since then, only four years of data are available (Natanson, 2005). Due to the few years and large amount of variance in the survey, we followed the recommendations of SEDAR 11 and excluded this data set from the final model, but included it in a sensitivity scenario.

The use of relative abundance indices requires standardization to remove variation due to factors not associated with abundance (Hilborn and Walters, 1992). To do so, a two part approach derived from Lo et al. (1992) was applied to each index. This standardization technique is especially useful for handling the large number of zeros in the data, as is often found in shark abundance indices. One part identifies factors other than year (such as area, season, depth, hook type) that explain a significant portion of the variance in the model for the proportion of positive catches (i.e., sets that catch at least one shark). Another part identifies factors significant in the model for the catch-per-unit-effort of those non-zero hauls. The product of these two parts is the standardized index. All indices were standardized using this method.

Assessment models

Surplus-production models have been used in many shark stock assessments, including NMFS assessments and International Commission for the Conservation of Atlantic Tunas assessments (Babcock and Pikitch, 2001; Cortés, 2002; Cortés et al., 2002; NMFS, 2006; NMFS, 2007). These models are useful in cases such as for *S. lewini* where only catch and relative abundance data are available (Prager, 1994). In fact, these simpler models can sometimes outperform more intricate age-structured models (Ludwig and Walters, 1985; Ludwig et al., 1988).

This study analyzed three forms of the surplus-production model: logistic (Schaefer, 1954), Fox (Fox, 1970) and generalized (Pella and Tomlinson, 1969; Polachek et al., 1993). All three assume density dependence, wherein production increases as individuals are removed to a point (maximum sustainable yield, MSY) at which production begins decreasing. Compensatory, or density-dependent, growth has been suggested in other shark species (Carlson and Baremore, 2005). The population size with the potential to produce MSY is termed N_{MSY}. The logistic model assumes $\mathrm{N}_{\mathrm{MSY}}$ is half of the unfished population size (K). The Fox model assumes N_{MSY} occurs at K/e or approximately 37% of K. $\mathrm{N}_{\mathrm{MSY}}$ in the generalized model is variable, depending on the value of the extra parameter. Model goodness-of-fit was compared through small sample size AIC (AICc), which provides an unbiased order of model choice (Bedrick et al., 1994).

The basic surplus-production model used for this study is:

$$N_{t+1} = N_t + G_t - C_t, \qquad (1)$$

where: N_{t} = the population size at time t;

G_{t} = the population growth or surplus production; and

C_{t} = the catch at time t.

For this study we compare model performance of three production curves using AICc:

Logistic: $$G_t = rN_t(1 - N_t / K), \qquad (2)$$

Fox: $$G_t = rN_t(1 - Ln(N_t) / Ln(K)), \qquad (3)$$

Generalized: $$G_t = rN_t(1 - N_t / K)^p, \qquad (4)$$

where: r = the intrinsic population growth rate;

K = the unfished (virgin) population size; and

p = an additional parameter that allows the curve to vary.

To estimate parameters r and K, the observation error estimator was applied (Hilborn and Walters, 1992). Assuming a lognormal error structure:

$$I_{i,t} = q_i N_t e^{\varepsilon_i} \tag{5}$$

where: $I_{i,t}$ = the abundance index i at time t;

q_i = the parameter that scales the population biomass to that of the index i, also termed the catchability coefficient; and

ε = normally distributed ($N(0,\sigma^2)$) observation error associated with index i.

Equal weight was used for all scenarios except one (INCV uses inverse variance weighting) and the objective function minimized (Prager, 1994; MATLAB, vers. 7.1) was:

$$\sum_i \sum_t [\log(I_{i,t}) - \log(\hat{I}_{i,t})]^2 \tag{6}$$

Punt (1990) found that setting the initial population size equal to K outperforms models where it is estimated separately. For comparison, this study also looked at how some initial depletion (i.e., $N_0 = 0.7K$) would affect the results. Parameter q_i is a constant of proportionality that depends on I and N and was estimated within the function. This method reduces error by reducing the number of parameters to be estimated (Jiao and Chen, 2004).

Sensitivity analysis

Model sensitivity to removal of abundance indices was tested (Table 2.3). Scenario BASE included all available abundance indices recommended by SEDAR 11 (NMFS 2006): NMFS LL SE, PCGN, NCLL, CSFOP, GNOP, and PLLOP. Scenario ALL included BASE indices, GACP, and NMFS LL NE (all available indices). Scenario BASE-NCLL included BASE indices, except NCLL was removed. Scenario INDY included only fishery-independent abundance indices: NMFS LL SE, PCGN, NCLL, and NMFS LL NE. Using the indices in scenario BASE, scenario INCV tests the sensitivity of the model to inverse variance weighting of the abundance indices. Scenario IDEP explores how the results vary with 30% initial depletion ($N_{1981} = 0.7K$).

We also tested sensitivity to incorporating uncertainty in the catch data. Two years of catch data (1982 and 1985) were over twice the magnitude of the third largest catch. In scenario CATCH, those two years are estimated by averaging the reported value of the year before and after. Information about catch composition is not well defined until the observer data start in 1994. Prior to that, the three hammerhead sharks, scalloped (*S. lewini*), great (*S. mokarran*), and smooth (*S. zygaena*), are recorded simply as hammerhead sharks in commercial catch data, but the catch was relatively small. Uncertainty was incorporated separately in recreational catch, commercial landings, and discards in scenario COMP. Proportions for each catch sector for each year (i) were estimated by generating normal random proportions with mean of the observed proportion and standard deviation based on the binomial distribution (Hogg and Craig, 1995):

$$\hat{p}_i \sim N(p_i, \sigma_i^2), \tag{7}$$

$$\sigma_i = \sqrt{\frac{p_i(1-p_i)}{n_i}}, \tag{8}$$

where: p_i = the observed proportion of *S. lewini* for year i; and

n_i = the sample size for year i.

Bootstrap and population projections

Median values and confidence intervals of estimated parameters were produced through the nonparametric bootstrap method (Hilborn and Walters, 1992). Lognormal residuals were randomly sampled with replacement and added to the fitted log abundance indices to produce a new log abundance index. This newly generated index was treated as a new independent sample and applied to the model to generate new parameter estimates. We ran the simulation for 1000 iterations producing probability distributions for each parameter and management reference point. This method is considered better than alternative methods for providing confidence intervals (Haddon, 2001).

The effect of various fishing regimes on population rebuilding was tested using the probability distributions produced through the bootstrap approach. To assess the potential for rebuilding at various fishing levels, Monte Carlo simulations projected the population into the future. These 1000 simulated populations were subjected to 0%, 50%, 100%, and 150% of 2005 catch levels (3,704 individuals).

Results

Model selection

There was not enough information in the data to estimate the third parameter of the generalized model. The Fox model slightly outperformed the logistic model (AICc=172.9 and 174.4, respectively). The parameters estimated in the Fox model were also generally more conservative (i.e., less productive population) than those in the other two models (Table 2.4; Fig. 2.2).

Interannual variability in the indices of relative abundance was high in some cases, resulting in the model having trouble fitting some trends very well (Fig. 2.3). The model best fit the NMFS LL SE index, which has the greatest geographical distribution, and should more closely reflect population abundance than smaller surveys. The model also was influenced by the longest time series, the NCLL survey.

Population status

Though the nominal catch was highest in the early 1980s, the catch relative to population size peaked in the early 1990s (Fig. 2.4). By the late 1990s, fishing pressure was reduced, population decline slowed, and a recovery potentially began. With all combinations of inputs and models investigated, *S. lewini* are currently overfished, i.e., current stock size is below the population size that produces MSY. The population is 21-74% of the size that would produce MSY (Figs. 2.5 and 2.6). Overfishing, or fishing pressure greater than that associated with MSY, most likely occurred in 2005; however, some scenarios indicated that fishing levels were below F_{MSY} in 2005 (Table 2.3).

When the logistic model was applied to the BASE scenario, the population was both overfished and experienced overfishing (Table 2.4). The population size in 2005 was 36% (95% Confidence Interval = 14-75%) of N_{MSY}. Fishing mortality was 102% (45-230%) of F_{MSY}. The estimated depletion was 82% (52-95%). The Fox model lead to very similar conclusions. When the BASE scenario was used, *S. lewini* was overfished and subjected to overfishing. In 2005, the population was 47% (17-83%) of N_{MSY}. Fishing mortality was estimated to be 114% (53-300%) of F_{MSY}. The depletion estimate was similar to that of the logistic model: 83% (69-95%).

Sensitivity analyses

Model sensitivity to NMFS LL NE and GACP relative abundance series in scenario ALL had minimal effect on the conclusions derived from the model (Table 2.3; Fig. 2.6). The model was, however, sensitive to the removal of fishery-dependent abundance indices in scenario INDY. When only fishery-independent abundance indices were used, overfishing was no longer occurring. The population was still overfished, though to a lesser degree. The model was sensitive to the removal of NCLL; results were more pessimistic when it was taken out of the BASE scenario.

When the BASE abundance indices were weighted by the inverse of the variance in scenario INCV, the population status was more pessimistic (Fig. 2.6). The same was true if initial depletion is included (scenario IDEP), though 30% initial depletion had little effect on results. There was little uncertainty in the catch composition in sectors and years with large catches, therefore scenario COMP produced little change in population status. Scenario CATCH, which tested the sensitivity to catch in years 1982 and 1985, showed little change in results when those years of catch data were excluded.

Population projections and alternative catch level evaluation

A Monte Carlo projection method was applied to the BASE scenario using the Fox model (Haddon, 2001). It was used to determine the likelihood of N reaching N_{MSY} with various constant catch levels over different time horizons (Table 2.5; Fig. 2.7). In 94% of the simulated populations with no fishing, N_{MSY} was reached within 10 years. When a constant catch of 1,852 fish (half of the 2005 Catch; $0.5{*}C_{2005}$) was applied, 87% of the populations reached $\mathrm{N}_{\mathrm{MSY}}$ within 10 years. If C_{2005}, or 3,704 fish, were continually removed for 10 years, the simulation study showed a 64% probability of recovery (reaching N_{MSY}). Only 27% of simulated populations subjected to a constant catch of 5,556 fish (150% of C_{2005}) recovered in 10 years (Fig. 2.7).

Discussion

Given the similar performance of the logistic and Fox models and the status of the species, the precautionary principle (Garcia, 1994; Richards et al., 1998) may be a factor in deciding which model to use for management purposes. The precautionary principle is a management strategy that is applied to reduce risk even when scientific information is incomplete (Garcia, 1994). Model selection based on conservative results is suggested if there is no distinguishable difference between two models. In the case of scalloped hammerhead sharks, the Fox model produced the more conservative estimates of MSY and F_{MSY} as a result of estimating a smaller population growth rate. We recommend using the more conservative Fox model for management purposes, although the performance, stock status, and the implications for future management recommendations are similar based on the two models.

In recent years, surplus-production models have been used less frequently in stock assessments. Age-structured models are often thought to be more biologically realistic (Simpfendorfer et al., 2000). The balance between reality and parsimony is a part of model selection for any stock assessment. Though data are not currently available for an age-structured model of *S. lewini*, it would be useful in the future to see how the age structure of the population affects population estimations. Multiple production models were investigated in fitting the scalloped hammerhead shark data, which provided a better understanding of the population dynamics and the fishery status of this species. The analyses using different models resulted in similar conclusions about stock status.

By utilizing a surplus-production model, this study has implicit assumptions that should be addressed as more data become available in the future. First, this model does not distinguish between immature recruits to the fishery and mature adults. The annual variation in proportions of these two groups will have an effect on the overall population growth rate. Second, the indices of abundance are assumed to be proportional to population size and this relationship is assumed to be constant over time. However, fishing practices are likely to have changed over time as a result of the acquisition of better equipment, which could have increased the catchability coefficients. Finally, this model assumes an evenly distributed population. Indices with small geographical coverage are given equal representation to those that cover larger areas. Scalloped hammerhead sharks, however, are most likely not evenly distributed as a result of life-history constraints, such as foraging and reproductive needs.

Species-specific assessments are important for the management of large coastal sharks. The recent SEDAR 11 assessment estimated the stock size of all large coastal sharks in 2004 was 125% of N_{MSY} and fishing mortality was 61% of F_{MSY} (NMFS, 2006). This situation represents the problem discussed at the assessment review, i.e., some highly productive species likely mask the decline of less productive species, such as *S. lewini*. The level of population depletion found in the present study (83%) is similar to that found by Baum et al. (2003), who estimated an 89% decline in the western North Atlantic Ocean population of scalloped hammerhead sharks. When restricting our analysis to the same time frame (1986-2000), the estimated depletion is 85%. Species-specific assessments, such as the one presented here, greatly improved our understanding of this population’s status and provide sound basis for future management.

The decline in catch seems to have steadied this population and given it the opportunity to begin rebuilding. It appears that despite its slow life-history characteristics, recovery of this *S.*

lewini population could occur within a decade if the 2005 catch is maintained or decreased. It is important to note, however, that surplus-production models are often too optimistic in estimating rebuilding times (NMFS, 2006). The results of the latest sandbar shark assessment (NMFS, 2006) may result in reduced quotas for all large coastal sharks in the United States. If implemented, this reduction could decrease the time necessary for the western North Atlantic Ocean population of *S. lewini* to reach N_{MSY}.

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Tables

Table 2.1. Catches of scalloped hammerhead sharks (*Sphyrna lewini*) by year and fishery sector. Blanks indicate missing data.

Year	Recreational	Commercial	Discards	Total
1981	5880	0		5880
1982	48138	1		48139
1983	20962	365		21328
1984	7003	0		7003
1985	44042	0		44042
1986	5321	0		5321
1987	6372	0	1228	7600
1988	4518	2	1674	6194
1989	6191	0	1389	7580
1990	18373	12	1151	19536
1991	8935	4	1221	10160
1992	7325	67	2257	9649
1993	21723	91	516	22330
1994	3886	301	368	4554
1995	3695	1479	567	5741
1996	882	1479	290	2652
1997	3905	1041	938	5884
1998	1083	642	234	1959
1999	545	386	344	1275
2000	6350	68	277	6695
2001	1112	1152	339	2602
2002	6113	1180		7294
2003	2859	2606		5465
2004	803	1351		2154
2005	803	2901		3704

Table 2.2. Commercial Shark Fishery Observer Program (CSFOP), Gillnet Observer Program (GNOP), Pelagic Longline Observer Program (PLLOP), NMFS Longline Southeast (NMFS LL SE), Panama City Gillnet survey (PCGN), North Carolina Longline survey (NCLL), Georgia Coastspan (GACP), and NMFS Longline Northeast (NMFS LL NE) indices of relative abundance of scalloped hammerhead sharks, standardized using the Lo method (Lo et al. 1992). Blanks indicate no data were available.

Year	CSFOP	GNOP	PLLOP	NMFS LL SE	PCGN	NCLL	GACP	NMFS LL NE
1981						1.3294		
1982						0.8164		
1983						1.1737		
1984						1.4382		
1985						0.3443		
1986						0.7187		
1987						0.8861		
1988						1.2227		
1989						0.1538		
1990						0.0489		
1991						0.0761		
1992			2.7356					
1993			1.3780			0.2163		
1994	0.1829	0.9785	0.7449			0.1015		
1995	0.3443	4.2184	1.1620	1.0551				
1996	0.3622		0.2849	0.4044	0.1270	0.2055		0.0600
1997	0.4291		1.0912	0.5672	0.5407			
1998	0.6009	1.1289	1.2011		0.2647	0.1115		0.3860
1999	0.1612	0.1582	0.4488	0.9469	0.7424	0.9865		
2000	0.0128	1.1511	0.6127	1.3220	1.0000	0.2772	0.3580	
2001	0.4212	0.3648	0.8864	1.2439	0.9119	0.1412	0.6860	1.9540
2002	0.8254	0.2744	0.4544	1.3472	0.8186	0.1472	2.3810	
2003	1.0000	0.2403	0.7076	1.5295	0.5963	0.1868	0.4560	
2004	0.7731	0.7552	0.4581	0.5839	0.4358	0.2163	1.2650	1.5990
2005	0.4521	0.7302	0.5065		0.4586	0.3915	0.8550	

Table 2.3. Results of logistic and Fox surplus-production models applied to eight scenarios. BASE includes the CSFOP, GNOP, PLLOP, NMFS LLSE, PCGN, and NCLL relative abundance indices; ALL includes all available abundance indices; INDY includes only fishery-independent surveys; INCV uses inverse variance weighting; IDEP sets N_{1981} equal to 0.7K; BASE-NCLL includes all BASE indices except NCLL; CATCH estimates catches of 1982 and 1985 by averaging the year before and after; COMP incorporates uncertainty in the different catch sectors. Virgin population size, K, is in hundred thousand fish; MSY and N_{MSY} are maximum sustainable yield and population size associate with MSY in thousand fish; depletion, fishing rate in 2005 relative to F_{MSY} (F_{2005}/F_{MSY}), and abundance in 2005 relative to N_{MSY} (N_{2005}/N_{MSY}) are percentages.

	BASE	ALL	INDY	INCV	IDEP	BASE-NCLL	CATCH	COMP
Logistic Results								
r	0.30	0.37	0.39	0.52	0.32	0.69	0.70	0.30
$K\ (\times 10^5)$	1.3	1.2	1.2	1.0	1.5	1.0	0.49	1.3
$MSY\ (\times 10^3)$	10	11	12	13	12	16	9	10
F_{MSY}	0.15	0.18	0.20	0.26	0.16	0.35	0.35	0.15
$N_{MSY}\ (\times 10^3)$	67	61	59	52	75	47	25	67
Depletion (%)	82	81	71	89	86	90	80	82
F_{2005}/F_{MSY} *(%)*	102	88	55	132	108	116	107	103
N_{2005}/N_{MSY} *(%)*	36	38	58	21	28	19	39	35
Fox Results								
r	0.12	0.13	0.18	0.16	0.11	0.20	0.18	0.12
$K\ (\times 10^5)$	1.6	1.5	1.4	1.4	2	1.3	0.88	1.6
$MSY\ (\times 10^3)$	6.9	7.4	8.8	8.3	8	9	6	6.9
F_{MSY}	0.12	0.13	0.18	0.16	0.11	0.2	0.18	0.12
$N_{MSY}\ (\times 10^3)$	59	57	50	51	73	46	32	59
Depletion (%)	83	83	73	91	87	92	78	83
F_{2005}/F_{MSY} *(%)*	114	109	57	178	135	183	105	115
N_{2005}/N_{MSY} *(%)*	47	45	74	25	34	21	61	47

Table 2.4. Biological Reference Points estimated using both the logistic and Fox models. BASE was used to estimate intrinsic population growth rate (*r*), virgin population size (*K*) in hundred thousand fish, Maximum Sustainable Yield (MSY) in thousands of fish, the fishing mortality rate associated with MSY (F_{MSY}), the population size that produces MSY (N_{MSY}) in thousands of fish, percentage of depletion, percentage of fishing mortality in 2005 relative to F_{MSY} ($F_{2005}/F_{\mathrm{MSY}}$), and percentage of population size in 2005 relative to N_{MSY} ($N_{2005}/N_{\mathrm{MSY}}$). Ninety-five percent confidence intervals are shown in parentheses.

Reference Point	Logistic	Fox
r	0.30 (0.11 - 0.94)	0.12 (0.05 - 0.30)
K ($\times 10^5$)	1.3 (0.78 – 2.0)	1.6 (1.1 - 2.1)
MSY ($\times 10^3$)	10 (5.6 – 18)	6.9 (4.0 - 12)
F_{MSY}	0.15 (0.06 - 0.47)	0.12 (0.05 - 0.30)
N_{MSY} ($\times 10^3$)	67 (39 - 98)	59 (39 - 78)
Depletion (%)	82 (52 - 95)	83 (69 - 95)
$F_{2005}/F_{\mathrm{MSY}}$ (%)	102 (45 - 230)	114 (53 - 300)
$N_{2005}/N_{\mathrm{MSY}}$ (%)	36 (14 - 75)	47 (17 - 83)

Table 2.5. Probability of populations rebuilding (final population size greater than N_{MSY}) in 10, 20, and 30 years under constant catch scenarios (C_{2005} = 3,704 fish) using the BASE scenario of the Fox surplus production model.

	No Catch	50% C_{2005}	100% C_{2005}	150% C_{2005}
10 Years	94	87	64	27
20 Years	98	96	84	53
30 Years	99	97	90	61

Figures

Figure 2.1. Catches of scalloped hammerhead sharks, 1982-2005.

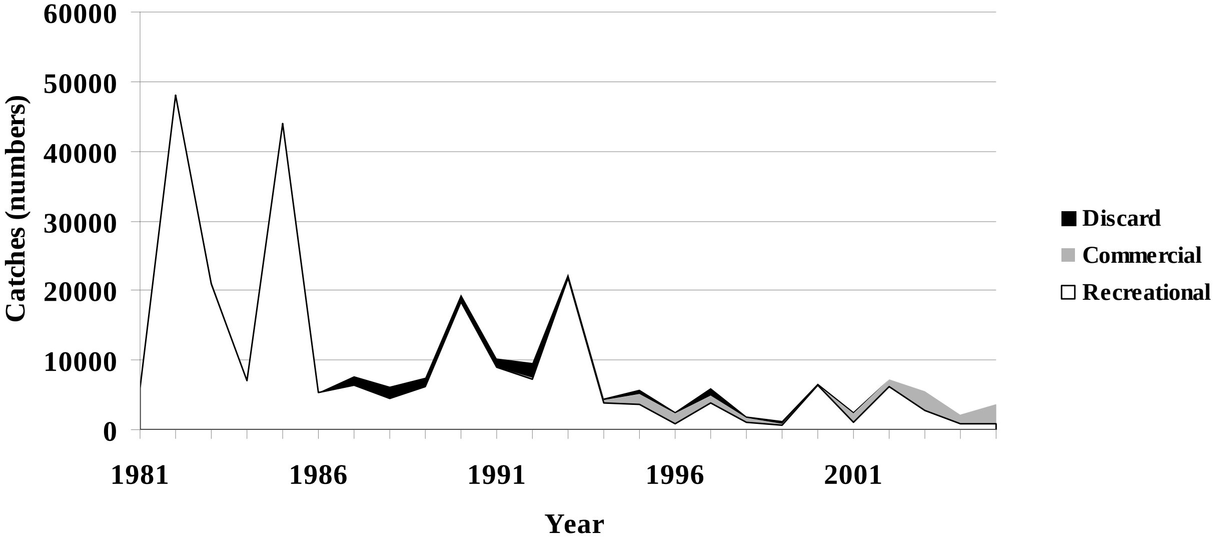


Figure 2.2. Surplus production curves obtained from the model. Surplus production and abundance are in numbers. N_{MSY} values are indicated with the vertical lines

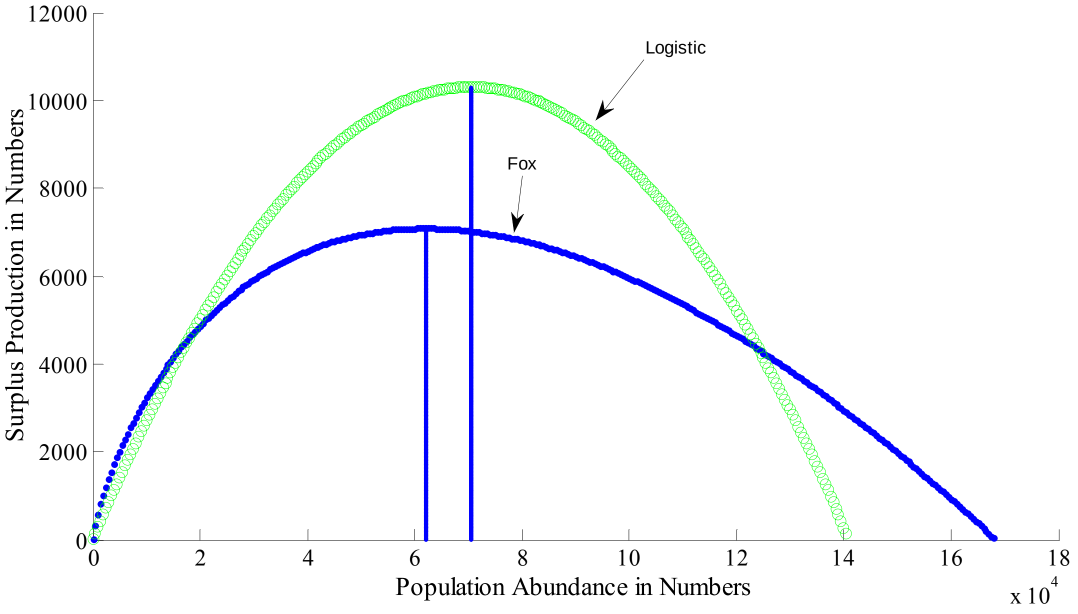
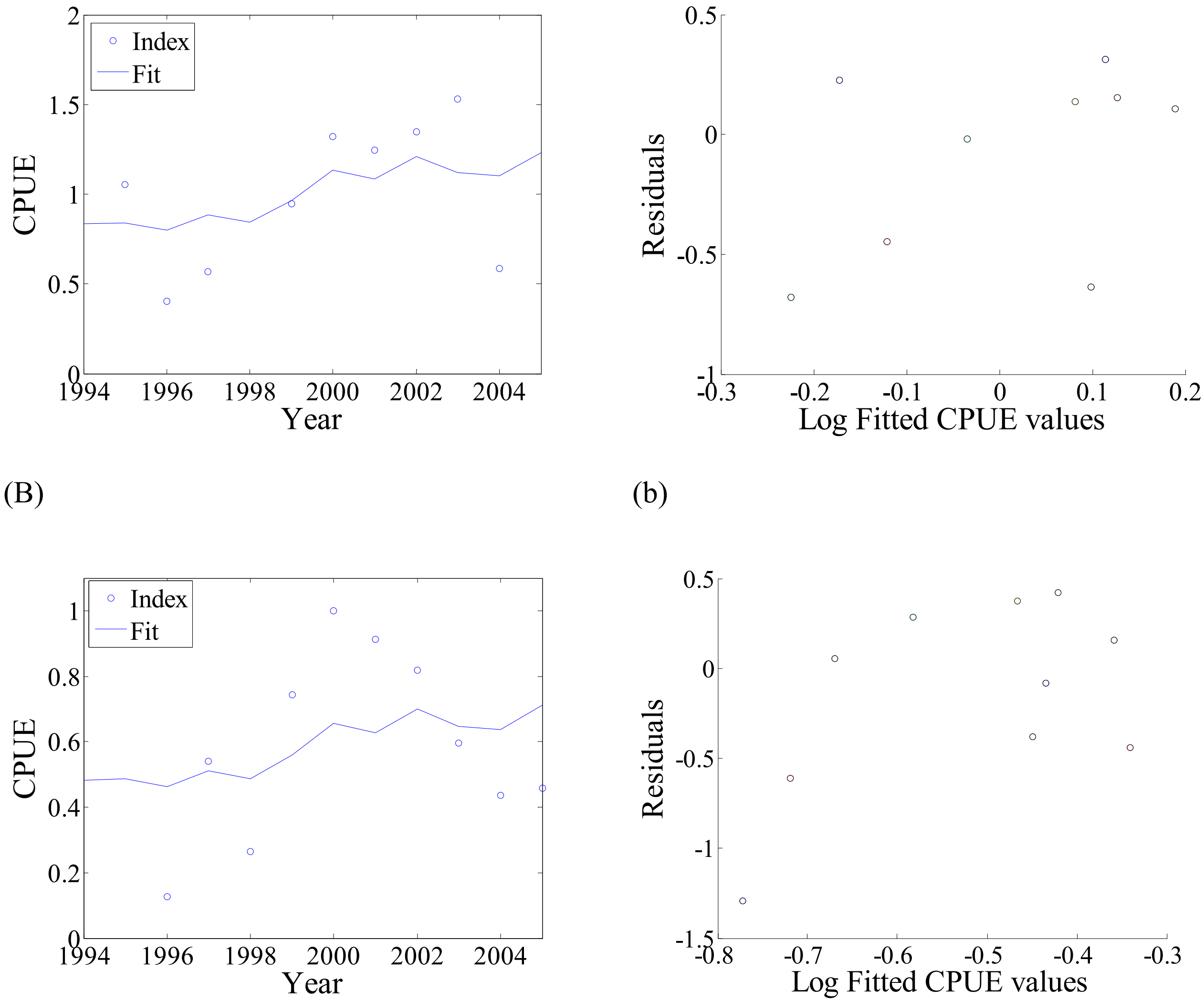


Figure 2.3. Fox model fit for (A) NMFS LL SE, (B) PCGN, (C) NCLL, (D) CSFOP, (E) GNOP, and (F) PLLOP relative abundance indices based on the BASE scenario (left panels). The corresponding residual distributions are shown in the right panels.

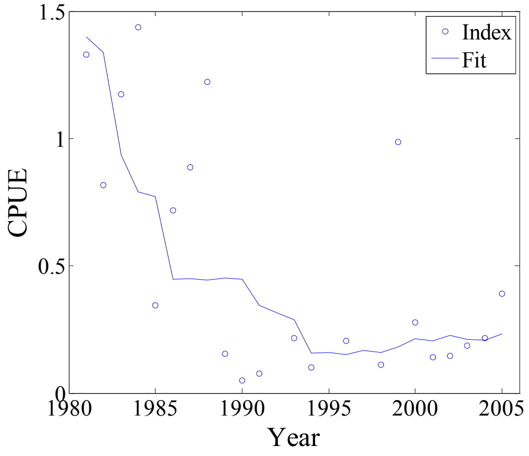

(A)

(a)

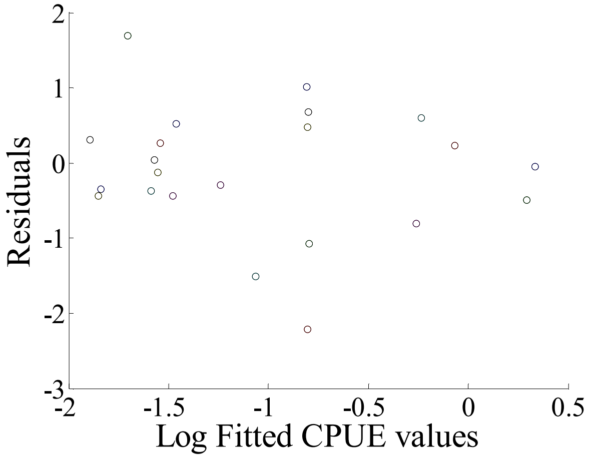
(B)

(b)

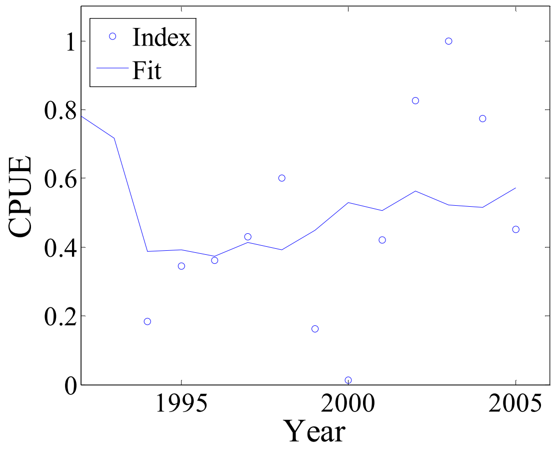
(C)


1.5
1
0.5
0
CPUE
1980
1985
1990
1995
2000
2005
Year
Index
Fit

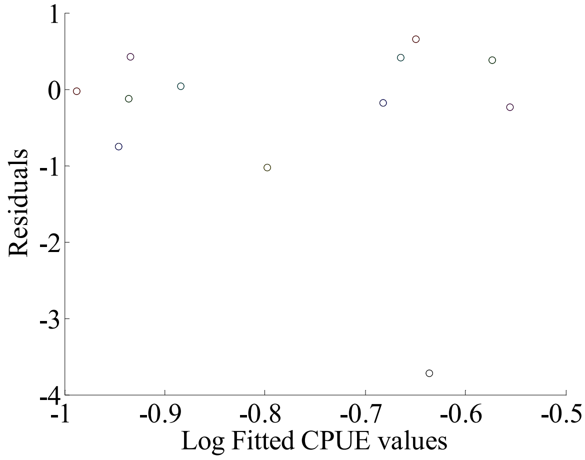
(c)


2
1
0
-1
-2
-3
Residuals
-2
-1.5
-1
-0.5
0
0.5
Log Fitted CPUE values

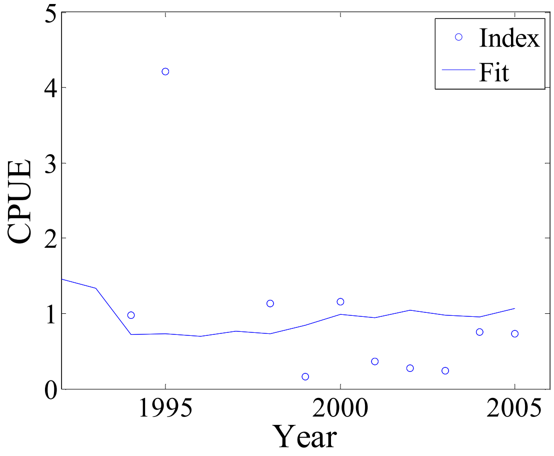
(D)


1
0.8
0.6
0.4
0.2
0
CPUE
1995
2000
2005
Year
Index
Fit

(d)

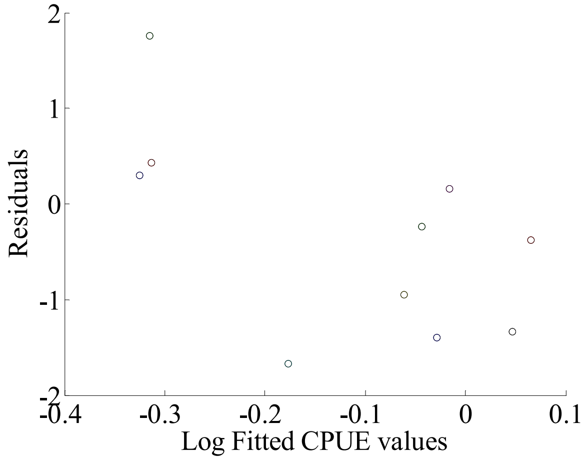

1
0
-1
-2
-3
-4
Residuals
-1
-0.9
-0.8
-0.7
-0.6
-0.5
Log Fitted CPUE values

(E)



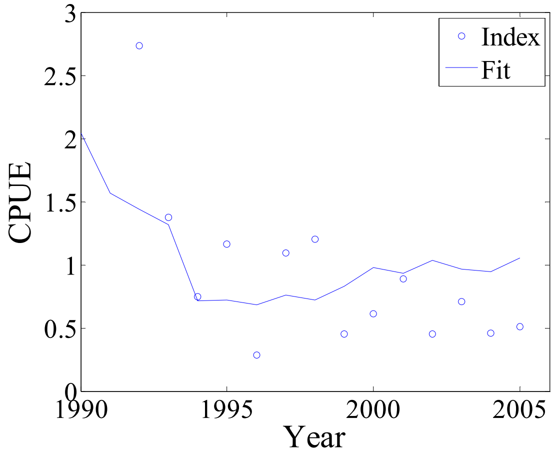
5
4
3
2
1
0
CPUE
1995
2000
2005
Year
Index
Fit

(e)



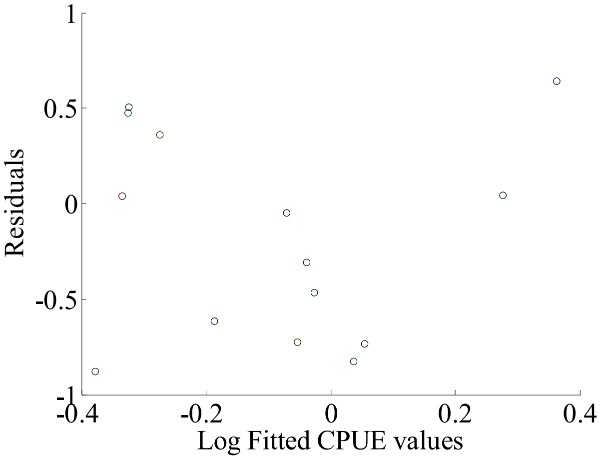
2
1
0
-1
-2
Residuals
-0.4
-0.3
-0.2
-0.1
0
0.1
Log Fitted CPUE values

(F)



3
2.5
2
1.5
1
0.5
0
CPUE
1990
1995
2000
2005
Year
Index
Fit

(f)



1
0.5
0
-0.5
-1
Residuals
-0.4
-0.2
0
0.2
0.4
Log Fitted CPUE values

Figure 2.4. Estimated fishing mortality rate of scalloped hammerhead sharks for 1981-2005 using (A) logistic and (B) Fox models. The solid line represents F_{MSY}.

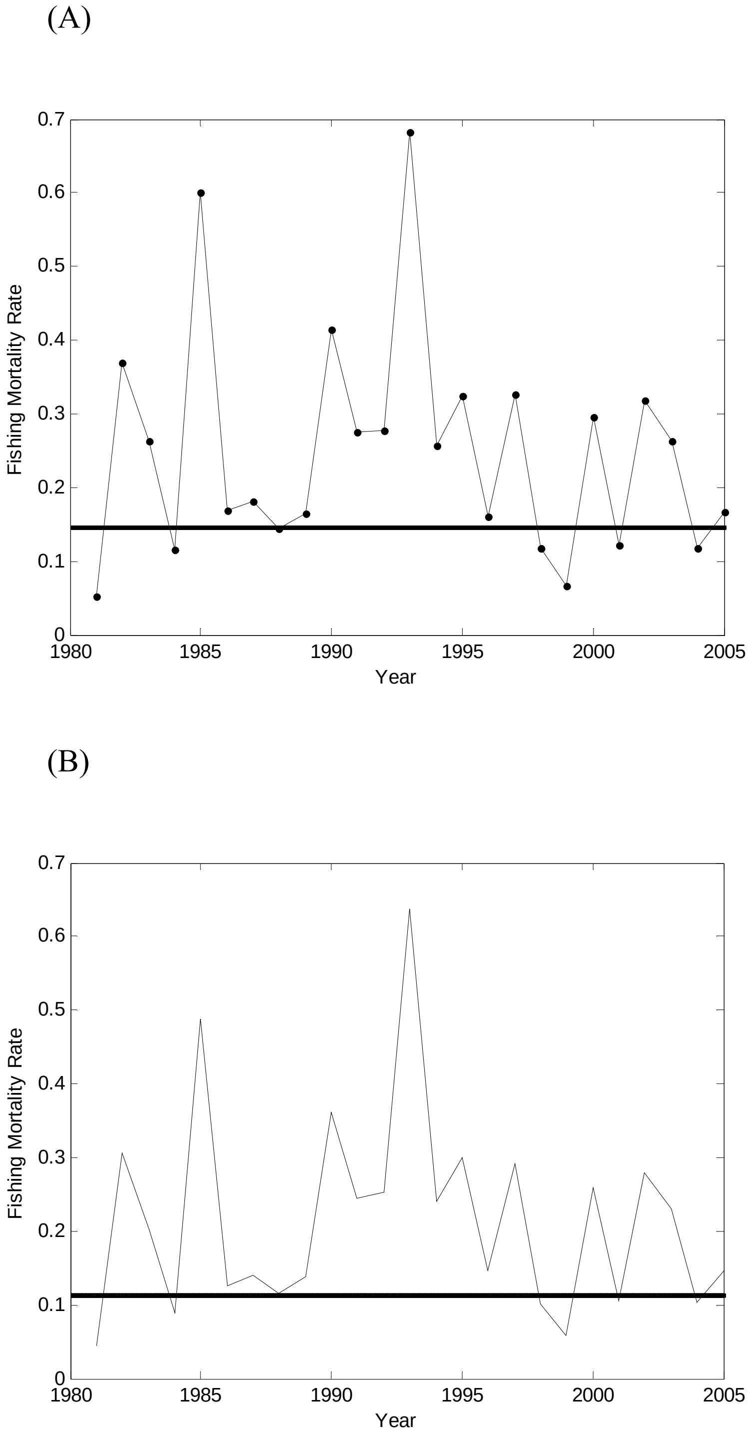


Figure 2.5. Abundance estimates between 1981 and 2005 in scenario BASE when Fox (line) and logistic (dotted line) models were used. The solid line represents $N_{MSY.}$

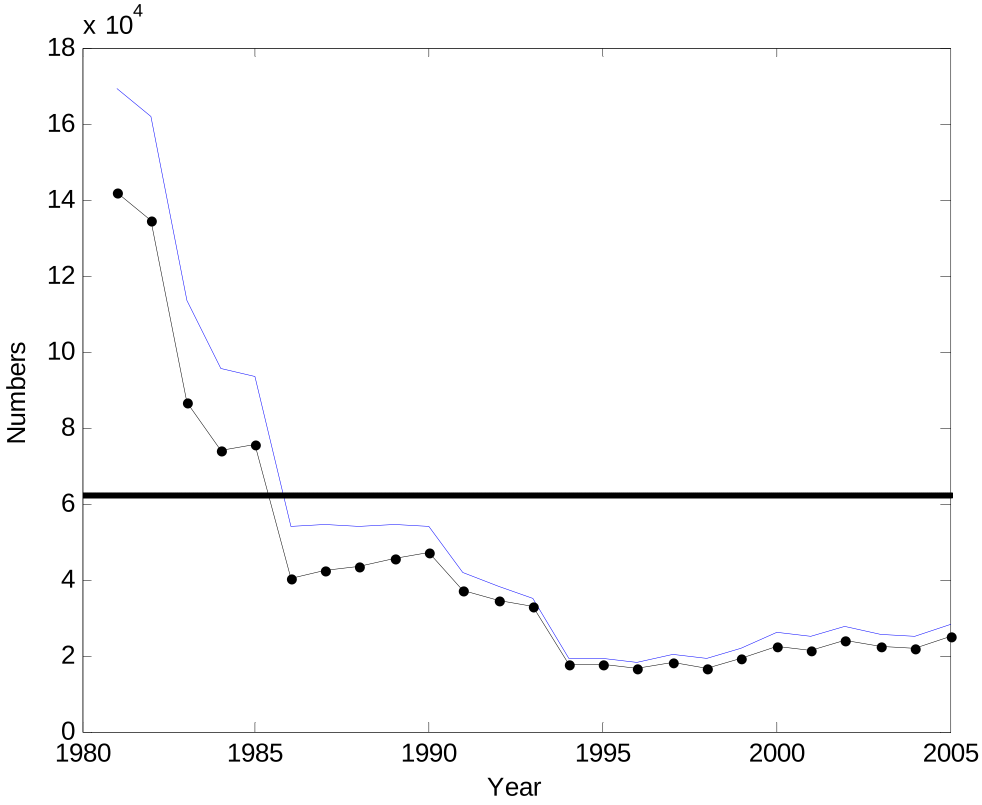
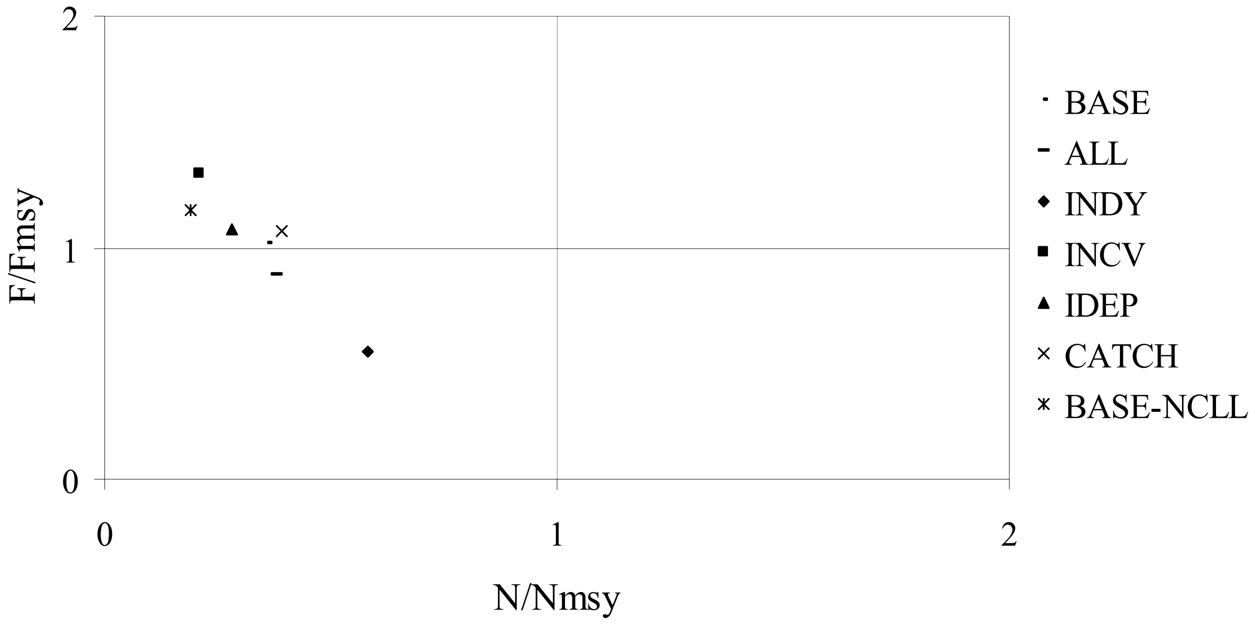


Figure 2.6. Phase plot for scalloped hammerhead sharks showed the population size in 2005 relative to N_{MSY} and fishing mortality in 2005 relative to F_{MSY} when the (A) logistic model and (B) Fox model were applied. BASE included CSFOP, GNOP, PLLOP, NMFS LL SE, PCGN, and NCLL; ALL included all available indices; INDY included the fishery-independent abundance indices; INCV weighted indices by inverse variance. IDEP included 25% initial depletion; CATCH included 1982 and 1985 catch estimates (averaged years before and after); BASE-NCLL was the BASE model with NCLL removed

(A)



(B)

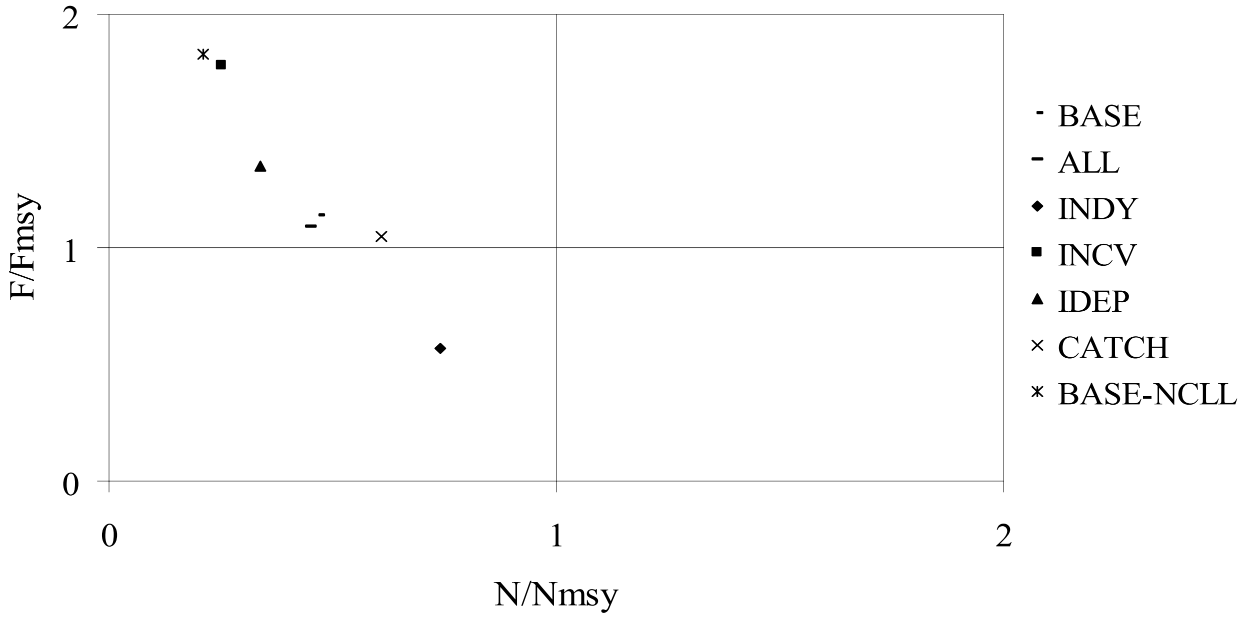
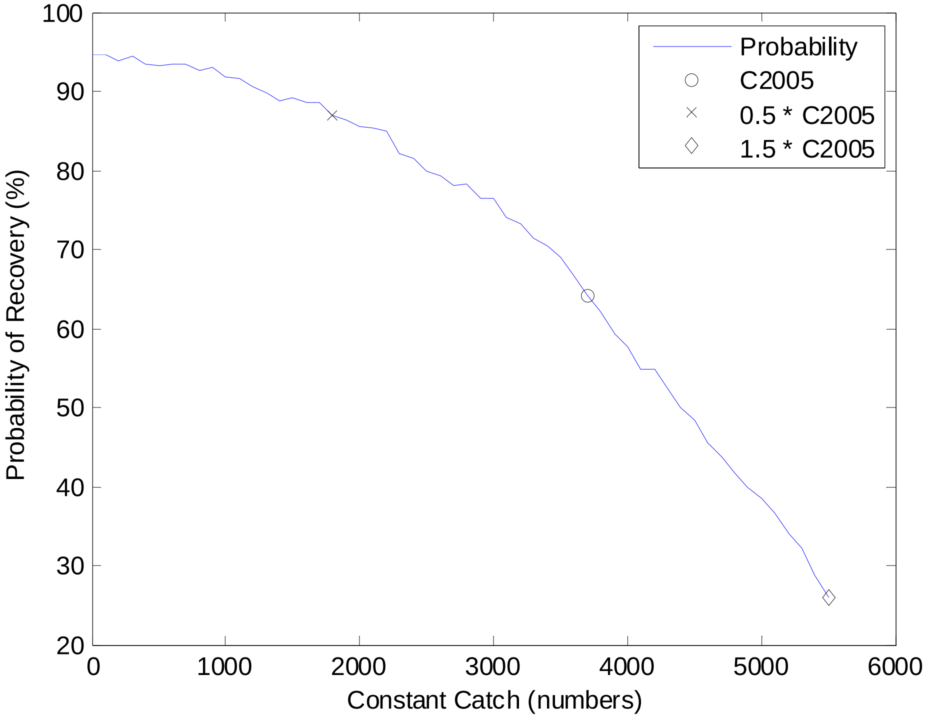


Figure 2.7. Probability of recovery in 10 years under three constant catch scenarios relative to the 2005 catch level (3,704 fish) obtained through Monte Carlo simulations.



Chapter 3 – Population evaluation of great (*Sphyrna mokarran*) and smooth (*S. zygaena*) hammerhead sharks in the western North Atlantic Ocean and Gulf of Mexico using production models.

Abstract

The World Conservation Union (IUCN) has listed great hammerhead sharks (*Sphyrna mokarran*) as Endangered and smooth hammerhead sharks (*S. zygaena*) as Near Threatened based on recent reports of severe population declines, but noted the lack of information available for both species. This study assessed the status of both species in the western North Atlantic Ocean and Gulf of Mexico using three production models with combined catch (recreational, commercial, and pelagic discards) and relative abundance data for both species. Sensitivity analyses were used to test the influence of the relative abundance indices and catch assumptions on assessment results. Few data exist for these species, and identification problems exist in those that are available, hence this study should be considered preliminary. However, abundances of both species in 2005 were estimated to be less than 10% of unfished size. We found that both species were most likely overfished: in 2005 great hammerhead and smooth hammerhead shark stocks were 11% and 24%, respectively, of the size necessary to provide maximum sustainable yield (MSY) according to results of the Fox model. Overfishing, or exploitation levels greater than those associated with MSY, may have occurred in 2005 for both great hammerhead and smooth hammerhead sharks. Monte Carlo simulation showed that with no removals, great hammerhead and smooth hammerhead shark populations had a 56% and 64% probability, respectively, of recovery within 30 years.

Introduction

Compared to most teleosts, sharks are slow-growing, late-maturing, and long-lived: life-history traits that are often associated with high risk of overexploitation (Holden, 1973; Manire and Gruber, 1990; Musick et al., 2000). Hammerhead sharks, specifically, have reportedly experienced a rapid decline in the past 25 years. Myers et al. (2007) estimated 99% depletion for smooth hammerhead sharks (*Sphyrna zygaena*) from a University of North Carolina bottom longline survey. Based on similar analyses of indices of relative abundance and declining catches, the World Conservation Union (IUCN) listed great hammerhead sharks (*Sphyrna mokarran*) as Endangered, and smooth hammerhead sharks as Near Threatened (IUCN, 2007), but recognized the lack of information available for both species.

Great hammerhead sharks are globally distributed and found near tropical continental shelves (Compagno, 1984). Physically, it is the largest species within the *Sphyrna* genus. No estimates of size at maturity exist for our study area, but in Australia, males mature at a length of 2.25 m and females at 2.10 m (Stevens and Lyle, 1989). The species is slow-growing and only reproduces every two years, giving birth to 13-42 live pups after an eleven-month gestation period (Stevens and Lyle, 1989; Smith, 1997). Unlike scalloped hammerhead sharks, great hammerhead sharks are not typically found in schools.

Smooth hammerhead sharks are typically found offshore in warm-temperate waters worldwide, moving north in the summer and toward the equator in the winter (Compagno, 1984; Compagno, 1998). On the eastern coast of North America, these sharks range from Nova Scotia in the summer to Florida during the winter, often migrating as a school (Castro, 1983). This species has been less studied than the great hammerhead shark, but estimates of maturity are 2.1-2.5 m for males and 2.7 m for females that give birth to 30-40 live pups every other year (Muus and Nielsen, 1999). These sharks are much less common in the catch data and are thought to be less abundant than scalloped or great hammerhead sharks in the study area.

Previous assessments of hammerhead sharks were based on trends in individual catch rates from the pelagic longline logbook program (PLL; Baum et al., 2003) and the University of North Carolina longline survey (NCLL; Myers et al., 2007). However, sharks are not targeted in the pelagic longline fishery, and pelagic longlines do not provide good samples of coastal sharks (Burgess et al., 2005). The small sample size and little geographic coverage make it difficult to draw inferences from the NCLL survey. Indeed, the NCLL survey referenced in Myers et al. (2007) only collected 7 smooth hammerhead sharks during 1972-2006 (Schwartz et al. 2007). Detailed population dynamics analyses are thus urgently needed for these species, whose status is of public and governmental concern.

We synthesized available indices of relative abundance and catch records of these two species for the western North Atlantic Ocean for the first time. We assessed the status of great hammerhead and smooth hammerhead sharks based on three surplus-production model forms: Schaefer's (1954), Fox's (1970), and Pella and Tomlinson's (1969). National Marine Fisheries Service (NMFS) catch data (Appendix 2A-B) and available indices of abundance (Appendix 3A-B) were used to estimate population dynamics. Thus, in addition to estimating depletion (2005 population size in numbers/1982 population size in numbers), biological reference points such as maximum sustainable yield (MSY), the current population size (N_{CURR}) relative to the size that produces MSY (N_{MSY}), and the current exploitation rate (F_{CURR}) relative to the rate associated with MSY (F_{MSY}) were estimated.

Fishery managers are required by the Magnuson-Stevens Fishery Conservation and Management Act to prevent or end overfishing (i.e., $F_{CURR} \leq F_{MSY}$) and rebuild overfished fish stocks (i.e., $N_{CURR} \geq N_{MSY}$; NMFS, 2006). Parameter estimates were further used to project the abundance of simulated populations subjected to various fishing pressures (Haddon, 2001), which helps fishery managers understand stock rebuilding probabilities under different fishing regimes.

Materials and methods

Catch data

Until recently, the greatest proportion of the catch was attributed to the recreational sector (Fig. 3.1). Recreational catch data were collected starting in 1982 through three surveys: the NMFS Marine Recreational Fishery Statistics Survey (MRFSS), the NMFS Headboat Survey, and Texas Parks and Wildlife Department's Marine Sport-Harvest Monitoring Program. Given that these data are in numbers and provide no reliable estimates of average weight, the catch could not be converted to biomass; therefore, the assessments were conducted in numbers. For great hammerhead sharks, the catch for 1983 was over twice that of the second largest catch in any year; hence it was estimated as an average of 1982 and 1984, although this assumption was tested in scenario 1983. There was a similar large catch in 1983 and no catch of smooth hammerhead sharks in 1984, so catches for 1982 and 1985 were averaged and used for 1982 and 1984, though recorded values were used in a sensitivity analysis.

NMFS also collects commercial catch data in weight from the Pelagic Dealer Compliance program, which covers the southeast region, and the general canvass program, which covers both southeastern and northeastern states. Using average weight data—obtained from back-transforming lengths into weights through published length-weight relationships—from the

Commercial Bottom Longline directed Shark Fishery Observer Program (CSFOP), catches were converted to numbers.

The pelagic longline fishery targets tunas and swordfishes, but some sharks, including hammerheads, are caught and discarded at sea. To account for these individuals, discard estimates obtained from the Pelagic Longline Observer Program (PLLOP) and dealer weigh-out data were used. Discard estimates for hammerhead sharks were not available prior to 1987 and hammerhead sharks no longer appeared after 2001, thus estimates for 1982-1986 and 2002-2005 were based on the average discards in 1987-1992 and 1993-2001, respectively (NMFS, 2006). The years used to estimate discards were split based on the regulatory action implemented in 1993 (NMFS, 2006). Model sensitivity to the inclusion of these estimates was tested in the sensitivity analysis NoDC.

Indices of relative abundance

Two indices of relative abundance (Figs. 3.2A-C) were available for great hammerhead sharks (Appendix 3A), one was from the CSFOP (Cortés et al., 2005), the other, from a fishery-independent survey conducted by NMFS in the Gulf of Mexico and western North Atlantic Ocean (NMFS LL; Ingram et al., 2005). Annual variation of the fishery-dependent index, CSFOP, includes changes in fishing behavior, selectivity, gear modifications, and geographic coverage. Variation in the fishery-dependent index could be attributed to fisher behavior and not necessarily linked to population abundance (Hilborn and Walters, 1992). The fishery-independent survey, NMFS LL, was assumed to better represent changes in abundance given that catchability is thought to be consistent from year to year (NMFS, 2006). Therefore NMFS LL was used to estimate parameters used in population projections. Sensitivity scenario CSFOP used the fishery-dependent CSFOP catch-per-unit-effort (CPUE) data only.

Only one index of relative abundance (Appendix 3B) was available for smooth hammerhead sharks. This species rarely occurs throughout the majority of United States waters. The only CPUE information available with a sufficient sample size was collected in the Pelagic Longline Logbooks (PLL; Fig. 3.2D).

Much of the variance in CPUE data can be attributed to factors other than annual changes in abundance (Hilborn and Walters, 1992). To remove some of that variance, a technique developed by Lo et al. (1992) was applied to each index. Significant factors other than year (e.g. depth, water temperature, hook type) were identified in the proportion of hauls with at least one hammerhead shark. Separately, significant factors that affect the CPUE of those non-zero hauls were identified. Standardized indices were calculated as the product of the year effect least squares means from the two components. The most recent NMFS shark stock assessments used this method to standardize the abundance indices (NMFS, 2006; 2007).

Assessment models

As is common with shark stock assessments, available data only allowed the use of surplus-production or age-aggregated models (Babcock and Pikitch, 2001; Cortés, 2002; Cortés et al., 2002; NMFS, 2006; 2007). These models are commonly used when only catch data and indices of relative abundance are available (Prager, 1994). Additionally, these models should be considered in any assessment as they may outperform more complex models by estimating fewer parameters, thus minimizing uncertainty associated with each parameter (Ludwig and Walters, 1985; Ludwig et al., 1988; Prager, 1994). Three production curves (Fig. 3.3) were fit to the data: Schaefer's (1954), Fox's (1970), and Pella-Tomlinson's (1969). Model performance was compared using Akaike's information criterion for small sample sizes (AICc; Akaike, 1974; Bedrick et al., 1994). To reduce error in the model, only two necessary parameters were estimated: virgin population size or carrying capacity, K, and the intrinsic population growth rate, r. A shaping parameter, p, is estimated additionally in the Pella-Tomlinson model. To conserve statistical power with the paucity of data, several parameters often estimated in surplus-production models were not estimated here. Punt (1990) found that surplus-production models where initial population size was set equal to K outperformed those where initial population size was estimated separately. The catchability coefficient, q, was estimated based on r and K (Jiao and Chen, 2004).

Surplus-production models treat the population as a single unit that changes over time. All recruitment, growth, and natural mortality are included in the population's surplus production. The basic surplus-production model used for this study is:

$$N_{t+1} = N_t + G_t - C_t, \tag{1}$$

where: N_t = the population size;

G_t = the population growth or surplus production; and

C_t = the catch.

Three production curves were considered:

Logistic: $$G_t = rN_t(1 - N_t / K), \tag{2}$$

Fox: $$G_t = rN_t(1 - Ln(N_t) / Ln(K)), \tag{3}$$

Pella-Tomlinson: $$G_t = rN_t(1 - N_t / K)^p, \tag{4}$$

where: r = the intrinsic population growth rate;

K = the unfished (virgin) population size or carrying capacity; and

p = an additional parameter in the Pella-Tomlinson model that allows the shape of the production curve to vary.

To estimate parameters r and K, the observation-error estimator was applied (Hilborn and Walters, 1992; Prager, 1994). We assumed a lognormal error structure for the observation equation:

$$I_{i,t} = q_i N_t e^{\varepsilon_i} \tag{5}$$

where: $I_{i,t}$ = the abundance index i at time t;

q_i = the parameter that scales the population biomass to that of the index i, also termed the catchability coefficient; and

ε = normally distributed ($N(0, \sigma^2)$) observation error associated with index i.

The objective function minimized (MATLAB, version 7.1) was:

$$\sum_i \sum_t [\log(I_{i,t}) - \log(\hat{I}_{i,t})]^2 \tag{6}$$

Sensitivity analysis

The influence of assumptions on initial depletion, catches, indices of relative abundance, and discard statistics on the assessment was tested through sensitivity analyses. For great hammerhead sharks, the first three scenarios assumed initial population size was equal to K (Punt, 1990), catch for 1983 was estimated based on the average of 1982 and 1984, and missing discards were estimated as described earlier. Scenario NMFS LL used only the relative abundance index of the fishery-independent survey, and was considered the base scenario and used for population projections. This index was assumed to better represent changes in abundance because it comes from a fishery-independent survey, and was not affected by changes in fisher behavior (e.g., in response to regulatory changes throughout the 1990s, distribution of effort, or technology changes). Scenario CSFOP included only the fishery-dependent index and scenario BOTH used the two indices of relative abundance (NMFS LL and CSFOP). Scenario

IDEP used the NMFS LL index and assumed 25% depletion in 1982. Scenario 1983 used the catch reported for 1983, instead of the average catch used in the other scenarios. Although catch data start in 1982, the NMFS LL index does not begin until 1995; scenario 1995 ignored catch data prior to 1995 to test the effect of catches in 1982-1994. Scenario NoDC only included discard estimates available, i.e., it did not include estimates for missing years.

There were fewer sensitivity analyses for smooth hammerhead sharks, for which there was only one relative abundance index. Scenario PLL assumed initial population size was equal to K (Punt, 1990). Catches for 1983 and 1984, an extremely high and a missing value, respectively, were estimated based on the average of 1982 and 1985 catches. Missing pelagic discard data were estimated. In scenario IDEP, initial depletion was estimated to be 25%. Scenario 1983-84 used the catch data reported for those years. Scenario 1992 disregarded catch data prior to the start of the PLL index. Years of missing discard data were ignored in scenario NoDC.

Bootstrap and population projections

Using nonparametric bootstrap methods, confidence intervals were estimated for parameters and associated management reference points, such as MSY (Hilborn and Walters, 1992; Haddon, 2001). In this method, lognormal residuals were randomly sampled with replacement. A new index was generated by adding these residuals to the fitted log abundance indices to produce a new log abundance index. New parameters were estimated using this simulated index. After 5000 iterations, a probability distribution was produced for each of the parameters. Haddon (2001) suggests that this method is superior to alternative methods for providing confidence intervals.

By randomly selecting parameters from the distributions produced through the bootstrap approach, a Monte Carlo simulation was used to assess the potential for stock rebuilding ($N > N_{MSY}$) at various fishing levels by projecting the population 30 years into the future 5000 times. The Fox model was used for the projections based on model comparisons.

Results

Population status

The fit to the NMFS LL CPUE series indicated a decline in the great hammerhead shark stock between 1982 and 2005, but fitting the CSFOP series individually or in addition to the NMFS LL series changed model results drastically (Table 3.1; Fig. 3.2A-C). The fit to the PLL series also indicated a dramatic decline in the smooth hammerhead shark stock (Fig. 3.2-D). The AICc values indicated that the Schaefer (22.87) and Fox (22.17) models performed similarly for great hammerhead sharks in the NMFS LL scenario, and estimates of current population status were similar (Table 3.1). However, adding the shape parameter of the Pella-Tomlinson model resulted in a higher AICc value (29.96), or a poorer fit. The Schaefer and Fox models provided similar estimates of surplus production (Fig. 3.3A).

Based on the NMFS LL scenario of the Schaefer and Fox models, great hammerhead sharks were depleted by 92% or 96%, respectively, between 1982 and 2005. Fishing levels were highly variable by year, but in 2005 fishing mortality was 130% or 220% of F_{MSY}, and the population size in 2005 was 15% or 11% of N_{MSY} according to the Schaefer and Fox models, respectively. In most scenarios that used the NMFS LL series only, great hammerhead sharks were overfished, depleted, and experienced overfishing in 2005 (Tables 3.1). Overfishing has occurred since the early 1980s (Fig. 3.4A), especially from the recreational fishery, and has depleted the population. Catches fell in the late 1990s as the fishery was subjected to stricter regulations. These reductions in catches slowed the population decline (Fig. 3.5A).

The model was highly sensitive to the indices of relative abundance included. When CSFOP was included (CSFOP and BOTH scenarios), the results were in stark contrast to those of the NMFS LL scenario (Table 3.1). However, population growth rates estimated in the NMFS LL (fishery-independent) scenario were much closer to published estimates based on demographic analyses of similar species (Cortés, 2002), which supports our choice of this scenario as the baseline and to conduct population projections. Moreover, the CSFOP and BOTH scenarios resulted in highly skewed confidence intervals.

Including initial depletion did not affect the estimated population growth rate, but increased the value of virgin population size, making depletion estimates slightly more severe (96%). Using the actual catch value for 1983 had little effect on results. Starting the model in 1995 increased the estimate of r, drastically reduced the estimate of K, and provided a much less pessimistic status of great hammerhead sharks (57% depletion). Finally, removing discard estimates had little effect on results. Overall, the sensitivity scenarios showed that the baseline model was largely insensitive to changes in assumptions, except those for the early catch years. However, the results changed drastically when the CSFOP series was used (CSFOP and BOTH scenarios), indicating that this series drives the model.

The fit to the PLL series indicated a decline in the smooth hammerhead stock (Fig. 3.2D). For smooth hammerhead sharks, the Fox (AICc = 6.34) and logistic (AICc = 6.51) models also provided better fits than the Pella-Tomlinson model (AICc = 10.80). Additionally, the Fox model was the most conservative, as it estimated the lowest level of surplus production (Fig.

3.3B). The Schaefer model estimated the most surplus production over nearly all population sizes. The estimated population growth rate for smooth hammerhead sharks was lower than that for great hammerhead sharks

The fishing mortality in 2005 was 150% of F_{MSY} and the population in 2005 was 19% or 24% of N_{MSY} and thus overfished according to the Schaefer and Fox models, respecitvely (Table 3.2). All three models estimated similar fishing levels (Fig. 3.4B), and had similar population estimates after the start of the PLL series in 1992 (Fig. 3.5B). This population experienced 91% depletion between 1982 and 2005 (Table 3.2). If the reported catch (26 individuals with no discards) is accurate, overfishing did not occur in 2005 (NoDC scenario), but overfishing occurred when estimated discards were included (PLL scenario). Including estimated pelagic discards greatly affected estimates of current fishing mortality, but not those of other parameters, except MSY (Table 3.2).

As was the case for great hammerhead sharks, most sensitivity analyses showed little change with respect to the base model for smooth hammerhead sharks. Initial depletion changed estimates of K, resulting in an increased depletion value. Including reported catches for 1983 and 1984 had little effect on results. Starting the model in 1992 provided a less pessimistic picture of population status, and overfishing did not occur in 2005. Excluding discard estimates also resulted in overfishing not occurring in 2005, but the population became slightly more overfished.

Population projections

Great hammerhead sharks had a 24% probability of recovery within 10 years when the 2005 catch level, 1319 individuals, was maintained (Table 3.3; Fig. 3.6A). Given 30 years, 40%

of simulated populations recovered. With no individuals removed from the population, great hammerhead sharks had a 27% and 56% probability of recovery in 10 and 30 years, respectively. For smooth hammerhead sharks, even when fishing ceased, only 11% of populations recovered within 10 years and 64% recovered within 30 years (Table 3.3; Fig. 3.6B). When fishing continued at the estimated 2005 level, populations had a 47% probability of recovery within 30 years.

Discussion

Results of these assessments are important to fishery managers because they provide the first comprehensive stock assessment for these two species thought to have experienced declines. However, there are two main data deficiencies that add uncertainty to the assessments: questionable historic catch data and lack of indices of relative abundance prior to 1992 in the case of smooth hammerhead sharks, and 1994 for great hammerhead sharks. Moreover, similar likelihoods make it difficult for the model to discern between a large population with low growth rate and a small population with higher growth rate, making biological reference points estimates less certain (Prager, 1994).

The magnitude of the catches varied widely between 1982 and 2005 (Appendix 2A-B). The largest catches for both species were over two orders of magnitude larger than the smallest catches, which suggests that some of the recreational catches, corresponding mostly to MRFSS, in the early years of the series may be overestimates. Although hammerhead sharks are now reported at the species level, subtle morphological differences may lead to misreporting, particularly in recreational fisheries, and ultimately result in inflated estimates (IUCN, 2007). If the catches were indeed smaller than those reported or estimated, the status may not be as pessimistic as reported here. Indeed, when catches in the early years were removed (scenarios 1995 and 1992), population status improved. In contrast, underreporting of commercial catches likely occurred in early years. Unobserved fishers, both recreational and commercial, may underreport catches to avoid increased regulation (Hilborn and Walters, 1992). Any unreported catches not included here would result in a more pessimistic status. Additionally, discards in the pelagic longline fishery were not available for 1982-1986 and hammerhead sharks no longer appeared in 2002-2005. Discards are an important consideration in total catches, as only about five percent of hammerhead sharks survive (Burgess et al., 2003).

The available relative abundance indices begin just before (1992) or after (1994) federal regulations for large coastal sharks were passed in 1993, and catch data begin in 1982. If an abundance index dating back to 1982 or earlier were available, better estimates of parameters would be possible. A sharp decline in relative abundance indices would be expected if the catches in those years were indeed large proportions of the population size. A relative abundance index showing population changes during high levels of fishing in the 1980s would significantly improve the ability of the model to estimate parameters, given that early catches appear to drive the model.

Questionable data give us little confidence in the magnitude of the results, but the trends are consistent with those found for other species of sharks (Musick et al., 2000; Baum et al., 2003; NMFS, 2006). The frequentist approach, presented in this study, is an objective method of estimating parameters, but problems appeared due to data limitations. Population growth rate and carrying capacity estimates were unreasonable in many of the bootstrap runs. A Bayesian approach, which utilizes known population growth rates and/or carrying capacity from other shark species to further constrain parameters, is suggested before the stock assessment is used for management purposes. Regardless of data insufficiencies, these populations have likely experienced considerable declines since 1982. Waiting for better data to be collected before conducting a stock assessment could result in continued decline in these populations, and therefore eventually require even longer recovery periods (Shertzer and Prager, 2007).

If using the precautionary approach to management (Garcia, 1994; Richards et al., 1998), the low recent catch levels of these two species should be maintained or reduced. The NMFS has lowered quotas of large coastal sharks, of which hammerhead sharks are part, several times since it began managing the fishery in 1993 (NMFS, 2006). Reductions in catches have allowed population decline to slow down and possibly even level off, although the most realistic models still indicated overfishing was occurring in 2005. Further reduction in catches may occur as a result of the most recent NMFS stock assessment (NMFS, 2006), which found that sandbar sharks (*Carcharhinus plumbeus*) were overfished and experiencing overfishing, leading to the expected imposition of more stringent quotas. Because it is difficult to target sharks by species, a reduction in catch for all large coastal sharks is likely to allow population recovery of hammerhead shark species to occur more quickly.

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Tables

Table 3.1. Results of the (A) Schaefer, (B) Fox, and (C) Pella-Tomlinson production models fitted to great hammerhead shark data. The NMFS LL scenario used a fishery-independent survey index; the CSFOP scenario used the commercial bottom-longline shark fishery observer program index; the BOTH scenario included both of these indices. IDEP scenario included 25% initial depletion in 1982 with respect to K, the 1983 scenario included the large reported catch of 1983; the 1995 scenario ignored catch data prior to 1995 and assumed virgin conditions in 1995; the NoDC scenario ignored unreported discards. Values for K, MSY and N_{MSY} are in thousands of fish. Ninety-five percent confidence intervals are in parentheses.

(A)

	NMFS LL	CSFOP	BOTH	IDEP	1983	1995	NoDC
AICc	**22.87**	**26.85**	**59.13**	**23.74**	**22.57**	**22.99**	**23.45**
r	**0.14** (0-0.39)	**0.42** (0-0.49)	**0.35** (0-0.45)	**0.14** (0-0.37)	**0.18** (0-0.42)	**0.19** (0-1.10)	**0.07** (0-0.36)
$K\ (\times 10^3)$	**190** (140-290)	**150** (130-350)	**210** (140-390)	**310** (200-360)	**230** (180-320)	**33** (17-150)	**270** (200-340)
$MSY\ (\times 10^3)$	**6.5** (0.00-15)	**15** (0.01-18)	**18** (0-20)	**11** (0-20)	**11** (0-21)	**1.6** (0-8.7)	**4.8** (0-20)
F_{MSY}	**0.07** (0-0.19)	**0.21** (0-0.25)	**0.18** (0-0.22)	**0.07** (0-0.19)	**0.09** (0-0.20)	**0.10** (0-0.55)	**0.04** (0-0.18)
$N_{MSY}(\times 10^3)$	**94** (71-140)	**73** (67-170)	**110** (70-190)	**150** (100-180)	**110** (90-170)	**16** (9-75)	**140** (100-170)
Depletion (%)	**92** (39-99)	**3** (0-89)	**2** (0-92)	**96** (33-99)	**94** (32-99)	**57** (0-91)	**94** (34-99)
F_{2005}/F_{MSY} *(%)*	**130** (5-220)	**4** (0-180)	**4** (0-190)	**190** (4-240)	**120** (3-190)	**96** (7-160)	**230** (3-360)
N_{2005}/N_{MSY} *(%)*	**15** (3-190)	**190** (18-220)	**180** (14-200)	**9** (2-200)	**11** (2-200)	**87** (21-200)	**12** (1-190)

(B)

	NMFS LL	CSFOP	BOTH	IDEP	1983	1995	NoDC
AICc	**22.17**	**26.77**	**45.56**	**22.91**	**22.16**	**22.02**	**29.56**
r	**0.08** (0-0.19)	**0.23** (0-0.40)	**0.28** (0-0.30)	**0.07** (0-0.18)	**0.07** (0-0.17)	**0.12** (0-0.25)	**0.05** (0-0.24)
$K\ (\times 10^3)$	**230** (210-380)	**200** (110-270)	**190** (160-450)	**300** (230-370)	**240** (200-370)	**34** (15-220)	**210** (180-350)
$MSY\ (\times 10^3)$	**6.7** (0-18)	**17** (0.8-26)	**19** (0-28)	**7.5** (0-9.2)	**6.7** (0-16)	**3.1** (0-11)	**3.5** (0-12)
F_{MSY}	**0.08** (0-0.19)	**0.23** (0-0.40)	**0.28** (0-0.30)	**0.07** (0-0.18)	**0.07** (0-0.17)	**0.12** (0-0.25)	**0.05** (0-0.24)
$N_{MSY}\ (\times 10^3)$	**86** (75-140)	**72** (45-160)	**71** (59-170)	**110** (87-140)	**110** (87-140)	**12** (5.5-80)	**77** (55-120)
Depletion (%)	**96** (4-99)	**10** (0-97)	**4** (0-97)	**97** (3-99)	**96** (3-99)	**70** (0-96)	**95** (5-99)
F_{2005}/F_{MSY} (%)	**220** (3-460)	**4** (1-490)	**3** (1-420)	**280** (10-540)	**220** (10-450)	**160** (5-450)	**260** (20-500)
N_{2005}/N_{MSY} (%)	**11** (1-240)	**240** (3-280)	**260** (5-260)	**8** (2-128)	**11** (2-128)	**82** (4-250)	**14** (8-250)

(C)

	NMFS LL	CSFOP	BOTH	IDEP	1983	1995	NoDC
AICc	**29.96**	**30.69**	**47.90**	**28.53**	**30.02**	**30.10**	**34.05**
r	**0.11** (0-0.25)	**0.23** (0-0.30)	**0.16** (0-0.49)	**0.15** (0-0.26)	**0.10** (0.0-0.25)	**0.12** (0-1.59)	**0.08** (0-0.28)
$K\ (\times 10^3)$	**240** (140-300)	**250** (130-280)	**270** (100-300)	**290** (140-350)	**240** (120-280)	**26** (14-40)	**220** (100-280)
$MSY\ (\times 10^3)$	**5.8** (1.0-14)	**12** (4.6-17)	**7.2** (4.0-37)	**11** (3.7-17)	**5.7** (1.0-18)	**1.4** (0.8-3.9)	**3.3** (0.4-12)
F_{MSY}	**0.04** (0-0.10)	**0.06** (0-0.13)	**0.04** (0-0.20)	**0.07** (0-0.08)	**0.04** (0-0.12)	**0.10** (0-0.35)	**0.03** (0-0.09)
$N_{MSY}\ (\times 10^3)$	**130** (86-320)	**130** (87-270)	**170** (67-300)	**150** (100-350)	**130** (80-360)	**15** (5-35)	**110** (80-270)
Depletion (%)	**94** (81-99)	**5** (0-80)	**1** (0-93)	**95** (79-99)	**94** (80-99)	**43** (0-99)	**92** (69-99)
F_{2005}/F_{MSY} (%)	**270** (8-390)	**8** (5-82)	**15** (4-90)	**150** (7-420)	**260** (10-400)	**120** (0-280)	**310** (28-600)
N_{2005}/N_{MSY} (%)	**11** (4-47)	**180** (13-330)	**160** (12-180)	**9** (2-170)	**11** (4-60)	**99** (0-110)	**18** (6-84)

Table 3.2. Results of the (A) Schaefer, (B) Fox, and (C) Pella-Tomlinson production models fitted to smooth hammerhead shark data. PLL included the pelagic longline logbook data. IDEP scenario included 25% initial depletion in 1982 with respect to K, the 1983-4 scenario included reported catch of 1983 and 1984; the 1992 scenario assumed virgin conditions in 1992; the NoDC scenario ignored unreported discards. Values for K, MSY and N_{MSY} are in thousands of fish. Ninety-five percent confidence intervals are in parentheses.

(A)

	PLL	IDEP	1983-4	1992	NoDC
AICc	**6.51**	**6.55**	**6.88**	**6.62**	**6.95**
r	**0.08** (0-0.09)	**0.07** (0-0.09)	**0.06** (0-0.11)	**0.22** (0-0.69)	**0.14** (0-0.61)
$K\ (\times 10^3)$	**56** (51-67)	**70** (52-66)	**56** (50-700)	**22** (15-30)	**45** (21-67)
$MSY\ (\times 10^3)$	**1.0** (0.08-1.2)	**1.1** (0.12-1.3)	**0.83** (0.09-1.4)	**1.2** (0-2.6)	**1.5** (0-3.1)
F_{MSY}	**0.04** (0-0.05)	**0.03** (0-0.05)	**0.03** (0.0-0.05)	**0.11** (0-0.34)	**0.07** (0-0.3)
$N_{MSY}\ (\times 10^3)$	**27** (25-33)	**33** (26-33)	**28** (25-35)	**11** (7.7-15)	**22** (10-34)
Depletion (%)	**91** (87-95)	**92** (87-95)	**91** (85-95)	**87** (79-97)	**93** (88-97)
F_{2005}/F_{MSY} (%)	**150** (7-250)	**160** (8-180)	**160** (6-184)	**75** (13-300)	**22** (1-210)
N_{2005}/N_{MSY} (%)	**19** (10-28)	**15** (9-28)	**18** (9-28)	**27** (6-78)	**14** (5-56)

(B)

	PLL	IDEP	1983-4	1992	NoDC
AICc	**6.34**	**6.48**	**6.33**	**6.47**	**6.68**
r	**0.03** (0-0.04)	**0.03** (0-0.04)	**0.03** (0-0.04)	**0.08** (0-0.10)	**0.05** (0-0.07)
$K\ (\times 10^3)$	**60** (57-71)	**73** (57-70)	**61** (59-74)	**24** (20-30)	**52** (41-68)
$MSY\ (\times 10^3)$	**0.58** (0-0.73)	**0.80** (0-0.76)	**0.66** (0-0.84)	**0.79** (0-0.9)	**1.0** (0-1.3)
F_{MSY}	**0.03** (0-0.04)	**0.03** (0-0.04)	**0.03** (0-0.04)	**0.08** (0-0.10)	**0.05** (0-0.07)
$N_{MSY}(\times 10^3)$	**22** (21-26)	**26** (21-27)	**23** (22-28)	**8.9** (8.0-11)	**19** (17-23)
Depletion (%)	**91** (87-99)	**93** (88-99)	**91** (85-99)	**86** (80-97)	**93** (88-99)
F_{2005}/F_{MSY} *(%)*	**150** (30-320)	**170** (27-270)	**170** (27-280)	**80** (32-250)	**22** (20-290)
N_{2005}/N_{MSY} *(%)*	**24** (1-30)	**20** (1-28)	**24** (1-31)	**39** (1-42)	**20** (1-26)

(C)

	PLL	IDEP	1983-4	1992	NoDC
AICc	**10.80**	**10.87**	**10.83**	**10.93**	**11.14**
r	**0.06** (0.01-0.08)	**0.05** (0.02-0.09)	**0.06** (0.01-0.09)	**0.10** (0.08-0.12)	**0.09** (0.04-0.11)
$K\ (\times 10^3)$	**56** (54-83)	**70** (57-88)	**68** (64-75)	**27** (26-30)	**52** (49-68)
$MSY\ (\times 10^3)$	**0.90** (0.32-1.4)	**0.95** (0.22-1.9)	**0.20** (0.18-0.23)	**0.7** (0.05-0.9)	**1.1** (0.61-1.3)
F_{MSY}	**0.03** (0.01-0.04)	**0.03** (0-0.04)	**0.01** (0-0.01)	**0.05** (0.02-0.06)	**0.04** (0.02-0.10)
$N_{MSY}(\times 10^3)$	**29** (28-42)	**36** (34-47)	**35** (34-39)	**14** (12-18)	**27** (25-54)
Depletion (%)	**92** (78-94)	**94** (84-97)	**93** (82-95)	**89** (78-98)	**95** (74-99)
F_{2005}/F_{MSY} *(%)*	**180** (32-220)	**220** (48-320)	**200** (40-280)	**17** (9-110)	**22** (2-120)
N_{2005}/N_{MSY} *(%)*	**15** (13-38)	**12** (6-31)	**14** (11-34)	**22** (0-130)	**10** (0-42)

Table 3.3. Probability (percent) of (A) great hammerhead shark and (B) smooth hammerhead shark population recovery over 10, 20, and 30 years under a no catch regime and with equal, double, and triple catch levels from 2005 (C_{2005}) in the base scenarios (NMFS LL and PLL, respectively) with the Fox model.

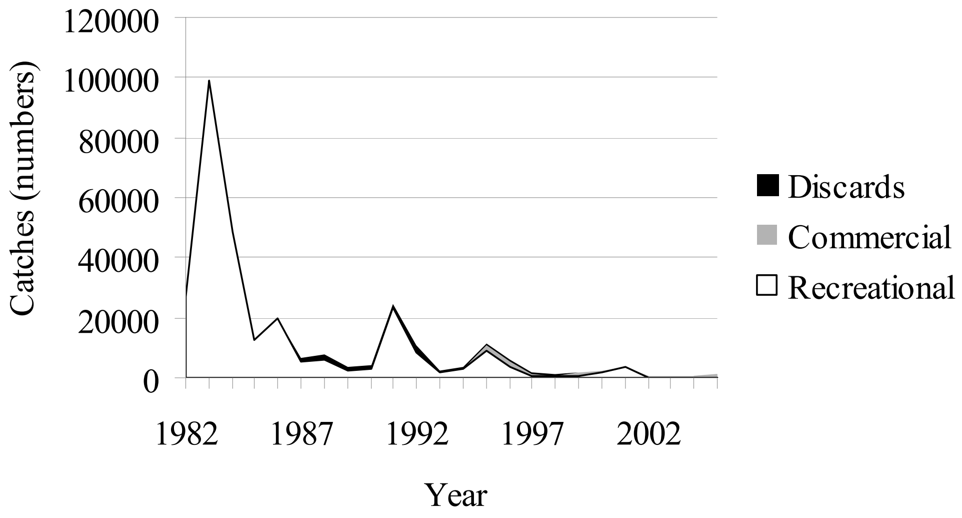
	Time horizon	No Catch	C_{2005}	200% of C_{2005}	300% of C_{2005}
(A)	10 Years	27	24	21	17
	20 Years	44	32	25	22
	30 Years	56	40	29	24

		No Catch	C_{2005}	200% of C_{2005}	300% of C_{2005}
(B)					
	10 Years	11	6	3	1
	20 Years	42	30	19	10
	30 Years	64	47	29	17

Figures

Figure 3.1. Annual catches in numbers by sector of (A) great hammerhead sharks and (B) smooth hammerhead sharks used in the base models (estimates for commercial catch and discards are shown).

(A)



(B)

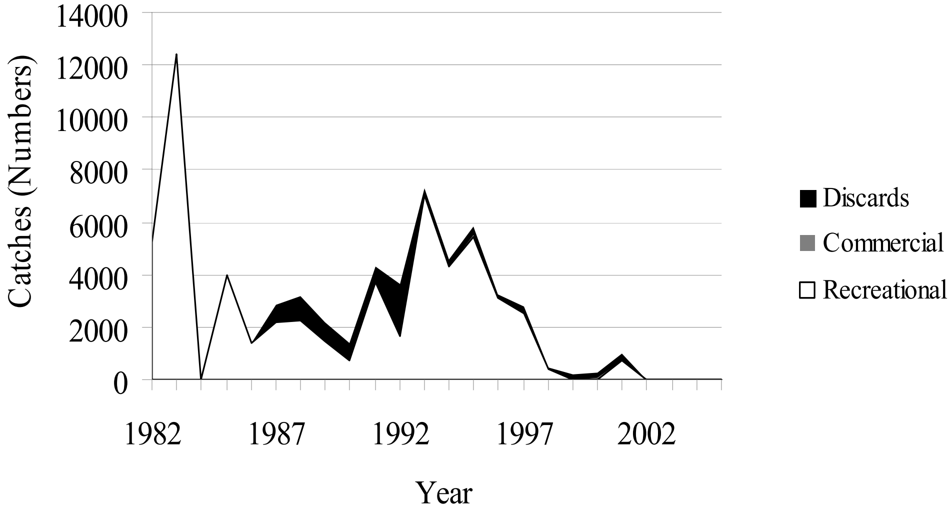
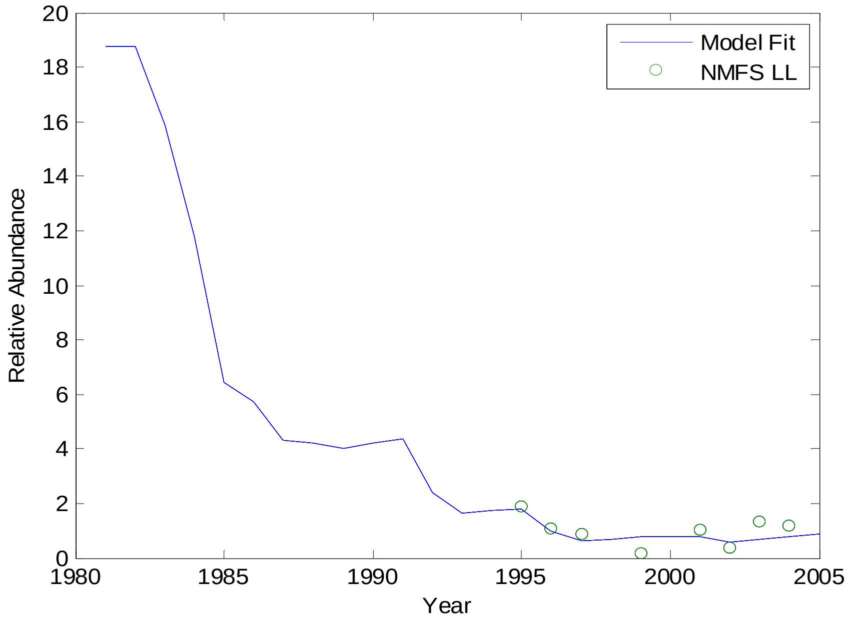
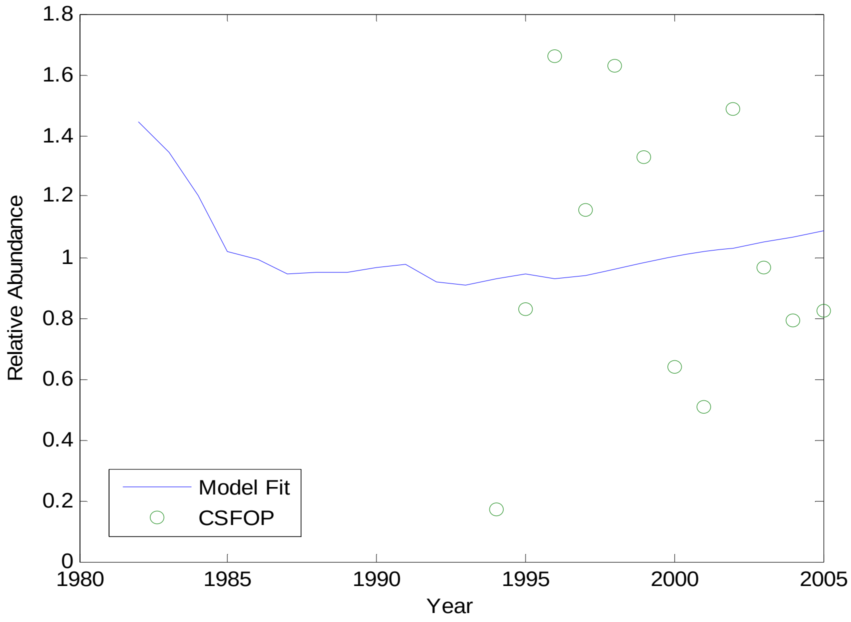


Figure 3.2. Great hammerhead shark model fit for the (A) NMFS LL scenario, (B) CSFOP scenario, (C) Both scenario, and smooth hammerhead shark model fit for (D) the PLL scenario. Circles are observed CPUE data points.

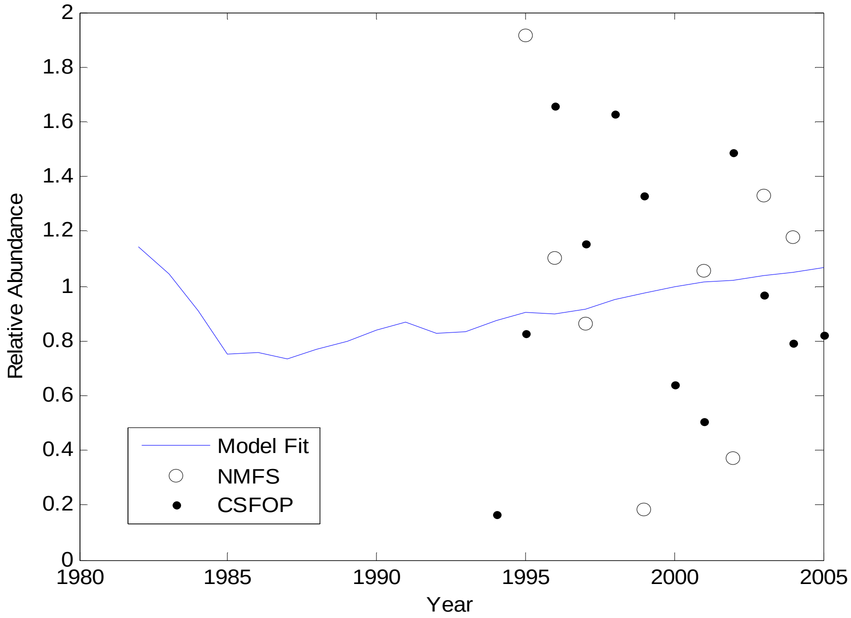
(A)



(B)



(C)


Relative Abundance
Year
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1980
1985
1990
1995
2000
2005
Model Fit
NMFS
CSFOP

(D)

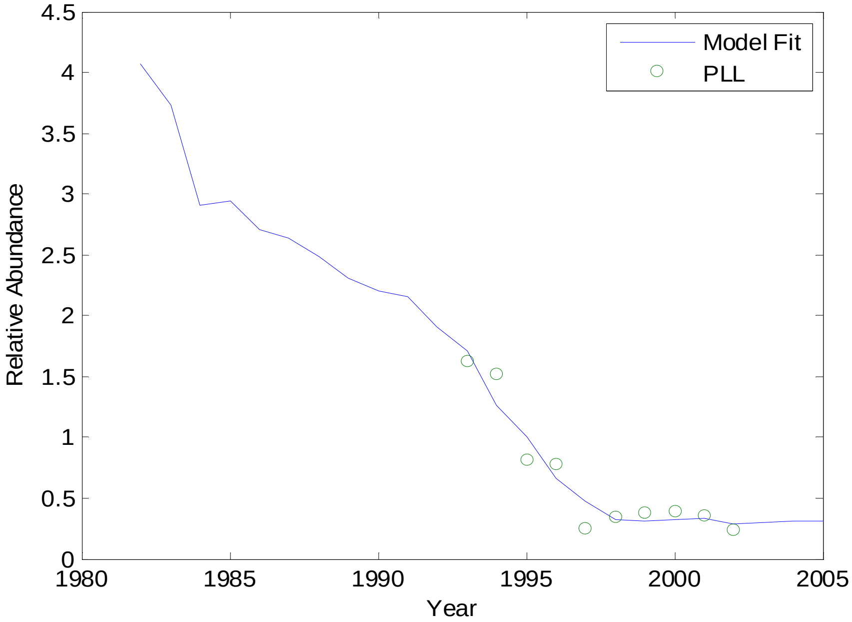
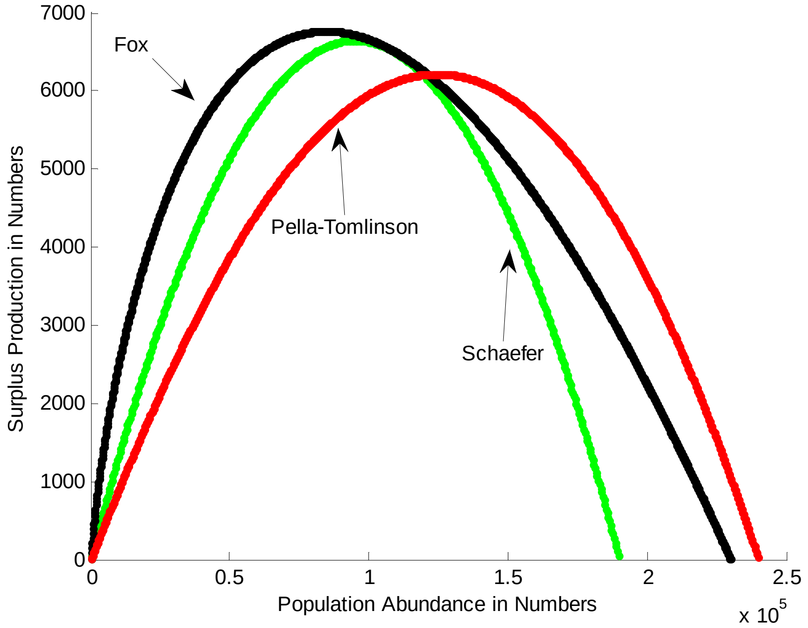

Relative Abundance
Year
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1980
1985
1990
1995
2000
2005
Model Fit
PLL

Figure 3.3. Surplus production in numbers for (A) great hammerhead sharks and (B) smooth hammerhead sharks based on three models.

(A)



(B)

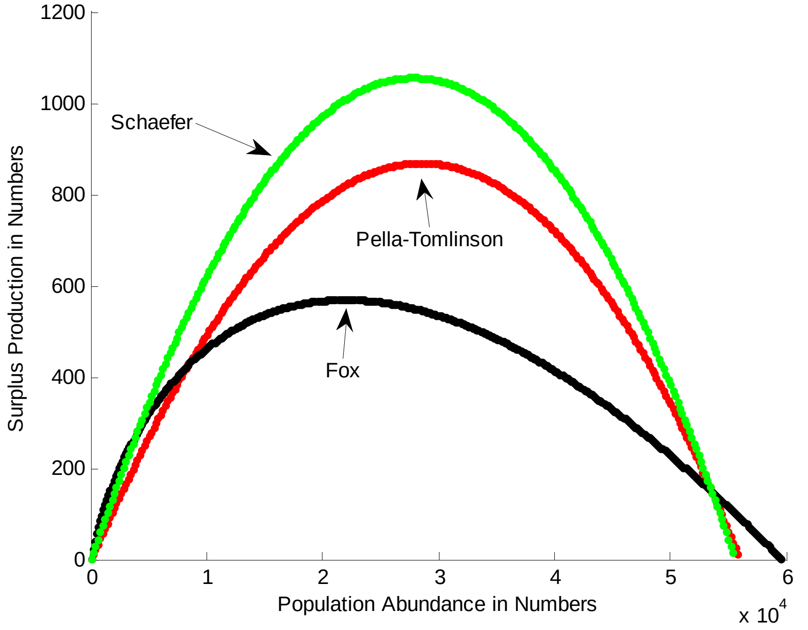
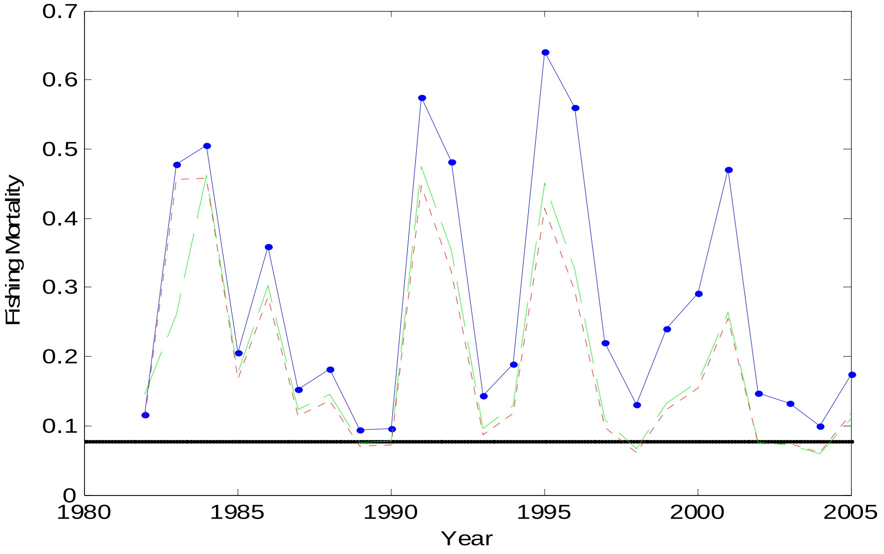


Figure 3.4. Fishing mortality from 1982 through 2005 for (A) great hammerhead and (B) smooth hammerhead sharks. The solid line represents estimated fishing mortality from the Fox model, the long dotted line denotes fishing mortality estimated in the Schaefer model, and the short dashed line is from the Pella-Tomlinson model. F_{MSY} from the Fox model is also indicated as a horizontal line.

(A)



(B)

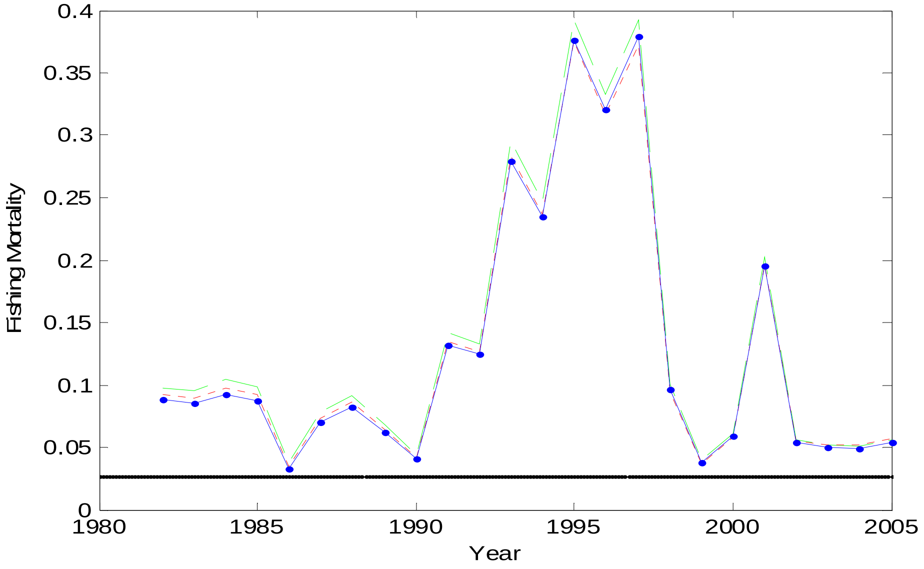


Figure 3.5. Abundance trajectory of (A) great hammerhead and (B) smooth hammerhead sharks for 1982-2005. The solid line represents estimated abundance from the Fox model, the long dotted line denotes abundance estimated in the Schaefer model, and the short dashed line is the abundance from the Pella-Tomlinson model. N_{MSY} from the Fox model is indicated as a horizontal line.

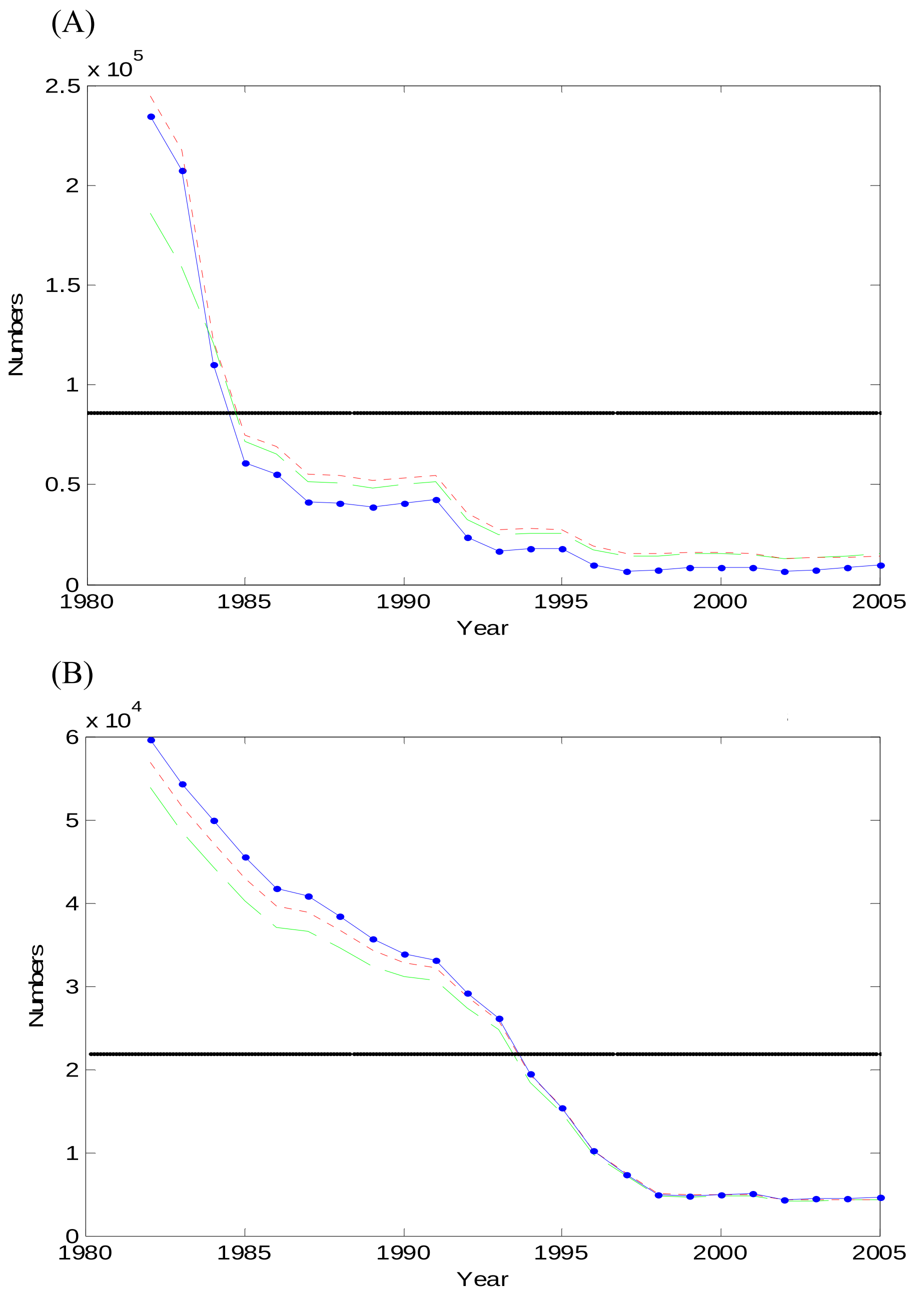
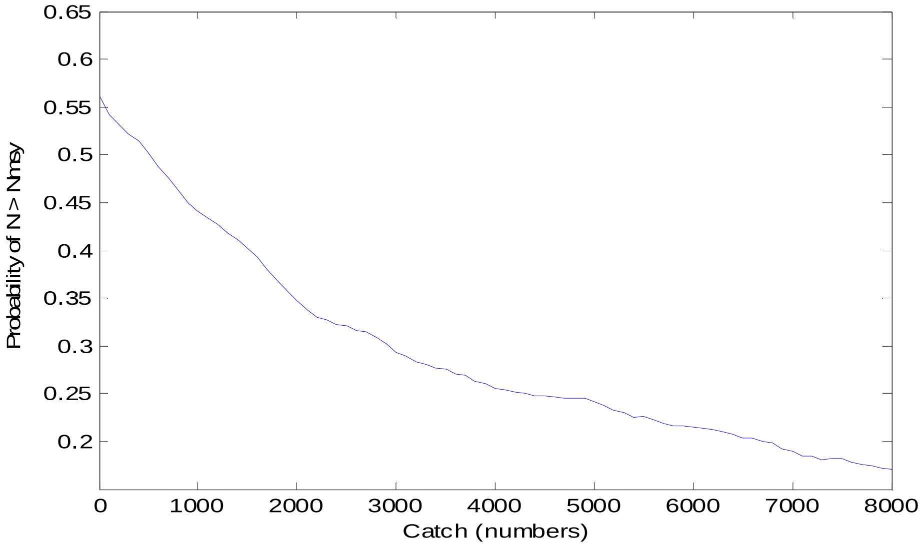
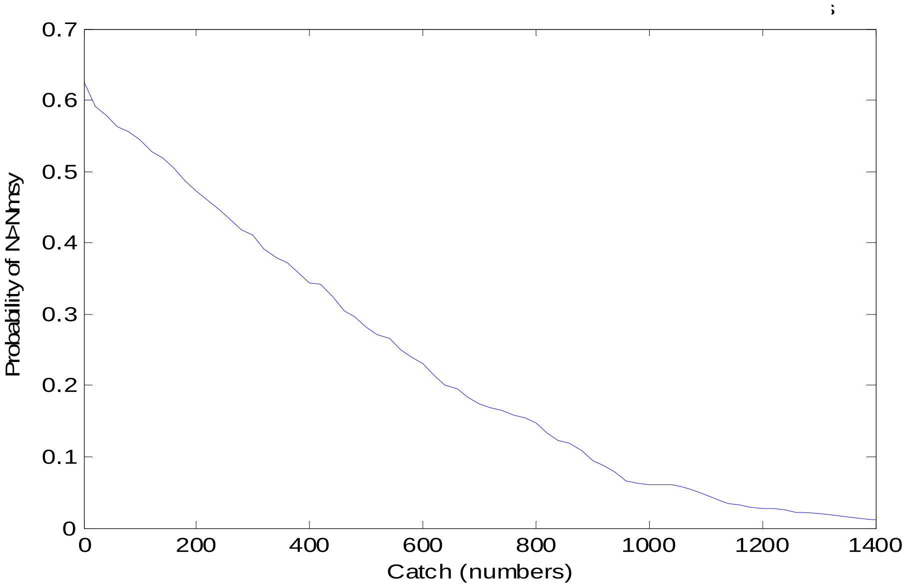


Figure 3.6. Probability of (A) great hammerhead shark and (B) smooth hammerhead shark stock recovery in 30 years depending on the level of catch. Probabilities were estimated from Monte Carlo simulations.

(A)



(B)



Appendix 2A. Catches (in numbers) of great hammerhead sharks (*Sphyrna mokarran*) by year and source. Missing data are indicated by blanks.

Year	Recreational	Commercial	Discards	Total
1982	27068	1		27069
1983	98757	241		98999
1984	48598	0		48598
1985	12532	0		12532
1986	19745	0		19745
1987	5212	0	1228	6440
1988	5836	2	1674	7511
1989	2364	0	1389	3753
1990	2827	8	1151	3986
1991	23335	2	1221	24558
1992	8220	44	2257	10521
1993	1857	60	516	2433
1994	2813	123	368	3303
1995	8960	2050	567	11578
1996	3747	1675	290	5712
1997	432	506	938	1876
1998	475	262	234	971
1999	390	1190	344	1924
2000	1701	475	277	2453
2001	3387	141	339	3867
2002	27	555		583
2003	47	554		601
2004	9	450		459
2005	9	1310		1319

Appendix 2B. Catches (in numbers) of smooth hammerhead sharks (*Sphyrna zygaena*) by year and source. Missing data are indicated by blanks.

Year	Recreational	Commercial	Discards	Total
1982	5262	0		5262
1983	12395	12		12407
1984	0	0		0
1985	3984	0		3984
1986	1393	0		1393
1987	2191	0	654	2845
1988	2262	0	891	3153
1989	1473	0	739	2212
1990	760	0	612	1373
1991	3696	0	650	4346
1992	1675	2	1968	3645
1993	7018	3	284	7305
1994	4287	41	234	4562
1995	5460	33	313	5807
1996	3144	0	117	3261
1997	2535	14	253	2802
1998	375	0	107	482
1999	1	0	182	183
2000	4	68	221	292
2001	703	0	273	976
2002	14	0		14
2003	1	0		1
2004	0	0		0
2005	0	26		26

Appendix 3A. Standardized relative abundance indices available for great hammerhead sharks: the commercial shark fishery observer program (CSFOP) and the NMFS longline abundance index (NMFS LL). Ninety-five percent confidence intervals are shown in parentheses.

Year	NMFS LL	CSFOP
1994		0.169 (0.031 – 0.333)
1995	1.916 (0.776– 4.730)	0.830 (0.192 – 1.297)
1996	1.100 (0.328 – 3.685)	1.661 (0.413 – 2.423)
1997	0.864 (0.285 – 2.616)	1.158 (0.279 – 1.740)
1998		1.628 (0.370 – 2.510)
1999	0.182 (0.011 – 2.905)	1.330 (0.357 – 1.795)
2000		0.641 (0.123 – 1.214)
2001	1.056 (0.356 – 3.135)	0.509 (0.109 – 0.858)
2002	0.371 (0.064 – 2.171)	1.489 (0.419 – 1.922)
2003	1.332 (0.486 – 3.654)	0.968 (0.281 – 1.209)
2004	1.179 (0.413 – 3.367)	0.793 (0.224 – 1.021)
2005		0.824 (0.224 – 1.102)

Appendix 3B. Standardized relative abundance index available for smooth hammerhead sharks: the pelagic longline observer abundance index (PLL). Ninety-five percent confidence intervals are shown in parentheses.

Year	PLL
1992	4.294 (1.851 – 9.954)
1993	1.622 (0.618 – 4.247)
1994	1.517 (0.575 – 3.989)
1995	0.818 (0.271 – 2.478)
1996	0.777 (0.240 – 2.478)
1997	0.256 (0.047 – 1.361)
1998	0.343 (0.073 – 1.584)
1999	0.384 (0.082 – 1.816)
2000	0.393 (0.086 – 1.799)
2001	0.361 (0.073 – 1.795)
2002	0.238 (0.034 – 1.589)

Chapter 4 – Comparing a multi-species to species-specific assessments of hammerhead sharks (*Sphyrna* spp.) using production models

Abstract

A number of fish species have been assessed as a complex because of insufficient data available to conduct species-specific analyses. However, few studies have addressed the advantages and shortcomings of assessing the status of species as part of complexes or individually. Following the approach proposed by the Southeast Data, Assessment and Review (SEDAR) process for large coastal sharks (NMFS, 2006), this study assessed the status of the hammerhead shark complex (*Sphyrna* spp.) and compared it to those from individual assessments of scalloped hammerhead (*S. lewini*), great hammerhead (*S. mokarran*), and smooth hammerhead (*S. zygaena*) sharks in the western North Atlantic Ocean and Gulf of Mexico. The hammerhead shark complex was overfished, i.e., below the population size associated with maximum sustainable yield (MSY). Overfishing, or the exploitation above the level associated with MSY, occurred in 2005. The complex has a high probability of recovery within two to three decades, but the relatively faster-growing scalloped hammerhead shark probably would account for the majority of the recovery and could mask the continued decline of the slower-growing species in the complex, the smooth and great hammerhead sharks. This study thus provided a unique empirical example of comparing a complex-based assessment with species-specific assessments, illustrating the problems inherent in multi-species assessments and the need for conducting single-species assessments when feasible.

Introduction

As a result of generally slow growth, late maturity, and low fecundity, large coastal sharks tend to have low intrinsic population growth rates—which are inversely related to a population's risk of overexploitation (Musick, 1999)—compared to many bony fishes (Smith et al., 1998; Musick et al., 2000). Because life histories differ among shark species, intrinsic population growth rates and resilience to exploitation are also variable (Musick et al., 2000).

Managing aggregated stocks based on the maximum sustainable yield (MSY), or some proxy, can lead to overexploitation of some stocks and underexploitation of others (Hilborn et al., 2003, 2004). Additionally, declines of slower-growing species may be masked by increases of faster-growing species. Changes in species composition were observed in a multi-species skate and ray fishery in the Falkland Islands (Agnew et al., 2000, Wakeford and Agnew, 2004), the snapper-grouper complex in the western North Atlantic Ocean and Gulf of Mexico (Coleman et al., 2000), and in the U.S. Atlantic large coastal shark fishery (NMFS, 2006). The present study provides a unique example of comparing species-specific stock assessments to a complex-based assessment.

As of 2006, the National Marine Fisheries Service (NMFS) assessed the scalloped hammerhead (*Sphyrna lewini*), great hammerhead (*S. mokarran*), and smooth hammerhead (*S. zygaena*) shark stocks as part of the large coastal shark (LCS) aggregate (NMFS, 2006). Only two of the eleven species presently in the complex were modeled at the species level, sandbar (*Carcharhinus plumbeus*) and blacktip (*Carcharhinus limbatus*) sharks (NMFS, 2006). Combined, these two species comprise about 90% of the large coastal shark catch and consequently better quality data are available for them. Approximately one third to half of the remaining LCS catches are hammerhead sharks (NMFS, 2006). However, a lack of species-specific catch and relative abundance records prevented individual assessments of the status of most shark species, including hammerhead sharks, until recently.

There have been few studies that specifically addressed the status of hammerhead sharks. Baum et al (2003) estimated an 89% decline of scalloped hammerhead sharks using data from the U.S. pelagic longline logbook program, but their conclusions were contested by some for failing to use other relative abundance indices available for the western North Atlantic Ocean region (Burgess et al., 2005). Myers et al. (2007) used a North Carolina bottom longline index that included only 7 individuals (Schwartz et al., 2007) to estimate a 99% decline of smooth hammerhead sharks. The present study is the first, to date, to assess hammerhead sharks as a complex.

Production models assume that population size changes according to an intrinsic population growth rate (r), which is a summation of recruitment and growth minus mortality (Schaefer, 1954). Compensatory population growth depends on the model used and the value of a second parameter, K, or virgin biomass. We explored three production models: Schaefer's (1954), Fox's (1975), and Pella Tomlinson's (1969). These models are useful when only catch and catch-per-unit-effort (CPUE) data are available, as is common in shark stock assessments. Additionally, simple production models may outperform more complex age-structured models, which require more parameter estimates, with each estimate increasing uncertainty exponentially (Ludwig et al., 1988; Prager, 1994).

Our objectives were to provide a comparison of stock assessments of three hammerhead sharks individually and as a complex to determine whether aggregated assessments are appropriate for management use. We used surplus production models to assess the hammerhead shark complex and compared the results with those from the individual assessments of each species in the complex. With the help of NMFS scientists, catch data and indices of relative abundance for both the complex and those for each species in the hammerhead shark complex were collected. Detailed assessments of each species were provided by Chapters 2 and 3.

Materials and methods

Data

Catch data were available for 1981-2005 (Appendix 4). Commercial catch data were collected by the NMFS through the Northeast Regional and Southeast Regional general canvass landings program and the Southeast Fisheries Science Center quota monitoring system. Recreational catch data were collected from the Marine Recreational Fisheries Statistics Survey (MRFSS), the NMFS Headboat Survey, and the Texas Parks and Wildlife Department's Marine Sport-Harvest Monitoring Program (NMFS, 2006). The recreational catch for 1983 was unusually high and thought to be unrealistic, thus we averaged the 1982 and 1984 catches to estimate catch for 1983 as in NMFS (2006).

Available relative abundance indices (Fig. 4.1) included one fishery-independent source, the NMFS Bottom Longline Survey (NMFS LL SE), and four fishery-dependent sources, the Commercial Shark Fishery Observer Program (CSFOP), the Pelagic Longline Observer Program (PLLOP), the Pelagic Longline Logbooks (PLL), and the Everglades National Park Creel Survey (ENP). We followed the recommendations of NMFS (2006) to determine which abundance indices to use for parameter estimation and population projections and gave the relative abundance indices equal weights in the model (NMFS, 2006).

The baseline model (BASE) included three relative abundance indices, NMFS LL SE, CSFOP, and PLLOP. The NMFS LL SE is based on a standardized bottom longline survey, which assesses the distribution and abundance of coastal sharks throughout their suspected ranges, and was available for 1995-2004. On average over all years, 10.8% of the hauls included at least one hammerhead shark. The CSFOP began in 1994 and requirements changed from voluntary to mandatory reporting in 2002. On average, 36.1% of hauls included at least 1 hammerhead shark. In 1992, NMFS implemented the PLLOP to provide an accurate record of the pelagic longline fleet by observing a representative 5% of fishing effort in each of the 11 fishing areas and in each fishing quarter designated in the program. On average, 8.9% of hauls included hammerhead sharks.

The other two available indices were included in sensitivity analyses. Most abundance indices only start in the early 1990s, but the PLL data start in 1986. Between 1992 and 2002 an average of 6.14% of hauls included at least one hammerhead shark. ENP data were collected through interviews of recreational fishermen in the Everglades National Park and span 1985-2004, making this abundance index potentially useful and very influential in the model. However, hammerhead sharks were only recorded in approximately 0.25% of the 184,000 trips captured in the survey. NMFS (2006) determined that this abundance index should be used with caution given the very high variance and small sample size, and inconsistent reporting and identification problems (NMFS, 2006) and thus we opted not to include it in the BASE scenario. The PLL was not used in the BASE scenario because the PLLOP was considered a more reliable source.

Catch rate standardization

Each index was standardized using the Lo et al. (1992) method. The large number of zeros (i.e., trips without catches) in the data require a two-part standardization procedure, in which the factors that influence positive (non-zero) catches and those that influence catch-per-unit-effort (CPUE) of hauls with a positive catch are modeled separately. This method has been used extensively by NMFS (2006) to isolate the effect of year on changes in CPUE indices.

Assessment model

The observation error estimator surplus-production model (Hilborn and Walters, 1992; Prager, 1994) used for this study and the species-specific assessments was:

$$N_{t+1} = N_t + G_t - C_t\,, \tag{1}$$

$$I_{i,t} = q_i N_t e^{\varepsilon_i} \tag{2}$$

where: N_t = the population size at time t;

G_t = the population growth or surplus production;

C_t = Catch;

$I_{i,t}$ = Index i;

q_i = catchability coefficient of index I_i; and

ε = normally distributed ($N(0, \sigma^2)$) observation error associated with index *i*.

Several parameters commonly estimated in surplus-production models were removed to reduce associated error. Being proportionality constants, q_i were estimated within the function based on r and K values (Jiao and Chen 2004). Initial population size was assumed to be equal to the unfished population size, and equal weighting of relative abundance indices was used in the BASE scenario.

For this study we explored the discrete form of three common production curves: Schaefer's (1954), Fox's (1970), and Pella-Tomlinson's (1969). Models were compared using Akaike's information criterion for small sample sizes (AICc), a quantitative method of assessing goodness-of-fit of statistical models (Akaike, 1974; Bedrick et al., 1994).

Sensitivity analysis

Sensitivities to the initial depletion assumption and abundance indices used were tested. In the BASE scenario, initial population size, $N_{0,}$ was equal to virgin biomass (K) and the model fit the NMFS LL SE, CSFOP, and PLLOP time series. The assumption N_0 equal to virgin biomass (K) has been shown to produce more robust results than estimating initial population size separately (Punt, 1990). However, we tested this assumption in a sensitivity analysis by setting N_0 at 75% of virgin biomass (IDEP), an estimate used in NMFS (2006).

In another sensitivity analysis, the PLL replaced the PLLOP index (PLL). The Everglades National Park was added to the BASE scenario in a separate sensitivity run (ENP). We also explored the effect of using only the fishery-independent survey, the NMFS LL SE (FIND). Finally, we looked at the effect of inverse variance weighting of indices, as used by NMFS (2006).

Quantifying uncertainty

To approximate the uncertainty of parameters r and K, a bootstrap method was applied to the BASE model. Lognormal residuals from the years with data were randomly re-sampled (with replacement) and added to the fitted log (abundance indices) to obtain generated log (abundance indices). The years with missing data were treated as such in the generated indices. Parameters were then estimated using the method outlined above. This technique was repeated 1000 times, each yielding a unique set of r, K, MSY, N_{MSY}, and F_{MSY} values.

Population projections

Using the sets of parameters obtained from the bootstrap method described, a forward projecting simulation model was used to determine the likelihood of the population remaining overfished under various fishing regimes compared to the current fishing regime. The effects of removals at 0%, 50%, 100%, and 150% of current levels were projected.

Comparing single and multiple species assessments

Results of the hammerhead shark complex assessment were compared to those of similar models of three species of hammerhead sharks: scalloped hammerhead (Hayes et al., in prep, A), great hammerhead, and smooth hammerhead (Hayes et al., in prep, B) sharks. To compare population parameters, K, MSY, and N_{MSY} were summed across species. Values for r, F_{MSY}, F_{2005}/F_{MSY}, and N_{2005}/N_{MSY} were calculated as the average values weighted by the average species composition (1982-2005) from the recreational fishery (MRFSS), CSFOP, and PLLOP (NMFS, 2006). For example, summed r was:

$$r_{SUM} = P_{SCH} \times r_{SCH} + P_{SMH} \times r_{SMH} + P_{GHH} \times r_{SHH} \quad (3)$$

where: r_{SUM} = population growth rate of the complex based on species-specific assessments;

P_{SCH} = proportion of scalloped hammerhead sharks (0.51);

r_{SCH} = population growth rate of scalloped hammerhead sharks (0.12);

P_{SMH} = proportion of smooth hammerhead sharks (0.12);

r_{SMH} = population growth rate of smooth hammerhead sharks (0.03);

P_{GHH} = proportion of great hammerhead sharks (0.37); and

r_{GHH} = population growth rate of great hammerhead sharks (0.08).

Abundance estimates from the three species-specific assessments were combined to test for changing species composition. A t-test was applied to the proportion estimates of each species between 1982 and 2005 to determine whether a significant change in composition existed.

Results

The Schaefer, Fox , and Pella-Tomlinson production curves yielded similar fits to the data, with the highest value of AICc, or poorest performance, corresponding to the Pella-Tomlinson model (AICc=53.5), but the difference in fit between the Schaefer (AICc=49.7) and the Fox (AICc=49.0) models was trivial. The Fox model produced the most conservative values for parameters r and K. Corresponding management reference points for maximum sustainable yield (MSY) and harvest rate associated with MSY (F_{MSY}) were also most conservative using this model. We followed a precautionary approach and used the more conservative parameter estimates from the Fox model for population projections.

In all model runs, the complex was found to be overfished, and overfishing was occurring in five of six model runs (Table 4.1, Fig. 4.2). Weighting the abundance indices by the inverse of the variance resulted in an overfished population, but not experiencing overfishing. Overfishing has likely occurred nearly every year since 1981 according to the BASE scenario (Fig. 4.3). When PLL was included in place of PLLOP, the results were slightly more pessimistic, though other sensitivity runs had little effect on the results.

Bootstrap confidence intervals for parameters r and K were 0.00-0.22 and 270,000-650,000, respectively (Table 4.1). The model often had trouble distinguishing between a large, slow-growing population and a small, fast-growing one. In fact, r and K were strongly correlated and skewed. Using Monte Carlo simulation, we found that if removals continue at 2005 levels, the complex has less than a 40% probability of recovery by 2015 (Table 4.2).

Although results for the complex are very similar to the summation of species-specific assessments (Fig. 4.4), the parameters and biological reference points (BRPs) estimated for the complex are slightly more conservative than the summation of those estimated for each individual species (Table 4.3). A hammerhead shark complex quota based on the product of population estimate in 2005 times F_{MSY} of the complex would be smaller (3,555), and slightly more conservative, than the sum of quotas ($N_{2005} * F_{MSY}$) for each species (4,243; Table 4.3).

Scalloped, great, and smooth hammerhead sharks were estimated to compose 51%, 37%, and 12%, respectively, of the complex. If catch levels are set based on the assessment of the complex, overfishing ($F > 2\ F_{MSY}$) would occur for the slow-growing smooth hammerhead shark, and overfishing ($F > 1.5\ F_{MSY}$) of great hammerhead sharks would occur. The faster-growing scalloped hammerhead sharks would be underutilized ($F < 0.6\ F_{MSY}$), although given the current status of the species (Hayes et al., in prep, A) underutilization would help the stock rebuild more quickly.

Analysis of CSFOP catch data showed no significant change in species composition of the catch over time. However, the stock assessment models revealed were significant changes in the composition of the hammerhead shark complex over time (Fig. 4.5). Scalloped hammerhead sharks made up an increasing proportion of the complex between 1982 and 2005 ($p < 0.01$), whereas great hammerhead sharks declined ($p < 0.01$), and smooth hammerhead sharks may also have declined ($p = 0.04$).

Discussion

Hammerhead shark data include uncertainty and inconsistency. The great hammerhead shark model, in particular, had wide confidence intervals and was highly sensitive to the inclusion of certain abundance indices. Here, to make inferences about stock status, and to compare the assessments of the complex to those of the individual species, we selected the most reasonable scenario of the production model. Though we constrained the parameter values, the frequentist approach presented here resulted in unreasonable parameter estimates in many of the bootstrap runs. Bayesian inference, which incorporates informative priors such as population growth rate of similar species, is commonly used in stock assessments for data poor species like great and smooth hammerhead sharks. We suggest including Bayesian analyses of these species before these results are used for management purposes.

The high degree of uncertainty associated with each species-specific assessment (Chapters 2 and 3) was ignored to allow for comparison to the assessment of the complex. In fact, the uncertainty is compounded by summing the results from the three assessments. There were also many assumptions associated with species composition, particularly relating to correct species identification in the recreational fishery. These factors should thus be considered when comparing the summed scenario with the complex assessment.

The precautionary principle, a management approach to reducing risk even when uncertainty of the data is high (Garcia, 1994), is increasingly a part of U.S. and international fisheries management (Richardson et al., 1998). Although reliable data remain scarce for hammerhead sharks, this assessment shed some light on the status of this group of large coastal sharks in the western North Atlantic Ocean. Reduced quotas and fishery closures in the 1990s have potentially slowed population decline, but hammerhead sharks are still overfished. Current levels of catch should allow scalloped hammerhead sharks to rebuild within 30 years (Chapter 2), although great and smooth hammerhead sharks still need reduced catches (Chapter 3). These populations are so depleted that overfishing was occurring in 2005, even with historically low catches.

A quota based on the results of the hammerhead shark complex would be less risk-prone (i.e., more conservative) than the summation of three separate quotas based on single-species stock assessments. However, if that hammerhead shark complex quota is divided based on the species composition of the complex and compared to the quotas obtained by single-species assessments, the potential to overexploit some stocks (great and smooth hammerhead sharks) and underexploit others (scalloped hammerhead sharks) becomes apparent. Results of the single-species assessments, which predict a change in species composition, indicate that great and smooth hammerhead sharks are disproportionately overexploited when compared to scalloped hammerhead sharks. However, this shift in composition is not supported by observer data, which show no significant trend.

Single-species assessments, while important for understanding severely depleted stocks, should not be the only tools used in assessing fish stocks. As information about predator-prey and competitive interactions becomes available for sharks, multi-species models may prove more useful than single-species models (Hallowed et al., 2000; Walters et al., 2005). For instance, the population dynamics of one shark species may affect another, as sharks are the primary predators of other sharks. Also, changes in abundance of the main prey species, teleosts and cephalopods, could influence surplus production. Future assessments could also include tagging studies, which can better account for changes to population and fishing effort distribution (Arreguin-Sanchez, 1996; Walters and Martell, 2004).

Species caught in the large coastal shark fishery exhibit a wide range of growth rates, but it is difficult to target only the faster-growing species. Therefore, fishing in multi-species fisheries can change the species composition over time because some species are more resilient to fishing pressure (Hilborn and Walters, 1992). While, in theory, all three hammerhead sharks can withstand some fishing pressure, they are currently depleted, and it will take some time for the stocks to recover to N_{MSY}. When managed within a complex, smooth and great hammerhead sharks have a higher probability of experiencing overfishing than scalloped hammerhead sharks. We noted a probable change in species composition, which suggests that the slower-growing smooth and great hammerhead sharks are being replaced by the relatively more resilient scalloped hammerhead shark.

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Tables

Table 4.1. Parameter estimates for the hammerhead shark complex for all scenarios. K, MSY and N_{MSY} are in numbers of fish. Scenario BASE sets $N_0 = K$, includes the NMFS LL SE, the CSFOP, and the PLLOP relative abundance indices, and uses equal weighting for the indices; IDEP assumes that N_0 is 75% of virgin population size; PLL includes the pelagic logbook index instead of the PLLOP index; ENP adds the Everglades National Park Survey index to the BASE scenario indices; FIND fits only the fishery-independent index, NMFS LL SE; INCV fits inputs from the BASE scenario, but uses an inverse variance weighting scheme.

XHH	BASE	IDEP	PLL	ENP	FIND	INCV
AICc	48.22	48.33	68.19	116.20	3.68	215.87
r	0.09 (0-0.22)	0.08 (0-0.20)	0.16 (0.04-0.36)	0.04 (0-0.16)	0.13 (0.5-0.25)	0.10 (0.03-0.20)
$K\ (\times 10^5)$	4.0 (2.7-6.5)	4.8 (3.1-8.7)	3.2 (2.2-4.7)	5.1 (3.1-7.2)	3.4 (2.6-5.2)	3.9 (2.8-6.0)
$MSY\ (\times 10^3)$	12 (0-21)	14 (1.2-24)	18 (7.2-29)	7.1 (0-19)	16 (9.7-24)	14 (4-20)
F_{MSY}	0.09 (0-0.22)	0.08 (0-0.20)	0.16 (0.04-0.36)	0.04 (0-0.16)	0.13 (0.5-0.25)	0.10 (0.03-0.20)
$N_{MSY}\ (\times 10^3)$	150 (100-250)	180 (120-320)	120 (80-170)	190 (110-270)	130 (96-190)	140 (110-200)
Depletion (%)	90 (62-96)	92 (71-97)	95 (90-98)	85 (73-97)	89 (28-94)	80 (70-89)
F_{2005}/F_{MSY} (%)	180 (0-500)	190 (60-580)	240 (130-610)	210 (0-900)	120 (32-220)	83 (45-160)
N_{2005}/N_{MSY} (%)	28 (13-68)	23 (10-55)	14 (5-22)	41 (14-64)	31 (19-130)	53 (20-82)

Table 4.2. Probability of the hammerhead shark complex population recovery to N_{MSY} in 10, 20, and 30 years at 0%, 50%, 100%, and 150% of the 2005 catch level.

% of 2005 Catch	0	50	100	150
Catch in numbers	0	2524	5049	7573
10 Years	84%	60%	38%	27%
20 Years	98%	98%	90%	60%
30 Years	99%	98%	97%	80%

Table 4.3. Comparison of single-species and complex assessment results. Parameters and reference points of the first three columns were estimated by Hayes et al. (in prep., A, B). The column titled "Summed" includes the summation of K, MSY, and N_{MSY} values for all three species species. Values for r, F_{MSY}, F_{2005}/F_{MSY}, and N_{2005}/N_{MSY} were calculated as the average values weighted by the average catch composition (1982-2005) reported from the recreational fishery (MRFSS), CSFOP, and PLLOP (NMFS, 2006). The "Complex" column includes the BASE results from this study. The row "$N_{2005} * F_{MSY}$" shows catches recommended if single-species assessments were used to set catch levels (first three columns). The row titled "Complex Catch by Species" divides the complex catch ($N_{2005} * F_{MSY} = 3{,}555$) by average catch composition (1982-2005).

	Scalloped	Smooth	Great	Summed	Complex
r	0.12	0.03	0.08	0.09	0.08
$K\ (\times 10^3)$	160	60	230	450	410
$MSY\ (\times 10^3)$	6.9	0.6	6.7	14.2	12.0
F_{MSY}	0.12	0.03	0.08	0.09	0.08
$N_{MSY}\ (\times 10^3)$	59	22	86	167	150
Depletion (%)	83	91	96	90	90
F_{2005}/F_{MSY} (%)	114	150	220	160	140
N_{2005}/N_{MSY} (%)	47	24	11	31	30
$N_{2005} * F_{MSY}$	3,328	158	757	4,243	3,555
Complex Catch by Species	1,813	427	1,315		

Figures

Figure 4.1. Standardized relative abundance indices used in the assessments.

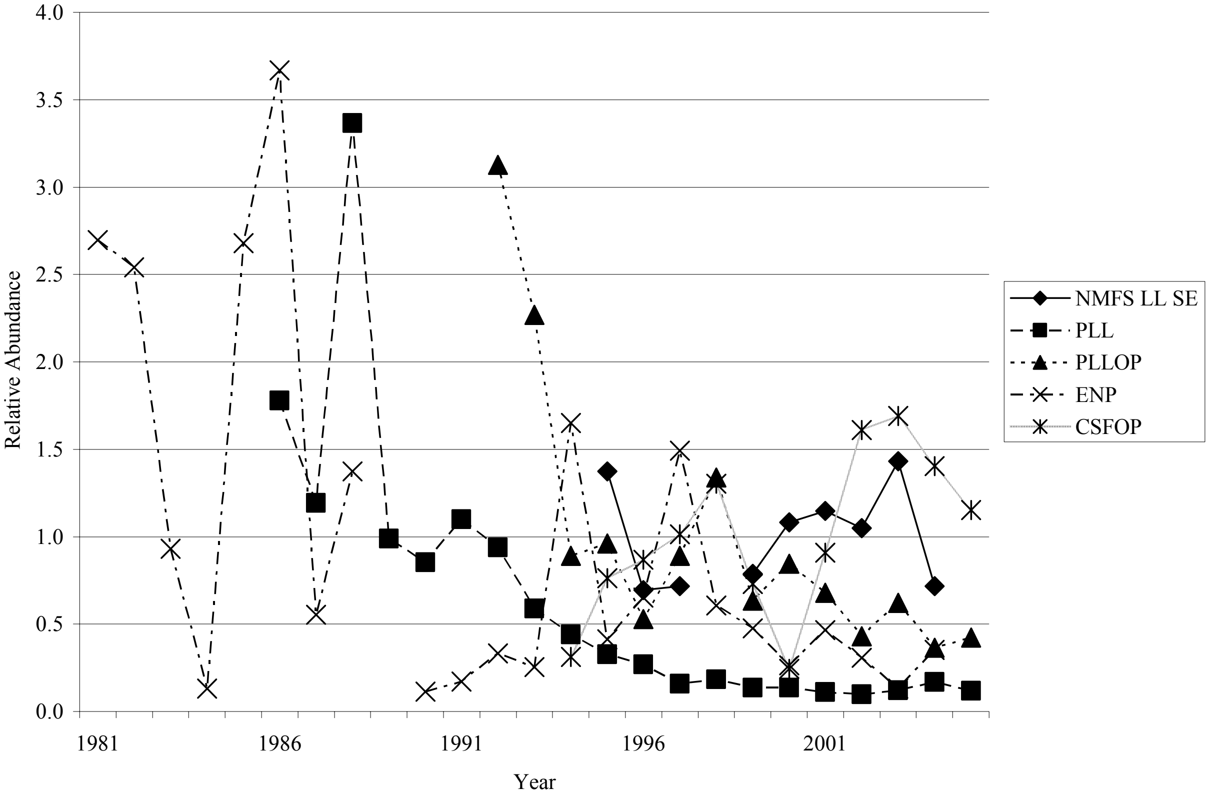


Figure 4.2. Phase plot of hammerhead shark complex population status. Points to the left of the vertical line indicate an overfished status (population size is smaller than that associated with MSY), and points above the horizontal line indicate overfishing.

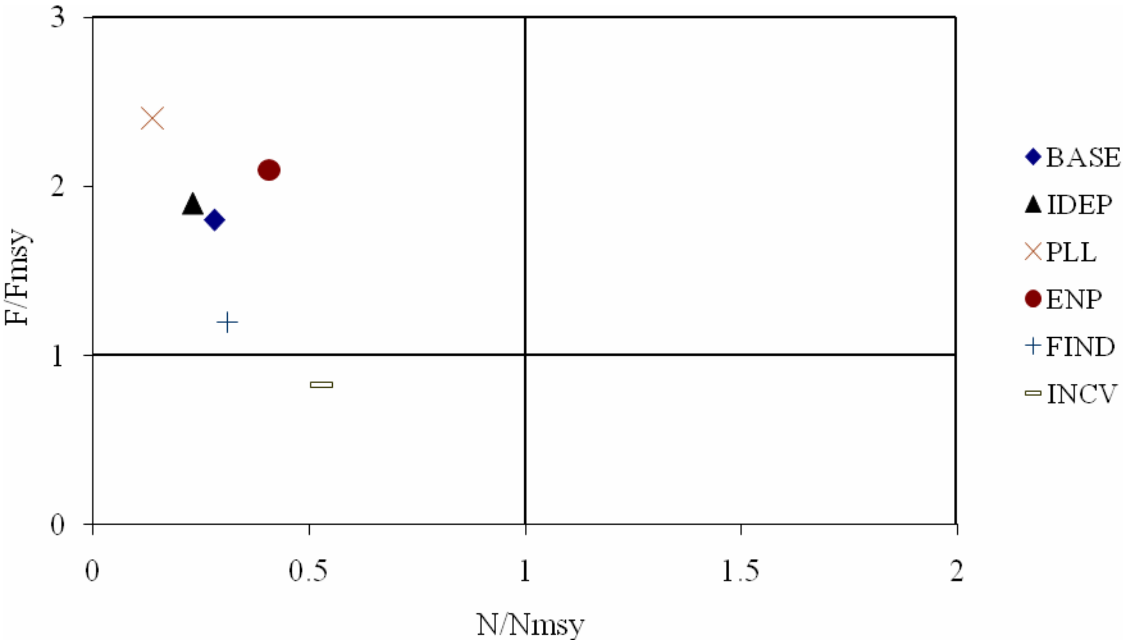


Figure 4.3. Fishing mortality experienced by the hammerhead shark complex, 1981-2005, based on the Fox model.

Figure 4.4. Population abundance estimates of (A) the hammerhead shark complex from this assessment and (B) scalloped hammerhead sharks (white), smooth hammerhead sharks (grey), and great hammerhead sharks (black) from individual stock assessments (Hayes et al., in prep., A; B).

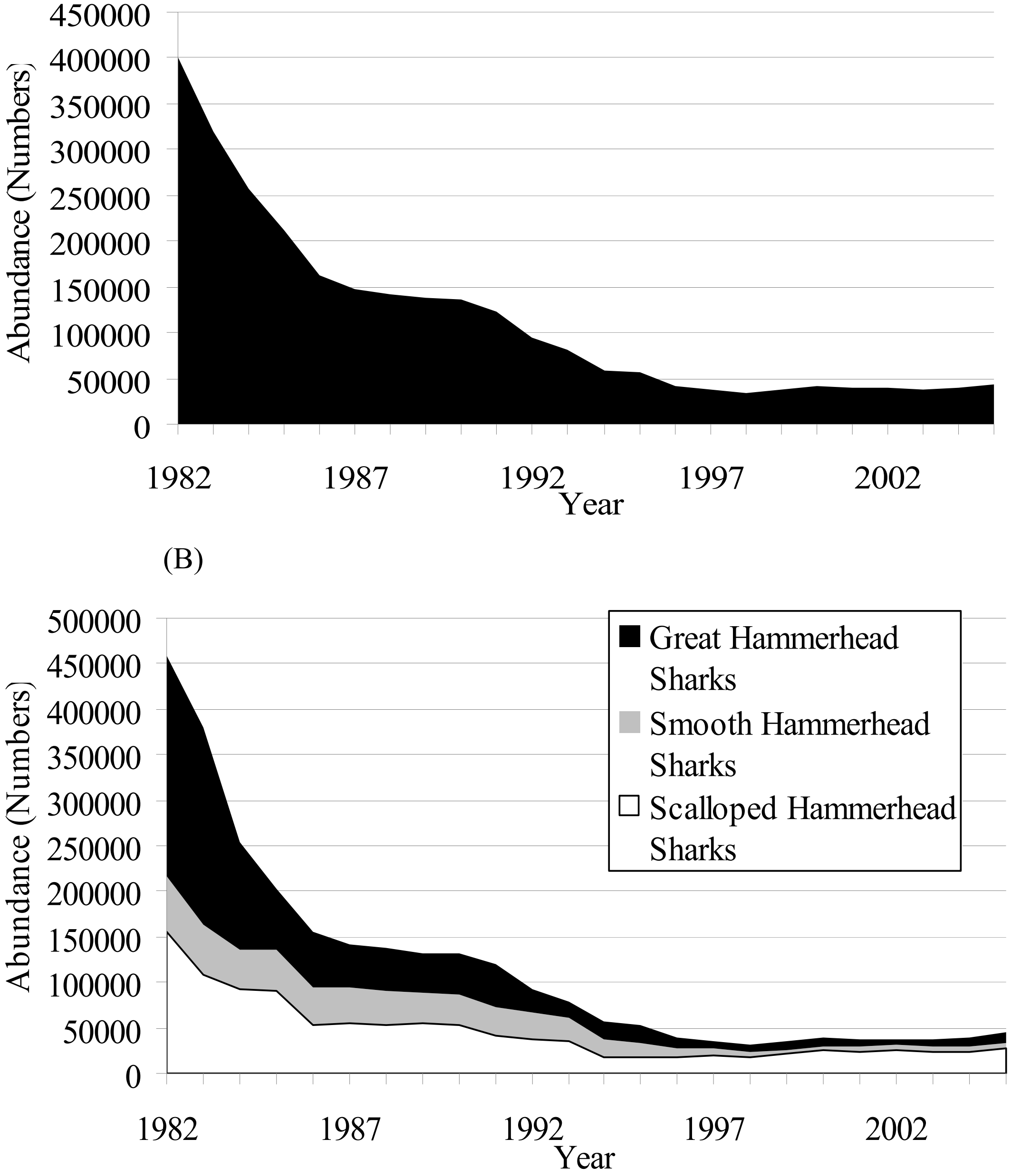
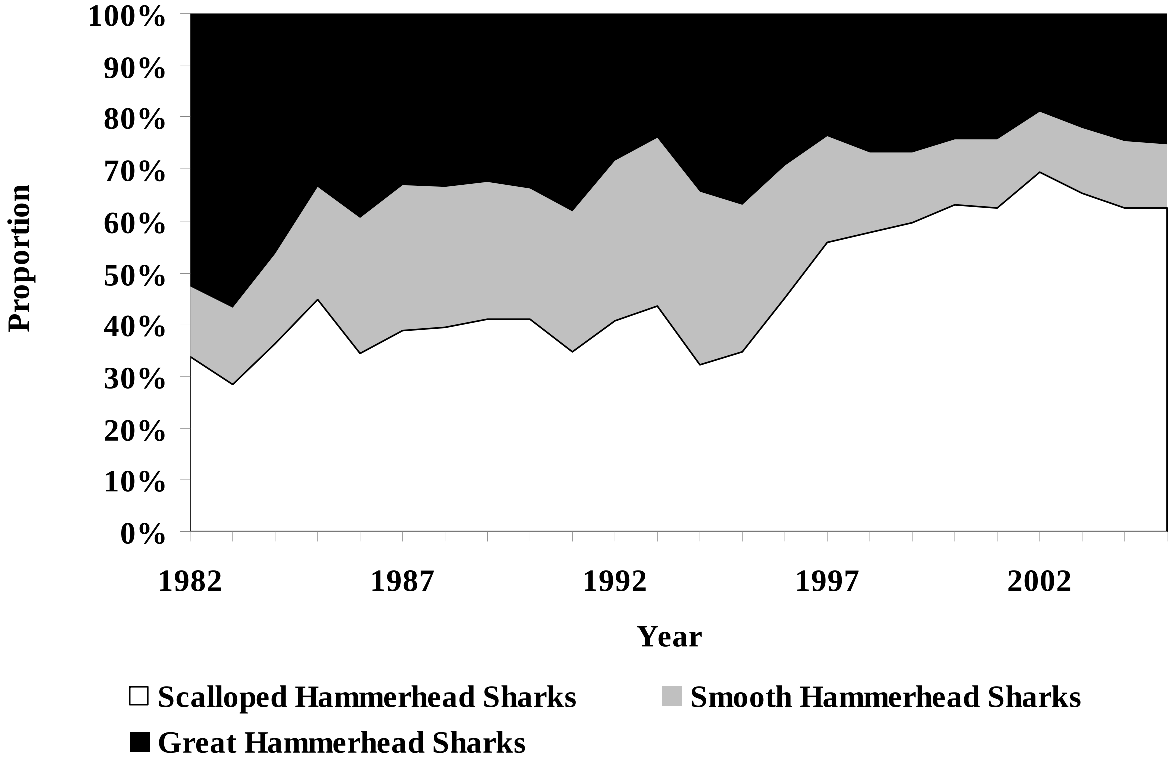


Figure 4.5. Species composition of the hammerhead shark complex based on individual stock assessments. Using a t-test, significant ($p < 0.01$) trends in changes of proportions of scalloped hammerhead sharks (white) and great hammerhead sharks (black) exist, and are a little weaker but still significant for smooth hammerhead sharks (grey; $p = 0.04$).



Appendix 4. Catch data and relative abundance indices available for the hammerhead shark complex (*Sphyrna* spp.).

Year	**Catch**	**NMFS LL SE**	**PLL**	**PLLOP**	**ENP**	**CSFOP**
1981	9858				2.696	
1982	84362				2.542	
1983	71928				0.931	
1984	59493				0.132	
1985	64450				2.679	
1986	30351		1.778		3.668	
1987	16885		1.193		0.553	
1988	16859		3.365		1.374	
1989	13545		0.989			
1990	24895		0.854		0.113	
1991	39064		1.099		0.172	
1992	23814		0.938	3.126	0.331	
1993	32069		0.588	2.268	0.255	
1994	12419		0.440	0.890	1.65	0.313
1995	23125	1.374	0.327	0.960	0.412	0.762
1996	11625	0.694	0.269	0.528	0.651	0.867
1997	10562	0.718	0.159	0.890	1.493	1.014
1998	3412		0.184	1.338	0.606	1.304
1999	3382	0.789	0.137	0.635	0.475	0.730
2000	9440	1.082	0.137	0.846	0.265	0.245
2001	7445	1.145	0.111	0.679	0.466	0.907
2002	8954	1.048	0.099	0.431	0.307	1.611
2003	7131	1.432	0.122	0.622	0.131	1.692
2004	3678	0.717	0.170	0.365	0.352	1.403
2005	6113		0.118	0.423		1.153