Stock Assessment of Dusky Shark in the U.S. Atlantic and Gulf of Mexico

by

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Table of Contents

SUMMARY

Dusky sharks (*Carcharhinus obscurus*) off the U.S. East Coast were classified as a prohibited species in the 1999 NMFS Fishery Management Plan for Atlantic Tunas, Swordfish and Sharks, but have never been individually assessed. In 1997, they were designated by NMFS as a candidate species for listing under the Endangered Species Act (ESA) and as recently as 2004, were listed by the IUCN Red List of Threatened Species as vulnerable in the Northwest Atlantic and Gulf of Mexico.

Despite uncertainty in the magnitude of the catches, due in part to the use of data sets from multiple data collection programs and potential identification problems, all landings/catches showed declines since the early to mid 1990s. Decreasing average size trends from two commercial and two recreational sources as well as a fishery-independent survey suggest that the stock of dusky sharks off the U.S Atlantic and Gulf of Mexico (genetic studies presently support the existence of a single stock) is heavily exploited. All data sources also indicated that the majority of animals caught were immature. Analysis of catch rate (CPUE) series from three commercial, one recreational, and one fishery-independent source, all standardized through Generalized Linear Modeling (GLM) statistical techniques, also yielded decreasing trends, with various degrees of decline from the beginning to the end of the time series considered.

Analysis of biological information in a stochastic demographic framework resulted in very low values of population growth rate as would be expected from a species with very late age at first reproduction (20 years), high longevity (>40 years), and very limited reproductive potential. Accordingly, generation times were also very protracted (30 years) and the juvenile stage identified as the main contributor to population growth according to elasticity analysis.

Multiple stock assessment methods were used to assess the status of dusky shark stocks: three forms of a Bayesian surplus production model, a fully age-structured model, and a catch-free age-structured model. In the baseline analysis, the three forms of surplus production models predicted current depletions of over 80% of virgin biomass. Sensitivity analysis further revealed that results were largely insensitive to the CPUE series used, changes to prior distributions, catch series considered, form and structural assumptions of the surplus production model fitted, importance function used for Bayesian estimation (priors vs. multivariate t), and method for numerical integration (SIR vs. MCMC). The method used to weight the CPUE indices had a larger effect (the most optimistic scenario with surplus production models was obtained with a no-weighting method: 73% depletion), but did not alter conclusions. Depletions estimated through the catch-free model were of similar magnitude to those from the biomass dynamic models. Current SSB (spawning stock biomass) and total biomass values estimated with the catch-free model did not exceed 7% and 8% of virgin biomass, respectively. The age-structured model generally provided the least pessimistic results, but the majority of scenarios still estimated depletions of 62-80% with respect to virgin levels. In all, the various stock assessment methodologies used to estimate present (for 2003) stock status were all consistent in showing large depletions with respect to virgin levels.

The multiple indicators used in this assessment all provided a consistent picture of heavy fishing impact and high vulnerability to exploitation of dusky sharks in the northwestern Atlantic Ocean and Gulf of Mexico. Decreasing temporal trends in mean size of catch and catch rates, in tandem with decreasing biomass and increasing fishing mortality rates derived

from all the stock assessment methodologies used, indicate that the stock considered has been very heavily exploited. Further, the biological indicators mentioned above also indicate that dusky sharks are particularly vulnerable to exploitation. This situation is exacerbated by the low value of the steepness parameter in the stock-recruitment curve (z=0.29) and high inflection point (0.72K) of the population growth curve estimated for dusky sharks, which imply that present stock size might be even farther away from MSY levels than predicted with traditional surplus production theory (where MSY is reached at 0.5K). In all, despite some recent signs of recovery, the dusky shark stock in the U.S. Atlantic and Gulf of Mexico has been severely depleted with respect to virgin (unexploited) levels.

1. INTRODUCTION/MANAGEMENT BACKGROUND

Fisheries affecting Atlantic shark resources are currently managed under the Fishery Management Plan for Atlantic Tunas, Swordfish, and Sharks (HMS FMP), which was implemented in July 1999 (NMFS 1999) and recently amended (NMFS 2003). One of the main objectives of the HMS FMP is to prevent or end overfishing of Atlantic tunas, swordfish and sharks and adopt the precautionary approach to fisheries management. To achieve this and other objectives, after consideration of the 1998 SEW Report (NMFS 1998) and other pertinent factors, NMFS implemented the following management measures (as well as others not listed below) for Atlantic shark resources under the HMS FMP: 1) reduce the recreational bag limit to 1 shark per vessel per trip, with a minimum size of 137 cm fork length for all sharks, and an additional 1 Atlantic sharpnose shark per person per trip; 2) prohibit possession of 19 species of sharks (Atlantic angel, basking, bigeye sand tiger, bigeye sixgill, bigeye thresher, bignose, Caribbean reef, Caribbean sharpnose, **dusky**, Galapagos, longfin mako, narrowtooth, night, sand tiger, sevengill, sixgill, smalltail, whale and white); and 3) limited access. More recently, after consideration of the 2002 large coastal shark stock assessment (Cortés et al. 2002) and other pertinent factors, NMFS (2003) has proposed that species in the prohibited species group be retained and that criteria for the addition or removal of species to/from the prohibited species group be established. NMFS has also implemented a time/area closure for the sandbar and dusky shark nursery and pupping area off North Carolina during the winter fishery to reduce bycatch of neonates and juveniles.

Dusky sharks have never been individually assessed. Prior to 1999, they were part of the large coastal shark group and as such were considered overfished in previous assessments (SEW 1994 [NMFS 1994], SEW 1996 [NMFS 1996], and SEW 1998 [NMFS 1998]) and requiring reductions in effective fishing mortality rate to ensure increase of the stocks toward MSY. The 2002 large coastal shark stock assessment (Cortés et al. 2002) indicated that prohibited species are particularly vulnerable to overfishing because of their low population growth rates and that a stock assessment for dusky shark seemed possible in the relatively near future because biological and fishery information was accumulating. The dusky shark was designated by NMFS as a Candidate Species under the Endangered Species Act (ESA) in 1997, thus warranting special attention. The IUCN Red List of Threatened Species for 2004 (*http://www.flmnh.ufl.edu/fish/organizations/ssg/RLsummary2004.pdf*) classifies it as lower risk, near threatened (close to vulnerable) on a global scale, but vulnerable (A1abd) in the Northwest Atlantic and Gulf of Mexico. The dusky shark is not listed under any of the CITES appendices, but is among the most highly desired species in the international shark fin trade (Clarke et al. 2006).

Available data to conduct a dusky shark stock assessment include landing estimates from commercial and recreational fisheries and some information for bycatch in commercial fisheries; more current biological data on age and growth and reproduction; a long-term fishery-independent relative abundance index as well as a number of fishery-dependent catch rate series capturing different sectors of the fishery; and size information from several sources. The present document is an assessment of resource status and projection of future abundance for the dusky shark in the U.S. Atlantic and Gulf of Mexico.

2. FISHERIES

2.1. Methods

2.1.1. Brief Description of the Fisheries

Prior to its classification as prohibited species in 1999, dusky sharks were regularly landed in both commercial and recreational fisheries along the U.S. east coast. The main commercial fishery catching dusky sharks was the directed shark bottom longline fishery, which operates mostly from North Carolina to Florida's west coast, but extends also westward to Texas and northward to Maine. While also caught incidentally on a variety of other gears, the second-most important gear catching dusky sharks is surface pelagic longline gear targeting tunas and tuna-like species in the western Atlantic Ocean and Gulf of Mexico. Recreationally, dusky sharks were caught predominantly by private anglers and charter boats, with few catches recorded from headboats.

2.1.2. Description of Fishery Data Sources

2.1.2.1. Commercial Catch

Commercial landings estimates of dusky sharks in U.S. east coast waters were obtained from three data collection programs: the Southeast and Northeast general canvass program (general canvass), the Southeast Fisheries Science Center (SEFSC) quota monitoring program (quota monitoring), and the SEFSC Coastal Fisheries Logbook Program (coastal logbook). These different programs provide somewhat different perspectives of landings history because they sample a different universe. In general, the general canvass provides the most comprehensive landings statistics but its species-specific information is not as robust as that in the quota monitoring and logbook programs.

The general canvass data are collected directly from all seafood dealers. Many of the states in the Gulf of Mexico and U.S. South Atlantic coast have trip ticket programs and require that all dealers submit a ticket for every trip that is unloaded in their state, even if the fish are just packed for transport to another dealer. Monthly summaries of these data by species and dealer are provided to the SEFSC. Because the general canvass data are collected from all dealers (i.e., not just dealers with shark permits as with the quota monitoring program), these landings statistics are usually more comprehensive than the data from the quota monitoring program. The amount of time required for individual states to process their trip ticket data is quite lengthy; consequently, the quotas need to be monitored with a separate data collection program. The general canvass also tends to have a larger proportion of unclassified sharks than the quota monitoring or logbook data (with the percent of unclassified sharks around 50% of the total "shark" landings), which further encourages the use of supplementary data sources. Additionally, the northeast general canvass (also known as dealer weighout) database is comprised of data submitted directly by seafood dealers whose facilities are located in the northeast region. Information is collected either by the state in trip-ticket format (general canvass) or by federal port agents, contingent upon the state's data collection process. Preliminary data containing landings of shark and swordfish are submitted to the Northeast Regional Office (NERO) where they are compiled into a Northeast Region Shark/Swordfish Report, which is sent to the SEFSC on a monthly basis. Submission of this subset of the main database was prompted by the immediate need for landings data required for quota monitoring purposes. The Northeast shark landings from this report are incorporated into the quota monitoring updates that are reported to NMFS' Highly Migratory Species (HMS) Division.

The quota monitoring data are also collected from seafood dealers, but only those holding a federal permit. The quota monitoring data are collected by the SEFSC from dealers that meet the following criteria: (1) the dealer has a Federal dealer permit for sharks, (2) the dealer is selected by the SEFSC to report, and (3) the dealer is located in the Southeast Region (North Carolina – Texas). The SEFSC selects all dealers with a shark permit to report. Dealers are required to report twice a month and must submit this report within five days of each two-week period, which allows sufficient turn around time for quota monitoring purposes. In 2001 and 2002, approximately 13% and 15% of the total reported shark landings, respectively, were reported as unclassified.

The coastal fisheries logbook data are submitted by commercial fishermen for vessels with any of the following permits: Gulf of Mexico Reef Fish, South Atlantic Snapper-Grouper, King and Spanish Mackerel, or Shark. A federal permit is required for vessels that fish in the Exclusive Economic Zone (EEZ) for species in these fisheries and the fishermen are required to submit a logbook for every trip where any of the species in these fisheries are caught regardless of whether the vessel fishes in either the EEZ or state territorial waters. Vessels that fish exclusively in state territorial waters are not required to have a federal permit and therefore are not required to report. Thus, there may be trips that are reported to the states and therefore included with the general canvass data, which are not reported to the coastal fisheries logbook program.

Dead discard estimates of dusky sharks in fisheries targeting tuna and tuna-like species were obtained based on mandatory logbooks from longline and other vessels (Large Pelagic Logbook; LPL) and observer reports from these fisheries (SEFSC Pelagic Longline Observer Program) as reported in various publications by Cramer and others. Discard estimates (as a proportion) were also obtained from the directed shark fishery Bottom Longline Observer Program (BLLOP), which was operated by the University of Florida's Museum of Natural History.

2.1.2.2. Recreational Catch

Recreational fishing estimates were obtained from three data collection programs extensively described elsewhere (see Shark Evaluation Annual Reports): the Marine Recreational Fishery Statistics Survey (MRFSS), the NMFS Headboat Survey (Headboat) operated by the SEFSC Beaufort Laboratory, and the Texas Parks and Wildlife Department Recreational Fishing Survey (TXPWD). Briefly, the MRFSS has been sampling private boat owners and charterboats operating in all coastal U.S. states since 1981. Catch estimates are produced by multiplying effort obtained from a random digit dialing statistical survey that samples coastal households and catch-per-effort information obtained from random dockside interviews. Because of inadequate sampling of the charterboat component of the fishery, a new methodology to estimate charterboat effort (for-hire-survey or FHS) was implemented after 1998, but this methodological change had very little effect on catch estimates for dusky sharks. The "old methodology" was thus used to produce catch estimates. Catch estimates presented herein include total catch (A+B1; A=fish brought ashore available for identification to interviewers, B1=fish not brought ashore whole but used as bait, discarded dead, etc.).

The Headboat Survey samples headboats from North Carolina to Louisiana and catch estimates for sharks are available since 1986. Catch estimates from the TXPWD Survey, which samples private boats and charterboats in Texas, are available since 1986.

2.1.2.3. Size Information

Average size information for dusky sharks was obtained from several contrasting sources: the shark fishery bottom-longline observer program (BLLOP), dealer weighout, the Virginia Institute of Marine Science shark longline survey (VIMS LL), MRFSS, and another recreational source, the Large Pelagic Survey (LPS). The LPS collects information on rod and reel and handline recreational fisheries off the U.S. coast from Virginia through Massachusetts. Fishermen are interviewed as they return to the dock and by phone to determine whether the trip was directed at large pelagic game fish (sharks, tunas, billfishes). Interviewers record the number of fish caught and, among other items, the target species, date, boat type, fishing method, and state for each trip. Size information from the Headboat and TXPWD surveys was missing in several years and sample size was too small in others to analyze any trends.

2.1.2.4. Catch Rates

Standardized catch rates for the VIMS LL, BLLOP, and LPS time series were developed using the same GLM methodology applied to other analyses of shark species (Cortés 2002a, Cortés et al. 2002) and other teleost fishes assessed by the SEFSC. Specifically, the approach used to estimate relative abundance indices was a Generalized Linear Mixed Model that treats separately the proportion of sets with positive catches (i.e., where at least one shark was caught) assuming a binomial error distribution with a logit link function, and the catch rates of sets with positive catches assuming a Poisson error distribution with a log link function and using effort as an offset variable. The models were fitted with the SAS GENMOD procedure (SAS Institute Inc. 1999) using a forward stepwise approach in which each potential factor was tested one at a time. Initially, a null model was run with no explanatory variables (factors). Factors were then entered one at a time and the results ranked from greatest to smallest reduction in deviance per degree of freedom when compared to the null model. The factor which resulted in the greatest reduction in deviance per degree of freedom was then incorporated into the model if two conditions were met: 1) the effect of the factor was significant at least at the 5% level based on the results of a Chi-Square statistic of a Type III likelihood ratio test, and 2) the deviance per degree of freedom was reduced by at least 1% with respect to the less complex model. The year factor was always included because it is required for developing a time series.

Results were summarized in the form of deviance analysis tables including the deviance for proportion of positive observations and the deviance for the positive catch rates. Once the final model was selected, it was run using the SAS GLIMMIX macro (which itself uses iteratively reweighted likelihoods to fit generalized linear mixed models with the SAS MIXED procedure; Wolfinger and O'Connell 1993). Goodness-of-fit criteria for the final model included Akaike's Information Criterion (AIC), Schwarz's Bayesian Criterion, and –2* the residual log likelihood (-2Res L). The significance of each individual factor was tested with a Type III test of fixed effects, which examines the significance of an effect with all the other effects in the model (SAS Institute Inc. 1999). The final mixed model calculated relative indices as the product of the year effect least squares means (LSMeans) from the binomial and Poisson components using bias correction terms to calculate confidence intervals.

For the CFL and LPL time series, the GLM methodology applied was that used in previous analyses. Briefly, it is a delta-lognormal approach first developed by Lo et al. (1992), in which the proportion of positive trips and the positive catch rates are modeled separately, and indices of relative abundance obtained with the appropriate log-transform bias adjustments.

2.1.2.4.1. Fishery-Independent Series

Virginia Longline Survey (VIMS LL). This survey, in operation since 1974, utilizes longline gear set in coastal waters of Virginia. Several cruises, which typically cover 4 or 5 fixed stations, are run each year, mostly during the summer. Sample sizes for some years were very low and no dusky sharks were caught in 1986, 1988, or 1994. A number of new variables for use in the analysis were created based on the fields available in the VIMS LL database. Seasons (spring, summer, fall, winter) were assigned based on the month of the year the set took place; the time of day the set started (day, night) was defined based on the time the set started (night from 1800 to 0600 hours); and bottom depth was defined as the mean of the minimum and maximum depths recorded. The measure of effort used was hooks per set multiplied by soak time in hours fished.

2.1.2.4.2. Fishery-Dependent Series

Bottom Longline Observer Program (BLLOP). The BLLOP has been placing scientific observers on bottom longline fishing vessels targeting sharks since 1994. This observer program provides information on species composition, relative abundance, and size composition by region and time of year for species in the large coastal, small coastal, and prohibited species management groups. As of January 2002, observer coverage requirements for this fishery changed from voluntary participation to mandatory compliance (NMFS 2003). Vessels with a current directed shark permit and that have reported shark landings in the past are selected at random. Vessel selection is also made to ensure that areas with higher fishing effort have more vessels selected (NMFS 2003). The analysis for dusky sharks covered the period 1994-2003.

A number of new variables for use in the analysis were also created based on the fields available in the BLLOP database. Seasons (spring, summer, fall, winter) were assigned based on the month of the year the set took place; three geographical areas were defined (Eastern Gulf of Mexico, Mid Atlantic Bight, and South Atlantic) as in the original database; the time of day the set started (day, night) was defined from the time the first hook was set in the water; surface water temperature was defined as the mean of the temperatures when the first hook was set and the last hook was retrieved; bottom depth was defined as the mean depth when the first hook was set and the last hook was retrieved; because of the many different hook sizes and types recorded, a hook size variable was created by collapsing sizes and types into a few categories (small, small J hook, small C hook, medium, medium J hook, medium C hook, large, large J hook, large C hook); the type of bait used is recorded at the beginning of the set and there are several hundred types of bait or bait combinations used, thus a few bait categories were created based on the sets that used only one type of bait or a type that could easily be identified (little tunny, Atlantic sharpnose shark, other shark, other teleost, skate or ray, eel, and other). The measure of effort used was the product of the number of hooks per set, miles of longline per set, and soak time of set in hours.

Large Pelagic Survey (LPS). As explained above, the LPS collects information on rod and reel and handline recreational fisheries off the U.S. coast from Virginia through Massachusetts. Angler interview data were available for the period 1986-2003. Standardized catch rates were developed using the same GLM methodology as used for previous analyses by Brown (most recently, Brown 2002a). Catch rates were expressed as dusky sharks caught per 100 trips and the log of hours fished was used as an offset in the positive catch model.

Large Pelagic Logbook (LPL). The LPL collects information based on mandatory logbooks from longline and other fishing vessels landing swordfish in the U.S. Atlantic, Caribbean, and Gulf of Mexico. Large coastal and pelagic sharks are caught as bycatch (predominantly using longline gear) and less frequently than targeted catch by these vessels (Brown and Cramer 2002). Standardized catch rates were developed using the same GLM methodology as used for previous analyses by Cramer (e.g., Brown and Cramer 2002). Data for dusky sharks were available for the period 1992-2003. Catch rates were defined as catch per 1,000 hooks.

Coastal Fisheries Logbook (CFL). As explained above, commercial fishing vessels operating in the U.S. Atlantic and Gulf of Mexico provide trip reports on catch and effort to a coastal fisheries logbook database. Bottom longline, which is usually targeted at reef fish or sharks, is one of the gear types contained in this database. This analysis used only trip records for which bottom longline gear was specified as used and for which the vessel carried a shark permit at any time (Brown 2002b). Although this logbook program began in 1990, reporting for shark fishing was not required until July 1993, and species identification problems were likely to occur prior to 1996 (Brown 2002b). For these reasons, the analysis for dusky sharks was restricted to the period 1996-2003. Standardized catch rates were developed using the same GLM methodology as used in a previous analysis by Brown (2002b). CPUE was defined as weight of catch divided by the product of the number of hooks per set, miles of longline per set, and soak time of set in hours, multiplied by a factor of 1,000. New variables for use in the analysis included seasons (spring, summer, fall, winter) and geographical areas (Gulf of Mexico, South Atlantic, Mid Atlantic, and North Atlantic). Factors were retained if they contributed significantly ($P<0.05$) to the model.

2.2. Results

2.2.1. Catches

Total annual commercial landings were calculated as the sum of the maximum reported catch in the general canvass southeast, quota monitoring, or coastal fisheries logbook, and the catch reported in the general canvass northeast (or dealer weighout). Total commercial landings peaked in 1995 and 1996 (385,000 and 315,000 lb dw, respectively) as a result of corresponding high values reported in the quota monitoring program in 1995 and 1996 and the coastal fisheries logbook program in 1996 (**Figure 2.1** and **Table 2.1**). Two lower peaks are present in 1992 (as a result of a high value reported in the general canvass southeast), and 1999 (due to a high value reported in the coastal fisheries logbook) and 2000 (as a result mostly of a high value reported in the dealer weighout).

Total estimated recreational catches showed a declining trend from beginning to end of the time series (**Figure 2.1** and **Table 2.2**). Estimates from the MRFSS accounted for the vast majority of the landings and thus mirrored the total landings series. Few dusky sharks were estimated to have been caught recreationally in Texas and generally less than 400 individuals were estimated to have been caught by headboats from 1986 to 2002. Discards from the pelagic longline fishery targeting tuna and swordfish also showed a generally decreasing trend since the series start in 1992, with a noticeable peak of about 2,800 animals or 390,000 lb dw in 1994 (**Figure 2.1** and **Table 2.3**). Annual discards from the directed shark bottom longline fishery were estimated by using an average discard rate obtained from the BLLOP (A. Morgan, FMNH, U. of Florida, pers. comm.) of 6.31% for the period 1994-2003 applied to the maximum reported landings from the general canvass southeast, quota monitoring, or coastal fisheries logbook programs.

Total catches showed several peaks, especially in 1992 and 1994-1997, mirroring corresponding highs in the various fishery sectors (**Figure 2.2** and **Table 2.4**). For the period in which data from the three sources of mortality overlapped (1992-2002), commercial landings accounted for 44% of total catches, recreational catches accounted for 38%, and discards accounted for the remaining 18%.

According to general canvass data, the majority of dusky sharks were commercially landed in the Mid-Atlantic region (all U.S. states between Virginia and New York; average for 1988-2003=58%), whereas 34% and 7% were landed in the South Atlantic (Florida east coast to North Carolina) and Gulf of Mexico (Florida west coast to Texas) regions, respectively (**Table 2.5**). Landings in the North Atlantic region (Connecticut to Maine) were insignificant. Longlines were the predominant gear used to capture dusky sharks in all regions (**Table 2.6**). In the Gulf of Mexico, longlines were the main gear used all years, except 1993 and 2002 (**Figure 2.3**). In the mid-Atlantic, gillnets reportedly accounted for 39% of landings vs. 54% for longlines, and were the predominant gear used in 1991, 1995-1997, and 2001-2002 (**Figure 2.3**). In the South Atlantic, longlines were the main gear used all years, except 1985, 2002, and 2003 (**Figure 2.3**). According to quota monitoring data for the southeast region, dusky sharks were predominantly landed in the Gulf of Mexico from 1993 to 1996, and in the South Atlantic from 1997 on. By state, Florida accounted for the majority of landings all years from 1993 to 2002, with landings on the west coast of Florida predominating during 1993-1998 and on Florida’s east coast, during 1999-2002.

According to coastal fisheries logbook data, the majority of dusky sharks were commercially caught in the Gulf of Mexico region (average for 1991-2003=60%), whereas 29% and 11% were caught in the South Atlantic and Mid Atlantic regions, respectively (**Table 2.7**). Longlines were the predominant gear used to capture dusky sharks in all regions, although in the Mid Atlantic gillnets were also important (**Table 2.8**). In the Gulf of Mexico, longlines were the main gear used all years, whereas in the mid-Atlantic gillnets were the dominant gear in 2000-2003 (followed by lines in 2002) and the sole gear capturing dusky sharks in 2001 and 2003 (**Figure 2.4**). In the South Atlantic, longlines were also the main gear used all years **(Figure 2.4**). By state, Florida also accounted for the majority of landings all years from 1991 to 2003, with landings on the west coast of Florida predominating in 1991-1994, 1996, 1998-1999, and 2001-2003, and on Florida’s east coast in 1995, 1997, and 2000. Other relatively substantial percent contributions from other states came from North Carolina in 1994, 1996, and 1999-2000 (26, 13, 12, and 15%, respectively), South Carolina in 2000 (20%), and Virginia in 1994, 1996-1997, and 2003 (13, 14, 17, and 42%, respectively). **Figure 2.5** shows catches of dusky sharks reported in the coastal fisheries logbook program for 1991-2003 by statistical area.

Data from the three recreational surveys combined indicated that dusky sharks were predominantly caught in the mid-Atlantic region (average for 1981-2002=54%), whereas the South Atlantic and Gulf of Mexico regions accounted for almost exactly the same proportion (23%; **Figure 2-6**). Dusky sharks were predominantly caught in the Mid-Atlantic region all years, except for 1983, 1996, and 2000 when the predominant region was the Gulf of Mexico, and 1981, 1992-93 when the South Atlantic was the main region of catches. In 1995, the Gulf of Mexico and Mid-Atlantic regions accounted for equal parts of the catches (50%).

2.2.2. Average Size

Trends in average size described below must be interpreted cautiously because sample sizes for some years were small and some outliers may have unduly influenced results. Nevertheless, we opted to proceed with the following analyses to provide a general picture of average size trends.

Average sizes from the BLLOP showed a generally declining trend from 1994 to 2003 (**Figure 2.7A**). When the complete data series was considered, the decrease in mean fork length was only significant at the 7% level (P=0.07), but became significant (P=0.045) after removing the value for 2000, which had a much smaller sample size (n=10) than any other year. Mean weight significantly decreased with the complete dataset (P=0.046), but especially after removing the value for 2000 (P=0.012). Examining trends for subsets of the entire series revealed a highly significant decrease both in length and weight from 1994 to 1998 (P=0.003 and P=0.004, respectively), a non-significant increase from 1998 to 2000, followed by a non-significant decrease from 2000 to 2003 (**Table 2.9**). Length-frequency distributions were constructed for the South Atlantic and Gulf of Mexico regions combined (**Figure 2.8**), mid-Atlantic region (**Figure 2.9**), and all areas combined (**Figure 2.10**). The vast majority of observations corresponded to the mid-Atlantic region, where most animals observed were not mature (<225 cm FL; **Figure 2.9**). Adults were especially scarce immediately after the species became prohibited in 2000, but also immediately before that. The same general trend was observed for all areas combined (**Figure 2.10**). **Figures 2.11** to **2.14** show individual dusky sharks reported in the BLLOP off the entire U.S. east coast and by season in the Gulf of Mexico, South Atlantic, and mid-Atlantic regions, respectively, along with bathymetry. **Figure 2.14** also shows the distribution of dusky sharks by maturity stage in relation to the time-area closure off North Carolina and associated bathymetry.

Average sizes from the MRFSS also showed a generally declining trend from 1981 to 2001 (**Figure 2.7B**). When the complete data series was considered, there was a significant decrease in mean total length and weight (P=0.011 and P=0.012, respectively) that became more pronounced after removing the value for the first year of data, 1981 (P=0.002 and P=0.004, respectively) and when considering only the first continuously declining portion of the data series from 1983 to 1992 (P=0.008 and P=0.018, respectively). The remaining subset of data revealed no trends in length or weight from 1994 to 2001 (P=0.81 and P=0.91, respectively; **Table 2.9**).

Average sizes from the VIMS longline survey also showed a generally declining trend from 1974 to 2003 (**Figure 2.7C**). When the complete data series was considered, there was a significant decrease in mean total length and weight (P=0.044 and P=0.039, respectively). Fluctuations in average size during 1974-1987 and the flat tendency during 1990-2003 resulted in no statistically significant trends (**Table 2.9**).

The LPS recreational survey also showed a generally declining trend in average size from 1985 to 1998 (**Figure 2.7D**). When the complete data series was considered, there was a significant decrease in mean total length and especially in weight (P=0.015 and P=0.001, respectively), but examining subsets of the time series for 1985-1993 and 1995-1998 resulted in no significant decreases or increases, respectively, except for a significant decrease in average weight for the period 1985-1993 (**Table 2.9**).

Finally, the dealer weighout data showed a rather flat trend in average weight (**Figure 2.7E**). There was no significant change when the entire data series was considered, but data for 1993-2003 showed a significant decrease (P=0.017).

2.2.3. Catch Rates

Bottom Longline Observer Program (BLLOP). About 26% of the sets analyzed encountered dusky sharks. The effect of the following factors was considered: area, bait type, year, hook type, season, temperature, time of set start, and depth. The proportion of positive catches was explained by the area, year, and bait type factors in that order (**Table 2.10**). An area-year first-order interaction was also considered, but found not to be significant. Mean catch rates for positive catches were explained by area, year, season, and bait type. When running the final model, however, season was not significant and was removed. The final mixed model thus included area, year, and bait type for both the proportion of positive catches and the catch rates of the positive catches. The relative standardized catch rates showed a general increase from 1994 to 1997 (less marked than in the nominal series, which increased till 1998), a steep decline from 1999 to 2000, followed by an increase from 2000 to 2003, which was more pronounced in the standardized time series (P=0.045). Only the 1995 and 1998 nominal values fell outside of the 95% confidence limits of the standardized value for those years (**Figure 2.15**). There was no significant trend in the time series as a whole (**Table 2.11**). The number of observations and proportion of positive sets by year are presented in **Table 2.12**.

Virginia Longline Survey (VIMS LL). About 19% of the sets analyzed encountered dusky sharks. The effect of the following factors was considered: area, year, season, temperature, time of set start, depth, and hook type. Area-year, area-season, and year-season first-order interactions were also considered. The proportion of positive catches was initially best explained by temperature, but this factor became non significant when other individual factors were added to the model. For this reason, area was retained as the sole factor explaining the proportion of positive catches (**Table 2.13**). Mean catch rates for positive catches were explained by year and season. The effect of a year-season interaction was also found to be significant and reduce the deviance/df by more than 1% with respect to the previous model. However, including this interaction in the model resulted in the season factor becoming non significant. For this reason, the final model for positive catches included only year and season. The year factor was added to the proportion positive model because year must be included in all models, but this resulted in year not being significant in the final mixed model. An alternative final mixed model for proportion positive consisting of year only was also included, and year became significant (**Table 2.13**). The final mixed model thus included area and year (or year only) for the proportion of positive catches, and year and season for the catch rates of the positive catches. The relative standardized catch rates showed a generally decreasing trend from 1974 to 2003 that tracked the nominal catch rates pretty closely (**Figure 2.16**). In general, there were peaks in CPUE in 1974-1976 and 1979-1980, with the magnitude of the catch rates declining considerably after that, save for lower peaks in 1987 and 2002. There was a generally increasing trend from the mid-90's (1995) to 2003. Note that no dusky sharks were caught in 1973, 1986, 1988 or 1994 (**Figure 2.16**). There was a highly significant decrease in the time series as a whole (P=0.0004), which could further be decomposed into a significant decrease from 1974 to 1990 and a significant increase from 1990 to 2003 (**Table 2.11**). However, this trend analysis must be interpreted cautiously because sample sizes for several years were very small.

Coastal Fisheries Logbook (CFL). Only about 3.5% of the sets analyzed encountered dusky sharks (**Table 2.12**). The effect of the following factors was considered: year, quarter, region, and vessel. The factors year, quarter, and vessel were significant for the proportion of positive catches model (P for all factors <0.0001), whereas region (P<0.0001), quarter (P=0.0127), and year (P=0.0500) were significant for the positive catch rate model (**Table 2.14**). In stark contrast with the relative nominal catch rates, the relative standardized catch rates showed no discernable trend (**Figure 2.17**; **Table 2.11**). The CVs in 2001 and 2003 were much smaller than those in the remaining years because of small sample sizes (**Table 2.12**).

Large Pelagic Survey (LPS). About 9% of the sets analyzed encountered dusky sharks. The effect of the following factors was considered: year, month, state, region, boat type, tournament, and interview type. The factors state and year explained mean catch rates for the proportion of positive catches, whereas month, state, and interview type explained the positive catch rate model. Although the year effect was not significant, it was retained for the final mixed model. In that model, state and year were significant for the proportion positive, and month, state (at the 8% level), and interview type were significant for the positive catches. The year factor was also included despite not being significant (**Table 2.15**). The relative standardized catch rates for the period 1986-2003 showed a highly significant decreasing trend (**Figure 2.18; Table 2.11**), but with very large CIs. Decomposition of the entire time series into segments revealed a significant decrease during 1986-1995 (P=0.001), followed by another significant decrease during 1996-2001 (P=0.002), and a non-significant increase (P=0.525) for the most recent period available, 2001-2003 (**Table 2.11**).

Large Pelagic Logbook (LPL). About 6% of the sets analyzed encountered dusky sharks. Following earlier work by Cramer (2000) and Brown and Cramer (2002), the factors year, area, quarter, gear type, target species, and light sticks were retained for the proportion of positive catches model, whereas the positive catch rate model additionally included the factors tuna catch rate and swordfish catch rate (**Table 2.16**). The relative standardized catch rates for the period 1992-2003 showed a highly significant decreasing trend (**Figure 2.19**; **Table 2.11**).

Figure 2.20 shows a combined view of the five standardized catch rate series for dusky shark described above. Each series was scaled to its respective mean for the overlapping years among series (1996-2003).

2.2.4. Gear Selectivity and Catchability

Selectivity curves were fitted to age-frequency distributions from the BLLOP, VIMS, LPS, and weighout sources. Age-frequency distributions were obtained from the corresponding length-frequency distributions through an age-length key (see section 3.4). A double logistic distribution scaled to the maximum selectivity value was fitted in each case to age:

$$\frac{1}{1+e^{-\left(\frac{x-a_{50}}{b}\right)}}\times\left(1-\frac{1}{1+e^{-\left(\frac{x-c_{50}}{d}\right)}}\right) \tag{2.1}$$

where a_{50} and c_{50} are median ages (age at which 50% of the population is fully selected) of the ascending and descending limb of the double logistic equation, respectively, and b and d are slopes. Parameter values for the equations fitted to each of the four data sets are summarized in **Table 2.17**. **Figures 2.21** and **2.22** show the fitted equations, proportions at age observed, and normalized ratios of observed to expected proportions at age. Expected proportions at age were obtained from regressing the natural logarithm of the observed proportions at age on age. Linear regression parameter values for each data set are also listed in **Table 2.17**. **Appendix 1** explains the derivation and calculation of selectivities in more detail.

The four selectivity functions were linked to the CPUE and catch series available as follows: VIMS selectivity for VIMS CPUE series, LPS selectivity for LPS CPUE series and recreational catch series, BLLOP selectivity for BLLOP and CFL CPUE series and commercial catch and bottom longline discards series, and weighout selectivity for LPL CPUE series and pelagic longline discards series (**Figure 2.23**). Additionally, the following CPUE and catch series were assumed to have the same catchability: LPS index and recreational catch series, BLLOP index and commercial catch series, BLLOP index and bottom longline discards series, and LPL index and pelagic longline discards series (**Figure 2.23**).

3. BIOLOGY

3.1. Distribution, Movement Patterns, Stock Identity, and Forensic Identification

The dusky shark is a common coastal-pelagic shark occurring in inshore and offshore warm-temperate and tropical continental and insular shelves and adjacent oceanic waters, and ranges from the surf zone to depths of 400 m (Compagno 1984). It is rarely found in areas of reduced salinities or estuaries (Musick et al. 1993). In the Western Atlantic, it ranges from southern New England to southern Brazil, including the Gulf of Mexico and Caribbean (Compagno 1984).

The dusky shark is reported to be strongly migratory in temperate and subtropical areas of the Western North Atlantic, moving north in summer and south in the fall when water temperature decreases (Musick and Colvocoresses 1986). Juvenile dusky sharks occupy coastal nursery grounds from New Jersey to South Carolina for several months (Castro 1993). Tagging studies from the NMFS Cooperative Shark Tagging Program show dusky sharks tagged off New England were recaptured in the southwestern Gulf of Mexico and the Yucatan Peninsula (Kohler et al. 1998). Heist and Gold (1999) used nucleotide sequences from mitochondrial DNA from several large coastal sharks and found that sequences from one individual dusky shark accurately predicted restriction fragment sites in specimens collected thousands of km from where the original specimen was collected. Based on this genetic identification study and the limited tagging data available, the working hypothesis is that there is a single stock of dusky sharks in the Western North Atlantic.

DNA sequence differences were used by Heist and Gold (1999) to provide a diagnostic means of discriminating among the most commonly landed *Carcharhinus* species in the U.S. Atlantic fishery, allowing separation of the dusky shark and similar species such as sandbar and bignose sharks. Pank et al. (2001) further used species-specific primers to distinguish between the dusky shark and the morphologically similar sandbar shark. Using a similar technique, Shivji et al. (2002) found that the dusky shark could be distinguished from five other species likely to be encountered in North Atlantic fisheries (shortfin and longfin makos, porbeagle, silky, blue), but not from the oceanic whitetip shark.

3.2. Age, Growth and Size

Female and male dusky sharks in the western North Atlantic reach at least 371 and 360 cm TL, respectively. Von Bertalanffy growth parameters derived by Natanson et al. (1995) for females and males are summarized in **Table 3.1**. Brody growth coefficients for this species are very low (<0.04) consistent with the "slow" life history strategy of this species, which is characterized by slow growth, high longevity, large offspring, and limited reproductive output (Cortés 2000).

3.3. Reproduction and Maturity

The reproductive cycle of dusky sharks is not well understood (Romine 2004). Gestation period may last up to 24 months according to Branstetter and Burgess (1996; cited in Romine 2004) and the lack of large yolky ova in late-term females is indicative of at least a one-year resting period following parturition (Branstetter and Burgess 1996), which means reproductive frequency in this species is likely to be triennial. Litter size can range from 2 to 12 pups (mean=7.1, SD=2.05; data from the BLLOP supplied by Alexia Morgan; **Table 3.1**). No increase in litter size with maternal size has been documented. Pups are born large, at a size between 85 and 100 cm TL. Maturity ogives were developed for females and males using data from the BLLOP (Alexia Morgan, pers. comm.). Natanson et al. (1995) reported that females became mature at 235 cm FL (284 cm TL), corresponding to an age of 21 yr, and males matured at 231 cm FL (279 cm TL), corresponding to an age of 19 yr. A logistic regression of the form:

$$P = \frac{1}{1+e^{-(a+bFL)}} \tag{3.1}$$

was fitted to binomial maturity data from the BLLOP for females (n=332) and males (n=544) separately, where P is fraction mature and a and b are parameters of the logistic regression (proc logistic, SAS Inc. 1999). Median size at maturity (size at which 50% of the population becomes mature) was estimated at 226 and 224 cm FL for females and males, respectively (273 and 271 cm TL, respectively). Maturity ogives for females and males looked almost identical (**Figure 3.1A**) and thus no statistical difference was found (P=0.373; Chi-Square test in a type-III analysis of the effect of sex; SAS Inc. version 8.1). When transformed through the corresponding von Bertalanffy growth equations from Natanson et al. (1995), these median lengths at maturity correspond to median ages at maturity of 20 and 18 yr for females and males, respectively (**Table 3.1**; **Figure 3.1B**).

3.4. Lifespan, Mortality, and Survivorship

Natanson et al. (1995) estimated a maximum age of at least 33 yr using vertebral sections, but noted that a dusky shark that had been at liberty for 12 yr was likely to be close to 40 yr of age. Ages in excess of 40 years are thus not unlikely.

Natural mortality was estimated through multiple indirect methods based on predictive equations of life-history traits. The methods of Pauly (1980), Hoenig (1983), Peterson and Wroblewski (1984), Chen and Watanabe (1989), Jensen (1996) (see Cortés 2004 and references therein for a review), Rikhter and Efanov (1976) and Lorenzen (1996) were used to estimate M (instantaneous natural mortality rate). The methods of Peterson and Wroblewski, Chen and Watanabe, and Lorenzen allowed derivation of size-specific natural mortality estimates, which were then transformed into age through the VBGF. M obtained through Pauly's method using a mean water temperature of 20 °C was 0.088 and annual survivorship from natural mortality ($S=e^{-M}$) thus 0.92. Hoenig's method for a 40-yr lifespan yielded M=0.104 (S=0.90). Jensen's method based on age at maturity (using a median t_{mat} for females of 20 yr) resulted in M=0.082 (S=0.92) whereas Jensen's method based on K (using the value for females of 0.039) yielded M=0.059 (S=0.94). Rikhter and Efanov's method, which is also based on age at maturity, yielded M=0.021 (S=0.98). The Peterson and Wroblewski method using weight (wet) at age obtained from length at age (derived with the length-weight relationship described in the next section) produced M estimates ranging from 0.210 (S=0.81) for age-0 sharks to 0.083 (S=0.92) for age-40+ sharks. Lorenzen's method (for ocean systems) produced similar age-specific estimates, which ranged from 0.248 (S=0.78) for age-0 sharks to 0.083 (S=0.92) for age-40+ sharks. Chen and Watanabe's method yielded M estimates ranging from 0.162 (S=0.85) to 0.051 (S=0.95) for age-0 to age-30 sharks, and an average M of 0.047 (S=0.95) for their period of "stable mortality" for sharks age-31+.

Total mortality (total instantaneous mortality rate, Z) was estimated through catch curves using an age-length key and the growth curves developed by Natanson et al. (1995). The probabilistic method developed by Goodyear (1997) could not be applied because all data required in this approach were not available. The first catch curve was constructed using an age-length key generated from the original length-age pairs used by Natanson et al. (1995) applied to length data from the BLLOP. The second catch curve was generated by estimating ages from lengths directly from the growth curves. Estimates of Z from both methods were almost identical ($Z=0.098$, $P<0.0001$, and $Z=0.091$, $P<0.0001$, respectively) (**Figure 3.2C**). The age-frequency distribution and the lack of an ascending limb to the catch curves indicated that dusky sharks recruit to the fishery in their first year of life (**Figure 3.2B,C**). An attempt to estimate F from average size statistics using the approach developed by Ault et al. (1996) and available in the computer program FiSAT (FAO stock assessment library; FAO 2003) was abandoned because the package was unable to estimate Z in some years and an average estimate of M was larger than the corresponding estimate of Z for most years.

3.5. Conversion Factors

Length to length and weight to length relationships used for transformations between variables in different analyses are presented here for convenience. Both equations came from Kohler et al. (1995):

$$FL(cm) = 0.8396TL(cm) - 3.1902 \tag{3.2}$$

$$W(kg) = 3.2415x10^{-5} FL(cm)^{2.7862} \tag{3.3}$$

3.6. Life Tables, Population Parameters, and Elasticities

To produce biologically motivated priors for parameters in the surplus production models, an age-structured life table with a yearly time step applied to data for females was used to generate population growth rates and other parameters of interest. Uncertainty in vital rates was incorporated through Monte Carlo simulation, an approach that allows consideration of a wide range of plausible parameter values. Lifespan, age-specific fecundity, and age-specific survivorship were randomly selected from assumed pdfs based on the biological data described in the sections above (**Table 3.2**). It was assumed that lifespan was represented by a linearly decreasing distribution scaled to a total relative probability of 1, with the likeliest value (39 yr) taken from empirical observations and the least likely value set to 51 yr (section 3.4). Age-specific annual survival probability was also assumed to be described by a linearly decreasing distribution scaled to a total relative probability of 1, with the likeliest value set to the minimum of the estimates from the Peterson and Wroblewski and Lorenzen methods (see section 3.4) and the least likely value set to the maximum of the estimates from the six other methods (which was Rikhter and Efanov's estimate). Age-specific annual fecundity was represented by a lognormal distribution with a mean of 7.1, SD=2.05, and range of 2 to 12 pups. This value was then multiplied by the proportion of mature females at age obtained from the maturity ogive and further divided by 4 or 6 to account for a 1:1 male to female ratio and a biennial or triennial reproductive cycle (see section 3.3). It was also assumed that

100% of females were reproductively active after reaching maturity. Age at first reproduction was set to 21 yr. Population parameter estimates were obtained with traditional life table techniques (see Cortés 2002, e.g.) within the probabilistic Monte Carlo approach. A total of 10,000 iterations were used to generate the output population parameter estimates of interest, which included r (intrinsic rate of population increase), λ ($=e^r$), R_o (net reproductive rate), three definitions of generation time (A, T, and υ_1; see Caswell 2001), and fertility, juvenile survival, and adult survival elasticities (proportional matrix sensitivities). Simulations were performed using MS Excel spreadsheets equipped with a risk assessment add-in (Crystal Ball 2000) and MS VBA macros for automation.

Population growth rates were low (r=0.023 or λ = 1.023) and generation times long (A=T=29, υ_1= 30 yr). Juvenile survival contributed by far the most to λ (66%), compared to adult survival elasticity (31%) and especially fertility elasticity (3%). **Table 3.2** presents summary statistics for population parameters of interest.

Several statistical distributions were fitted to the 10,000 values of r generated in the simulation with the aim of obtaining parameter estimates for a distribution to be used as a prior in Bayesian surplus production models (see section 4.1.1.4). A normal distribution (mean=0.02, SD=0.01) provided the best fit (Chi-square P-value=0.14; values >0.50 indicate a close fit).

3.7. Stock-recruitment and MSY Reference Points

The stock-recruitment relationship in sharks is largely unknown, but it is generally believed that recruitment is directly related to stock size. Several recent Atlantic shark stock assessments (Apostolaki et al. 2002, Brooks et al. 2002, Cortés 2002, Cortés et al. 2002, Simpfendorfer and Burgess 2002) assumed a Beverton-Holt stock-recruitment relationship and used a convenient reparameterization for recruitment in the form of z, the steepness of the stock-recruitment curve. Steepness ranges from 0.2 (direct relationship between recruitment and spawning stock) and a theoretical maximum of 1 (Hilborn and Mangel 1997). The steepness parameter was shown by Myers et al. (1999) to be related to the maximum lifetime reproductive rate through the equation:

$$z = \frac{\alpha}{4+\alpha} \tag{3.4}$$

In this case, the value of α represents the number of pups produced by each reproductive female over its entire lifetime at very low densities, i.e., assuming no density dependence (Myers et al. 1999). This is analogous to R_o, the net reproductive rate from life tables, multiplied by pup (age 0) survival, which is simply:

$$\alpha = R_0 S_0 = \sum_{x=1}^{n} l_x m_x S_0 \tag{3.5}$$

where l_x and m_x are the survivorship and fertility schedules, respectively, at age (from age 0 to maximum lifespan).

Fowler (1988) showed that different organisms had varying positions of the inflection point of their population growth curves. Slow-growing and long-lived species such as many species of sharks would have their inflection point (R) shifted to the right or, in terms of MSY, it would be reached at a higher proportion of carrying capacity than the value of 0.5K traditionally assumed in fisheries work. Using an equation derived by Fowler (1988) that relates R to the rate of increase per generation (rT), Cortés (in press) postulated that several species of pelagic sharks may reach MSY at values much closer to 1K than 0.5K. A recent assessment of shortfin makos, for example, estimated R values close to 0.7 for this species (ICCAT 2005).

In the Monte Carlo simulation described in section 3.6, values of R (position of the inflection point of population growth curves) and z (steepness) were also monitored. The values of R_o and α for dusky sharks were low (1.97 and 1.69, respectively) as was the corresponding value of z (0.29). The simulations also predicted that dusky sharks would reach MSY at 0.72K on average (**Table 3.2**). Statistical distributions were also fitted to the 10,000 values of z generated in the simulation. A gamma distribution (location=0.05, scale=0.01, shape=48.44) provided the best fit (Chi-square P-value=0.56).

4. STOCK ASSESSMENT

4.1. Stock Assessment Models

4.1.1. Bayesian Surplus Production Models

Three Bayesian variants of Schaefer's biomass dynamic model were applied. The population dynamics are given by the familiar equation:

$$B_{t+1} = B_t + rB_t(1 - \frac{B_t}{K}) - C_t \tag{4.1}$$

where B_t is stock abundance in year t, r is the intrinsic rate of increase from the logistic equation, K is carrying capacity, and C_t is catch in year t.

4.1.1.1. Bayesian Surplus Production (BSP) Model

The Bayesian Surplus Production (BSP) model program (McAllister and Babcock 2004) fits a Schaefer model to CPUE and catch data using the SIR algorithm. The model was used in its discrete time form (i.e., the traditional Schaefer model).

The expected catch rate (CPUE) for each of the available time series j in year t is given by:

$$\hat{I}_{j,t} = q_j B_t e^{\varepsilon_t} \tag{4.2}$$

where q_j is the catchability coefficient for CPUE series j, and ε_t is the residual error, which is assumed to be normally distributed. The program allows for a variety of methods to weight CPUE data points.

In the inverse variance method (method 3 in the BSP software and hereafter referred to as method 3), the annual observations are proportional to the annual CV^2 (if available) and the average variance for each series is equal to the MLE estimate. The log likelihood function of the abundance indices is expressed as:

$$\ln L = -\sum_{j=1}^{j=s}\sum_{t=1}^{t=y}\left\{\frac{0.5}{c_j {CV_{j,t}}^2 {\hat{\sigma}_j}^2}\left[\ln\left(\frac{I_{j,t}}{q_j N_t}\right)\right]^2 - 0.5\ln(c_j {CV_{j,t}}^2 \hat{\sigma}_j^2)\right\} \tag{4.3}$$

where s is the number of CPUE series, y is the number of years in each CPUE series, $CV_{j,t}^2$ is the coefficient of variation for series j in year t, c_j is a constant of proportionality for each series j chosen such that the average variance for each series equals its estimated average variance, σ_j^2 (the MLE estimate). The catchability coefficient for each time series (q_j) is also estimated as the MLE such that:

$$\hat{q}_j = e^{\left(\frac{\sum_{t=1}^{t=y}\left(\ln(I_{j,t})-\ln(\widehat{B_t})\right)/c_j {CV_{j,t}}^2 \widehat{\sigma_j^2}}{\sum_{t=1}^{t=y} 1/(c_j {CV_{j,t}}^2 \widehat{\sigma_j^2})}\right)} \tag{4.4}$$

In the input variance method (method 6), the annual observations are divided by the inputted variances or CVs. The log likelihood function of the abundance indices is simply:

$$\ln L \simeq -\sum_{j=1}^{j=s}\sum_{t=1}^{t=y}\frac{\left[\ln(I_{j,t})-\ln(\widehat{q_j}\widehat{B_t})\right]^2}{{CV_{j,t}}^2} \tag{4.5}$$

In the no weighting or inputted equal weighting method (method 1), $\sigma^2=1$ for all points and the log likelihood function of the abundance indices is:

$$\ln L \simeq -\sum_{j=1}^{j=s}\sum_{t=1}^{t=y}\frac{\left[\ln(I_{j,t})-\ln(\widehat{q_j}\widehat{B_t})\right]^2}{2\sigma^2} \tag{4.6}$$

Additionally, weighting method 10 is the same as method 1, but only one global σ is estimated.

4.1.1.2. Bayesian Surplus Production Model-Spreadsheet version

This version of the Bayesian Surplus Production model was developed to emulate the BSP and also fits a Schaefer model to CPUE and catch data using the SIR algorithm (Cortés 2002). The marginal posterior distributions for each of the population parameters of interest are obtained by integrating the joint probability with respect to all the other parameters, as described in McAllister and Kirkwood (1998; equation 20, p. 1043). Posterior CVs for each population parameter estimate are computed by dividing the posterior SD by the posterior expected value (mean) of the parameter of interest (McAllister and Kirkwood 1998; equation 21, p. 1043). The importance function used in the SIR algorithm is the joint prior pdf of θ (vector of parameter estimates K, r, B_{74}/K, and C_0). This model was implemented in MS Excel and the VBA language. The functions used to generate random variables came from the Excel add-in, PopTools (Hood 2000), which uses DLL functions originally written in Pascal in the TPMath numeric library.

In this model, the likelihood function is given by:

$$L\left(data \mid K, r, C_0, B_{74}/K\right) = \prod_{j=1}^{j=s}\prod_{t=1}^{t=y} \frac{1}{\hat{\sigma}_j CV^2{}_{j,t}\sqrt{2\pi}} e^{\frac{-\left(\ln I_{j,t} - \ln \hat{I}_{j,t}\right)}{2\hat{\sigma}_j{}^2 CV^2{}_{j,t}}} \tag{4.7}$$

where σ^2 is the MLE estimate for each CPUE series:

$$\sigma^2 = \sum_{t=1}^{t=y} \frac{\left(\ln I_t - \ln \hat{q}\hat{B}_t\right)^2 / CV^2{}_t}{n} \tag{4.8}$$

and q is also the MLE estimate for each CPUE series:

$$\hat{q} = e^{\left(\frac{\sum_{t=1}^{t=y}\left(\ln I_t - \ln \hat{B}_t\right)/CV_t^2}{\sum_{t=1}^{t=y} 1/CV^2{}_t}\right)} \tag{4.9}$$

4.1.1.3. WinBUGS Bayesian Surplus Production Model

This implementation of the Schaefer surplus production model uses Gibbs sampling, an MCMC method of numerical integration to sample from the posterior distribution using WinBUGS (Spiegelhalter et al. 2000). The model was originally developed by Meyer and Millar (1999a) and modified by Cortés (2002) and Cortés et al. (2002) to apply it to small and large coastal sharks, respectively. To minimize correlations between model parameters and speed mixing of the Gibbs sampler, the surplus production model (eq. 4.1) is reparameterized by expressing the annual biomass as a proportion of carrying capacity:

$$P_t = P_{t-1} + rP_{t-1}(1 - P_{t-1}) - \frac{C_{t-1}}{K} e^{P_t} \tag{4.10}$$

where $P_t = B_t/K$. The model is a state-space model, which relates the observed catch rates (I_t) to unobserved states (B_t) through a stochastic observation model for I_t given B_t (Millar and Meyer 1999, Meyer and Millar 1999b):

$$I_t = qKP_t e^{O_t} \tag{4.11}$$

The model thus assumes lognormal error structures for both process and observation errors (e^P and e^O), with $P_t \sim N(0,\sigma^2)$ and $O_t \sim N(0,\tau^2)$. In the present implementation, the catchability coefficient for each CPUE series is taken as the MLE.

The crucial equation for Bayesian inference is the joint posterior distribution of the unobservable states given the data, which is equal to the product of the joint prior distribution and the sampling distribution (likelihood):

$$\begin{aligned} &p(K, r, q, C_0, B_{74}/K, \sigma^2, \tau^2, P_1, ..., P_n, I_1, ..., I_n) = \\ &p(K)\,p(r)\,p(q)\,p(C_0)\,p(B_{74}/K)\,p(\sigma^2)\,p(\tau^2)\,p(P_1 \mid \sigma^2) \\ &\times \prod_{i=2}^{i=m+1} p(P_t \mid P_{t-1}, K, r, C_0, \sigma^2) \prod_{i=m+2}^{i=n} p(P_t \mid P_{t-1}, K, r, \sigma^2) \prod_{t=1}^{t=n} p(I_t \mid P_t, q, \tau^2) \end{aligned} \tag{4.12}$$

where, in this case, m is the number of years of unobserved catches (C_0).

4.1.1.4. Prior Probability Distributions, Alternative Hypotheses, and Performance Indicators

Alternative hypotheses were generated by drawing alternative values from the parameters assigned priors (r, K, B_{1974}/K, and C_0). The prior for K was uninformative, uniform on the natural log of K over the range 10 to 1.5 x 10^9 lb dw (roughly equivalent to the prior used for shortfin mako in a recent assessment; ICCAT 2005). This prior is proportional to the inverse of K and thus assigns less credibility to higher values of K (McAllister and Kirkwood 1998). The prior chosen for r was based on results from stochastic demographic modelling (see section 3.6) and was thus informative: a lognormal distribution with mean=0.023 (mean and median value obtained in the life table simulations) and SD=0.01 (or SD in the logarithm of r (σ_r) equal to 0.42). The SD in the logarithm of r is calculated as (McAllister et al. 2001):

$$\sigma_r = \sqrt{\ln\left(1 + \left(\frac{SD_r}{\bar{X}_r}\right)^2\right)} \tag{4.13}$$

Although a normal distribution provided the best fit to the 10,000 r values generated through demographic modelling, a lognormal distribution was chosen instead to ensure that values of $r<0$ did not occur, also concentrating most of the density towards the lower values of r. For the BSP model, the lognormal distribution was further constrained with lower and upper bounds set at 0.001 and 2.0, respectively; for the WinBUGS model, lower and upper bounds were set at 0.01 and 0.50.

Informative priors were also used to describe the ratio of the stock abundance in 1974 with respect to K (B_{1974}/K) and the average catch from 1974 to 1980 (C_0). For B_{1974}/K, the prior was lognormal with mean=0.85, SD in the logarithm of 0.20, and lower and upper bounds of 0.2 and 1.1 (BSP and WinBUGS). This prior reduces the probability that B_{1974}/K will be much higher than K (18% of the pdf is >1 with this prior vs. 45% if the mean=1). For the BSP and BSP-spreadsheet models, the prior for C_0 was also lognormal (BSP) with mean=292,580 lb dw (average observed catch during 1981-2003) and SD in the logarithm of C_0 of 0.2. Lower and upper bounds of 10 and 1,000,000 were used in the BSP model. In the WinBUGS model, the prior for C_0 was assumed to be a normal pdf with mean=292,580 lb dw and SD=57,735. Although the same priors were initially specified for the BSP and WinBUGS models, they were sometimes changed to avoid convergence problems.

Priors for the observation error variance (τ^2) and process error variance (σ^2) in the WinBUGS model were inverse gamma distributions as used in previous stock assessments (Millar and Meyer 199a, Cortés 2002, Cortés et al. 2002), i.e., the 10% and 90% quantiles were set at approximately 0.05 and 0.15, and 0.04 and 0.08, respectively.

Performance indicators for the BSP model included the maximum sustainable yield (MSY=rK/4), the stock abundance in the last year of data (B_{2003}), the ratio of stock abundance in the last year of data to carrying capacity and MSY (B_{2003}/K and B_{2003}/MSY), the fishing mortality rate in the last year of data as a proportion of the fishing mortality rate at MSY (F_{2003}/F_{msy}), and the catch in the last year of data as a proportion of the replacement yield (C_{2003}/R_y). For the spreadsheet version of the BSP model, only MSY, B_{2003}, and B_{2003}/K and B_{2003}/MSY were computed. For the WinBUGS model, performance indicators included MSY, B_{2003}, B_{2003}/K and B_{2003}/MSY, and the relative biomass and fishing mortality trajectories, i.e., B_i/B_{MSY} and F_i/F_{MSY}, where i is year (these were also computed for the BSP model).

4.1.1.5. Methods of Numerical Integration, Convergence Diagnostics, and Decision Analysis

For the BSP model, numerical integration was carried out using the SIR algorithm (Berger 1985, McAllister and Kirkwood 1998, McAllister et al. 2001) built in the BSP software. The marginal posterior distributions for each of the population parameters of interest were obtained by integrating the joint probability with respect to all the other parameters. Posterior CVs for each population parameter estimate were computed by dividing the posterior SD by the posterior expected value (mean) of the parameter of interest. Two importance functions were used in the SIR algorithm: the multivariate Student t distribution and the priors. For the multivariate Student t distribution, the mean is based on the posterior mode of θ (vector of parameter estimates K, r, B_{74}/K, and C_0), and the covariance of θ is based on the Hessian estimate of the covariance at the mode (see McAllister and Kirkwood [1998] and references therein for full details). A variance expansion factor of 2 was generally used to make the importance function more diffuse (wider) and ensure that the variance of the parameters was not underestimated when using the multivariate Student t distribution.

The spreadsheet version of the BSP model also used a form of the SIR algorithm for numerical integration, which saves the sets of parameter vectors that will be later used for the decision analysis. This is accomplished by setting a threshold that allows a sufficient number of parameter vectors to be selected. The threshold is set to a value corresponding to the maximum likelihood for any parameter vector θ, which guarantees that no parameter vectors will be sampled more than once. This is the same rationale applied in the Bayesian spreadsheet models developed by Punt and Hilborn (2001).

WinBUGS uses an MCMC method called Gibbs sampling (Gilks et al. 1996) to sample from the joint posterior distribution. All runs were based on two chains of initial values (where the P_t values were set equal to 0.5 and 1.0, respectively) to account for over-dispersed initial values (Spiegelhalter et al. 2000), and included a 5,000 sample burn-in phase followed by a 100,000 iteration phase.

Convergence diagnostics for the BSP model included the ratio of the CV of the weights to the CV of the product of the likelihood function and the priors, with values <1 indicating convergence and values >10 indicating likely convergence failure, and the maximum weight of any draw as a fraction of the total importance weight, which should be less than 0.5% (McAllister and Babcock 2004). For the spreadsheet version of the BSP model, the fraction of the total likelihood accounted for by the most likely parameter vector (maximum) was monitored as recommended by Punt and Hilborn (2001), who indicate that values should not exceed 5%, and preferably be <0.5%.

In the WinBUGS analyses, convergence of the MCMC algorithm for the two chains was tested using convergence diagnostics implemented with BOA (Smith 2001), which is an S-Plus program that carries out convergence diagnostics of the output of WinBUGS and other Bayesian analysis software. The tests implemented included examining lags and autocorrelations of parameters, cross-correlations matrices, and the convergence diagnostics of Brooks, Gelman and Rubin (Gelman and Rubin 1992), Geweke (Geweke 1992), Heidelberger and Welch (Heidelberger and Welch 1983), and Raftery and Lewis (Raftery and Lewis 1992).

For the BSP model, posterior expected values for several indices of policy performance were calculated using the resampling portion of the SIR algorithm built in the BSP software, which involves randomly drawing 5,000 values of θ with replacement from the discrete approximation to the posterior distribution of θ, with the probability of drawing each value of θ being proportional to the posterior probability calculated during the importance sampling phase. Details of this procedure can be found in McAllister and Kirkwood (1998) and McAllister et al. (2001), and references therein. Once a value of θ was drawn, the model was projected from 1974 to 2003, and then forward, while applying one of the constant TAC (total allowable catch; 0 and current TAC) policies from 2004 on. The projections included calculating the expected value of B_{fin}/K (with fin=2013, 2023, and 2033) and the probabilities that B_{fin} were $< 0.2K$, $B_{fin} > 0.5K$, and $B_{fin} > B_{2003}$.

Decision analysis was also carried out using the spreadsheet version of the BSP model. The parameter vectors saved during the stock assessment phase were used to evaluate the consequences of different TACs in the future. For this assessment, only process error was considered following Punt and Hilborn (2001). The projection model becomes stochastic to account for autocorrelation in process error to mimic factors such as recruitment variability that would propagate through time. Equation 4.1 thus becomes:

$$B_{t+1} = \left(B_t + rB_t(1 - \frac{B_t}{K}) - C_t \right) e^{\varepsilon_t} \tag{4.14}$$

where e^{ε_t} is the factor for the lognormal, multiplicative process error:

$$\varepsilon_t = \rho_p \varepsilon_{t-1} + \sigma_p \sqrt{1 - \rho_p{}^2}\, \varepsilon'_t \tag{4.15}$$

and $\varepsilon'_t \sim N\left(0,1^2\right)$, ρ_p is the process error correlation, and σ_p^2 is the process error variance. The process error for the first year of the projection interval was assumed to be 0 for simplicity. Following Punt and Hilborn (2001), the process error variance was given a low value (σ_p=0.1) and the process error autocorrelation, a higher value (ρ_p =0.5).

4.1.1.6. Sensitivity Analysis

Sensitivity analyses included changing the following items with respect to those in the baseline scenario one at a time and were implemented with the BSP model:

- Changing the method for weighting the CPUE series: methods 1, 6, and 10 were used to compare with method 3 in the baseline scenario

- Changing the importance function from the priors to a multivariate t distribution

- Decreasing the values for the prior of K: the lower bound of the distribution (300, 000 lb dw) was set as having approximately the same magnitude as the average catch in the time series, which in turn represented 1% of the upper bound (30x10^6 lb dw)

- Considering an alternative catch series spanning back to 1960: this implied that both the model and the catch series started in 1960 and that C_0 was not estimated. The alternative catch series was obtained using the effort series derived from the catch-free model (1960-2003) as a basis. The average ratio of fleet-specific landings to effort for the period 1993-2003 was multiplied by the derived effort series to obtain inflated landings (which included discards) for 1960-2001. Landings for 2002 and 2003 were taken as 10% of the 2001 value to reflect that the moratorium had greatly reduced landings but some incidental catch was still occurring. Finally, to break out landings from discards for the directed shark bottom longline fleet, the average ratio of discards from the observer program to the 1993-1999 total landings was applied to all years. That ratio was 0.06

- Changing the prior for B_{74}/K to LN(1,0.2)
- Eliminating one CPUE series at a time and considering commercial, recreational or fishery-independent CPUE series only

4.1.2. Age-Structured Models

4.1.2.1. Age-structured Catch-Free Model (ASCFM)

In fisheries where there is a high degree of uncertainty in reported catches, or catches are not reported at all, stock assessment models that rely on catch data may not be appropriate. For numerous shark species there is uncertainty about the magnitude of commercial and recreational catches, in part due to identification problems. The level of reported discards is especially uncertain and may be underestimated because sharks are often not brought aboard for positive identification and may therefore go unreported. Without accurate knowledge of the magnitude of total catches and discards, it is not possible to estimate absolute abundance levels for the population. An alternative modeling methodology appropriate to these situations is to re-scale the model population dynamics as proportional to virgin (unexploited) conditions. If estimates of effort are available for the time series of exploitation, this information can be incorporated to guide model estimates of annual fishing mortality. Information about population declines relative to virgin can also be incorporated if there is expert opinion or data to suggest possible estimates of depletion. If catch and effort information are available from sampled trips or observer programs, then standardized catch rates can be developed and incorporated into the model.

In the present application, dusky shark landings are first available in the early 1980s at very low levels. Commercial landings during this time period are 2 to 3 orders of magnitude lower than those from the recreational fishery. It is not believed that this is a real trend in landings, but rather that it reflects underreporting and lack of species identification. Discarded dusky shark estimates from the pelagic longline fishery are first available in 1992 as a result of the observer program that placed observers on a fraction of the vessels to estimate both discards and landings. With such high uncertainty in the series of reported catch and discard, the catch-free methodology was selected as an appropriate application.

4.1.2.1.1. Model development and equations

This model description is a brief synopsis of the methodology reported in Porch et al. (2006), which should be consulted for full details. A first step in applying the catch-free methodology is to determine a year in which the population can be considered to be at virgin conditions. From that year forward, information on fleet-specific effort and/or prior information about possible levels of depletion allow the model to estimate the relative number at age for the year that data (e.g., catch rates) are first available. The period from virgin conditions just prior to availability of fishery data is referred to as the *historic* period. The time period spanning the first year with fishery data through the most recent observation is referred to as the *modern* period.

The underlying equations are simply a re-scaled age-structured production model. The stock-recruitment relationship is defined in terms of the spawning stock in year y and the resultant recruits in year y+r, and the first model age is a_r. Assuming that all survival beyond recruitment is density independent, then at virgin conditions the population age structure beyond a_r can be calculated from the expected survival at age from natural mortality:

$$N_{a,1} = \begin{cases} 1 & a = a_r \\ N_{a-1}\,\mathrm{e}^{-M_{a-1}} & a_r < a < A \\ N_{a-1}\,\dfrac{\mathrm{e}^{-M_{a-1}}}{1-\mathrm{e}^{-M_{A-1}}} & a = A \end{cases} \qquad (4.16)$$

where A is the age of the plus-group.

Subsequent annual relative recruitment, r_y, is modeled with a Beverton-Holt function. This function can be parameterized in terms of α, the maximum number of recruits produced by each spawner over its lifetime (Myers et al. 1999). The parameter α is equivalent to the slope of the spawner-recruit curve at the origin times φ_0 (unexploited number of spawners per recruit). The slope of the stock-recruit curve at the origin is equivalent to density-independent survival of pups (e^{-M_0} ; see eq. 3.5). The Beverton-Holt function is given by:

$$r_y = \frac{e^{-M_0}\varphi_0 S_{y-a_r}}{1+(e^{-M_0}\varphi_0 - 1)S_{y-a_r}} \qquad (4.17)$$

In (4.17), r_y is the median expected recruitment and S_{y-a_r} is a measure of relative spawning stock biomass, which is calculated as:

$$S_y = \frac{\sum_{a=a_r}^{A} E_a\,\mathrm{e}^{((-F_{a,y}-M_a)t_s)N_{a,y}}}{\sum_{a=a_r}^{A} E_a\,\mathrm{e}^{((-M_a)t_s)N_{a,1}}} \qquad (4.18)$$

In (4.18), E_a is per-capita eggs (or a proxy such as weight) by age class, $F_{a,y}$ is total fishing mortality on age a in year y, and t_s is the fraction of the year elapsed at the time of spawning. The parameter φ_0 (eq. 4.17) is calculated as:

$$\varphi_0 = \sum_{age} fec_{age} \cdot mat_{age} \prod_{j=1}^{age-1} \mathrm{e}^{-M_j} \tag{4.19}$$

where fec_{age} is fecundity at age and mat_{age} is maturity at age (Goodyear 1993).

This implementation of the catch-free model can incorporate multiple fleets that may be exploiting the resource. Annual, fleet-specific apical fishing mortality is estimated from fleet-specific effort series, if available. (Apical in this context refers to the fishing mortality that would be experienced by an age class that is fully vulnerable). Total age-specific fishing mortality is then calculated by:

$$F_{a,y} = \sum_{fleets} Fapical_{fleet,y} v_{fleet,a} \tag{4.20}$$

where $v_{fleet,a}$ is fleet-specific vulnerability at age. When fitting to indices of abundance and catch rates, the model estimates predicted values for index j in year y as:

$$Index_{j,y} = q_j v_{j,a} N_{a,y} \mathrm{e}^{(-M_a - F_{a,y})t_j} \tag{4.21}$$

if the units of the index are in numbers, or

$$Index_{j,y} = w_a q_j v_{j,a} N_{a,y} \mathrm{e}^{(-M_a - F_{a,y})t_j} \tag{4.22}$$

if the units are in weight. In (4.21) and (4.22), q_j is the catchability coefficient, $v_{j,a}$ is age-specific vulnerability for index j, and t_j is the fraction of the year that has elapsed prior to the timing of index j.

4.1.2.1.2. MSY calculations

As catch is not available, the model is unable to scale to absolute levels of population biomass, and therefore cannot calculate an absolute level of MSY. Rather, it is possible to estimate MSY relative to the unexploited level of recruitment (R_0). This is done as follows.

First, the vector of vulnerability used for equilibrium calculations is derived from the vector of total age-specific fishing mortality in the final year of the model:

$$\dot{v}_a = \frac{F_{a,y}}{\max\{F_{a,y}\}} \tag{4.23}$$

Next, the value of fishing mortality ($\tilde{F}_{MSY}$) that generates the maximum sustainable relative yield (MSY/R_0) is found by solving

$$\frac{MSY}{R_0} = \max_F \left\{ \frac{\dot{R}_F}{R_0} \sum_a w_a F v_a \frac{1 - e^{(-M_a - Fv_a)}}{M_a + Fv_a} e^{(-\sum_{i=0}^{a-1}(M_i + Fv_i))} \right\} \tag{4.24}$$

In the above expression, the term to the right of the summation is simply the calculation of yield per recruit for a given fishing mortality, F; this then gets scaled by the relative equilibrium recruitment that results from that F, R_F. Relative equilibrium recruitment can be calculated from

$$\frac{\dot{R}_F}{R_0} = \tilde{r}_F = \frac{\tilde{s}_F}{SPR_F} \tag{4.25}$$

where SPR_F is simply the ratio of spawners per recruit with fishing mortality F to φ_0 (eq. 4.19), i.e.

$$SPR_F = \frac{\sum_{age} fec_{age} \cdot mat_{age} \prod_{j=1}^{age-1} e^{(-M_j - Fv_j)}}{\sum_{age} fec_{age} \cdot mat_{age} \prod_{j=1}^{age-1} e^{(-M_j)}} = \frac{\varphi_F}{\varphi_0} \tag{4.26}$$

Finally, in (4.25), the equilibrium number of relative spawners at fishing mortality F ($\tilde{s}_F$) can be calculated by dividing eq. (4.17) by r and then solving for s:

$$\tilde{s}_F = \frac{e^{-M_0}\varphi_0 SPR_F - 1}{e^{-M_0}\varphi_0 - 1} \tag{4.27}$$

Replacing the term for relative recruitment in (4.24) with $\tilde{s}_F$ /SPR_F and solving for the F that maximizes the expression, results in the equilibrium estimate of relative MSY.

4.1.2.1.3. Biological inputs

Length and weight at age—von Bertalanffy parameter estimates for females were used. Length at age was converted to weight at age through the power relationship between weight and length (Eq. 3.3). All values are given in **Table 3.1**.

Maturity and fecundity at age—Age-specific values for the proportion of sharks mature at a given age were calculated from the logistic function:

$$mat_{age} = \frac{1}{1+\mathrm{e}^{(-k(age-a.50))}} \tag{4.28}$$

where k = ln(19)/(a.95-a.50). The parameters a.95 and a.50 refer to the age where the proportion of mature individuals at age is 0.95 and 0.5, respectively. In this application to dusky shark, a.50 = 19.8, a.95 = 25, and k = 0.566. Fecundity at age is expressed in terms of the number of pups produced per female. The mean value was 7.1 pups per female (see section 3.6) and was assumed for all age classes in the model. The interval for reproduction is thought to be 2 or 3 years. For the base case model, a 2-year reproductive cycle was assumed. As the catch-free model is not sex-specific, the stock-recruit relationship (eq. 4.17) is calculated with the total number of spawners at age. Assuming that the sex ratio is 1:1, then annual age-specific fecundity per capita is 7.1*0.5*0.5=1.775, which accounts for only half of the spawners being female, and the fact that only half of the population (on average) would reproduce each year (see also section 3.6).

Derivation of natural mortality at age (M_a)—It is generally believed that natural mortality of most sharks decreases with age (Cortés 2002). For the catch-free model, we used a slightly different formulation of the Lorenzen (1996) method (see sections 3.4 and 3.6) to estimate size-specific mortality, wherein estimates of M at length are derived assuming that M is inversely proportional to length: $M_l = M_r(l_r/l)$, where l_r is the reference length and M_r is the natural mortality rate at the reference length. This formulation assumes linear growth in length, which Lorenzen (2000) argued would be appropriate for his study of stocked fish given that time at liberty was short and growth was approximately linear over the interval. The Brody growth coefficient (K) for female dusky sharks was estimated to be 0.039, so that the curvature of the von Bertalanffy growth curve, given by $e^{-0.039} = 0.962 \approx 1$, is minimal (**Figure 4.1A**).

The age-structured models used 40 age classes, with the age 40 class being a plus group. A Lorenzen-type approach could be used to find M at age by assuming linear growth from age 1 to 40. Alternatively, we can assume that the rate of change in M with age is linear (**Figure 4.1B**):

$$\frac{dM}{da} = -cM \tag{4.29}$$

which gives

$$M_{age} = M_0 e^{-c*age} \tag{4.30}$$

The range suggested for survival at age 0 is 0.78-0.98 (**Table 3.1**), which corresponds to M in the range of 0.248-0.020. As survival from age 1 to maturity was estimated to range from 0.80-0.98, and adult survival from 0.90-0.98, it was decided to use the lower end of survival rates for age 0. Therefore, in (4.30), we fixed M_0=0.248. The constant in the exponent (c=0.05) was estimated so as to provide M_a values that fell within the appropriate ranges. A comparison of M_a from (4.30) gave almost identical results to using the Lorenzen (2000) approach to estimate M_a, with M_0=0.248 and l_0=82.2 cm FL being used for the reference length group (**Figure 4.1C**).

4.1.2.1.4. Model inputs

The time period modeled is 1960-2003. Index data are first available in 1974, so the overall time period is divided into a historic period, where data are few (1960-1973), and a modern period, where there are more data (1974-2003).

Fishing fleets—Three fleets were modeled: the directed commercial shark bottom longline fleet (BLL), the recreational fleet (REC), and the pelagic longline fleet (PL) which primarily targets tuna and swordfish, but mostly contributes to overall mortality of sharks through discarding. Selectivities for each fleet were presented in **Figure 2.22** (note that dealer weighout, WGH-OUT, represents the selectivity of the LPL fleet, LPS represents the REC fleet, and BLLOP represents the BLL fleet). It is apparent when examining Fig. 2.22 that the majority of selectivity is occurring on ages that are not yet mature.

Historic effort series development—A substantial shark fishery mainly for extraction of vitamin A from shark liver developed in the Gulf of Mexico and U.S. South Atlantic waters in the mid-1930s, but with the synthesis of vitamin A, most U.S. shark fishing was abandoned by 1950 (Wagner 1966). It is assumed that the period of relatively no exploitation from about the late 1940s to 1960 would have allowed shark stocks to recover to pre-exploitation levels by 1960. Virgin conditions were thus assumed in 1960. It must be noted that if in fact the stock was not at virgin conditions in 1960, then model results based on this assumption would likely be overestimating current status.

Fleet-specific effort series were constructed to inform the model as to relative trends in fishing intensity in 1960-2003. Effort (nominal number of hooks) for the pelagic longline fleet (PL) is available from the ICCAT database through 1997. A series of relative effort for this fleet was created by standardizing the total number of hooks per year to the 1997 value (G. Scott, pers. comm.). An average of 1990-1996 relative effort was used to arrive at estimates for the years 1998-2003 (**Table 4.1**). Applying the average of 1990-1996 effort for the years 1998-2003 was a decision made in plenary during the assessment for blue and shortfin mako shark (ICCAT 2005), and this decision was maintained for this assessment.

For both the REC and BLL fleets, we did not expect there to be much effort in the period before 1970. The BLL fleet is known to have developed in the 1970s, while in the recreational sector, it is thought (anecdotally) that the directed fishery developed rapidly as a result of the movie "JAWS", which was released in 1975. Therefore, from 1960 to 1970, both REC and BLLOP effort were set to very low levels to reflect that the fishery had not really developed yet (**Table 4.1** and **Figure 4.2**). For the remaining years, relative effort trends for both the REC and BLL fleets were derived by comparing total removals (landings + dead discards) to LPL removals (assuming that removals would be proportional to effort). Removals for REC were first available in 1981, and dusky sharks did not appear in the canvass data until 1985 (**Table 2.1**). For the years where removals were available, there were often large fluctuations in annual landings, on the order of 1-3 orders of magnitude. It is believed that this is not a reflection of drastic changes in effort, but rather that it is possibly due to misidentification, misreporting, or expansion factors based on very small samples. However, for the period 1993-1999, fleet-specific annual removals were more or less of the same order of magnitude, so this time frame was used to derive an average ratio of REC:PL and BLL:PL. These estimated ratios were then used to obtain relative effort in the 1990s for REC and BLL by multiplying the annual PL relative effort by the two ratios (1.41 for REC and 1.80 for BLLOP). These estimated annual relative effort series were then projected back from 1990 to 1970 by assuming a linear decrease with a slope equal to the value in 1990 divided by 21 (number of years from 1970-1990; **Figure 4.2**). Although dusky sharks have been a prohibited species and cannot be landed since 2000, there is still incidental catch and discard. For this reason, we did not reduce relative effort for 2001-2003.

Effort coefficients— For both time periods (historic and modern), fleet-specific apical fishing mortalities are estimated. Given annual, fleet-specific effort, $f_{fleet,y}$, equations relating effort to fishing mortality are as follows:

$$Fapical(BLL,y) = \begin{cases} p_{BLL,1} & y < 1974 \\ p_{BLL,2}\, f_{BLL,y} \exp(\delta_{BLL,y}) & 1974 \le y \le 2003 \end{cases} \tag{4.31}$$

$$Fapical(REC,y) = \begin{cases} p_{REC,1} & y < 1974 \\ p_{REC,2}\, f_{REC,y} \exp(\delta_{REC,y}) & 1974 \le y \le 2003 \end{cases} \tag{4.32}$$

$$Fapical(PL,y) = \begin{cases} p_{PL,1}\, f_{PL,y} & y < 1974 \\ p_{PL,2} Fapical_{PL,1973} \exp(\delta_{PL,y}) & 1974 \le y \le 2003 \end{cases} \tag{4.33}$$

For both BLL and REC fleets, the apical fishing mortality is estimated to be a constant, $p_{fleet,1}$, in the historic period because these fleets did not develop until the 1970s. During the modern period, those apical fishing mortalities are estimated as a proportionality constant, $p_{fleet,2}$, times the fleet-specific effort. In addition, annual lognormal deviations ($\delta_{fleet,y}$) are estimated:

$$\delta_{fleet,y} = \rho\delta_{fleet,y-1} + \gamma_y \tag{4.34}$$

Here, ρ is the correlation coefficient, and $\gamma \sim N(0, \sigma^2)$. Due to the sparseness of data in the historic period, no annual deviations are estimated.

For the PL fleet, the effort in the historic period was reflective of the fishery operation, and so the apical fishing mortality was estimated as a proportionality constant times that effort. In the modern period, the apical fishing mortality from 1973 (last year in the historic period) is scaled by another proportionality constant, which is then multiplied by annual deviations to obtain apical fishing mortality for the years 1974-2003.

In this model implementation, fleet-specific deviations are estimated, but both the correlation coefficient (ρ) and the standard deviation (σ) of the random normal deviate (γ) are the same for all fleets. For all model runs, $\rho=0.5$ and $\sigma^2=0.1$.

Indices of abundance—The five CPUE series described in section 2.2.3 were used (as for the Bayesian surplus production models). Selectivities for each fleet were derived as described in section 2.2.4 and Appendix 1 and depicted in Figure 2.22.

Relative biomass index—In addition to the five CPUE series, a relative biomass index was developed to reflect the level of depletion of the stock as a proportion of unexploited levels. This index is comprised of two points, $B_{1960}=1.0$ (unexploited level), and B_{1974}, which is the first year that data are available (the first observation for the VIMS-LL index of abundance). The index value for B_{1974} is relative to the total virgin biomass (B_{1960}), and is therefore a number between 0 and 1. This index tracks the total biomass of all age classes, and can be compared directly with B_t estimates from the production models (section 4.1.1).

4.1.2.1.5. Prior probability distributions, alternative hypotheses, and performance indicators

The following parameters were estimated in a Bayesian framework: pup survival, B_{1974}, and the effort proportionality coefficients.

Pup survival—The survival of pups (at low density) from birth to age 1 (e^{-M_0}) was modeled using a lognormal prior with a median of 0.78 (mean of 0.82) and CV = 0.3. Upper and lower bounds of 0.5 and 0.98 were imposed to constrain the distribution to biologically plausible values. This prior, with probabilities re-scaled over the permissible range, was not overly peaked and reflected the level of uncertainty in this parameter (**Figure 4.3A**).

B_{1974}/K—This prior was developed to reflect the fact that the population had experienced exploitation (in the form of discard mortality) from the pelagic longline fleet for at least 14 years, as well as a potentially small amount of directed exploitation from the commercial bottom longline fleet and recreational fishing. As described in section 4.1.1.4, a lognormal distribution with mean of 0.85 and CV=0.2 assigns about 40% probability that the total biomass in 1974 is between 0.8 and 1.0, and only 18% probability of being greater than 1.0 (which would imply more biomass than at virgin level; **Figure 4.3B**). This prior is almost identical to that used with the surplus production models.

Effort proportionality coefficients—The proportionality constants for estimating fleet-specific apical fishing mortality were initially given uninformative priors. However, there is not much information from which to estimate those parameters. Consequently, initial model runs frequently led to one or more of these parameters being estimated at an upper or lower bound. In subsequent model runs, upper and lower bounds were adjusted and prior probability distributions were tightened. For the baseline case, the priors listed in **Table 4.2** allowed for model convergence without any boundary estimation issues (see also **Figure 4.4**). Despite the addition of tight constraints on some of these parameters, the final model estimates of stock status, fits to indices, and fishing mortality did not vary. For all sensitivity runs, it was not uncommon to have to alter the distributions listed in Table 4.2 to avoid a boundary solution, but again, the final model estimates did not appear to be sensitive to constraints on these parameters.

4.1.2.1.6. Methods of numerical integration, convergence diagnostics, and decision analysis

Numerical integration for the catch-free model was done in AD Model Builder (Otter Research Ltd. 2001), which uses the reverse mode of AUTODIF (automatic differentiation). For models that converge, the variance-covariance matrix is obtained from the inverse Hessian. Uncertainty in model parameters, and in a Bayesian context the posterior density, can be examined with MCMC or likelihood profiling. AD Model Builder uses the Metropolis-Hastings algorithm to implement MCMC, and likelihood profiles are calculated by assuming that the posterior probability distribution is well approximated by a multivariate normal (Otter Research Ltd. 2001). To evaluate convergence of the MCMC runs, the values of parameters of interest were outputted to a text file and imported into BOA for R (Smith 2005). Two chains of length 2,500,000 were simulated and thinned such that every 100th value was saved (-mcsave 100 command line option). BOA offers a suite of analysis options, from summary statistics to convergence diagnostics (described in sections 4.1.1.5 and 4.1.3.1). The appropriate way to view convergence diagnostics is as tests of a null hypothesis, where H_0 is that the chain has converged. These diagnostics do not prove convergence, rather they can only provide evidence that the null hypothesis of convergence should be rejected.

4.1.2.1.7. Sensitivity analysis

The **baseline case** for the ASCFM used inverse CV weighting of the relative abundance indices, age-specific M, the derived effort series, and the priors on pup survival and the level of depletion in 1974 with respect to virgin conditions (B_{1974}/K) described earlier.

A variety of **sensitivity runs** were constructed to evaluate the influence of the assumptions in the baseline case. The following differences with respect to the baseline scenario were considered:

- S1. Equal weighting of all CPUE indices
- S2. No relative biomass index
- S3. No effort series
- S4. No effort series, equal weighting of all CPUE indices
- S5. No effort series, no biomass index, equal weighting of all CPUE indices

- S6. Constant M at lower limit of estimated range (M=0.03 for ages 1+)
- S7. Constant M at upper limit of estimated range (M=0.10 for ages 1+)

For runs S3-S5, with no effort series, fleet-specific apical fishing mortalities were estimated as:

$$Fapical(Fleet, y) = \begin{cases} p_{Fleet,1} & y < 1974 \\ p_{Fleet,2}\delta_{Fleet,y} & 1974 \le y \le 2003 \end{cases}$$

Thus, a constant value for F was estimated for both the historic and modern period, with annual deviations in the modern period (*cf.* equations 4.31-4.33).

4.1.2.2. Age-structured Model (ASM)

4.1.2.2.1. Model development and equations

The age-structured model used for this part of the analysis is similar to the age-structured catch-free model described above. This model, however, incorporates catch information in the analysis and therefore it calculates actual as well as relative values of the model parameters. The annual catches are used to calculate the number of fish, $N^{e}_{g,y,t,a}$, at each age class, a, at the end of each time step, t (a three-month time step is used) as follows:

$$N^{e}_{g,y,t,a} = \begin{cases} N_{g,y,t,0} & a = 0, t = t_p \\ (N^{b}_{g,y,t,a} \cdot S_a^{1/8} - C_{g,y,t,a}) \cdot S_a^{1/8} & a \ge 1 \end{cases} \quad (4.35)$$

where $N^{b}_{g,y,t,a}$ is the number of fish at each age class a, at the beginning of each time step t. S_a is the annual survival at age a from natural causes of death and $C_{g,y,t,a}$ is the number of fish of sex g, from each age class a, which were caught at time step t, in year y. $N_{g,y,t_p,0}$ is the number of pups of sex g, born in year y, and is equal to $f_g \cdot N_{0,y}$, where $N_{0,y}$ is the number of pups born in year y, f_g is the fraction of pups of sex g, and t_p is the time step when pupping is taking place. It is assumed that pupping is taking place in the middle of each year and pups could be vulnerable to fishing.

The time step used for the calculations is equal to three months. Thus, the number of fish caught at time step t, in year y, with gear j, $C_{y,t,j}$, is equal to one fourth of the corresponding annual catches. The catches are taken in a pulse in the middle of each time step after the population has experienced natural mortality for half of the time period which corresponds to one time step (Punt and Walker 1998):

$$C_{g,y,t,a,j} = (N^{b}_{g,y,t,a} \cdot S_a^{1/8} - \sum_{j'=1}^{j-1} C_{g,y,t,a,j'}) \cdot v_{g,a,j} \cdot u_{y,t,j}, \tag{4.36}$$

where $v_{g,a,j}$ denotes vulnerability of fish of age a and sex g to gear j, and $u_{y,t,j}$ is the exploitation rate per gear j at time step t in year y. The catch (number of fish) per fishing period and gear is used to calculate the exploitation rate for each fishing period, $u_{y,t,j}$:

$$u_{y,t,j} = \frac{C_{y,t,j}}{\sum_g \sum_a v_{g,a,j} \cdot \left[N^{b}_{g,y,t,a} \cdot S_a^{1/8} - \sum_{j'=1}^{j-1} C_{g,y,t,a,j'} \right]} \tag{4.37}$$

Fish weight at age a is expressed as a function of fish length, $L_{g,a}$ (see eq. 3.3), while the fish length at age is calculated using the von Bertalanffy growth equation.

It has been assumed that catch data are known without error and the observed catch per unit of effort (CPUE) values are lognormally distributed about the model-predicted values. The probability to get the observed CPUEs for a given set of values of the parameters of the model was calculated using the same likelihood function given in Eq. 4.3. Bayesian methods are also utilized to describe uncertainty in the input data and in the results of the analysis taking into account previous knowledge (prior information).

4.1.2.2.2. Model inputs

The catch series used for the calculations correspond to the catches of the recreational fishery, commercial catches mostly from the bottom longline fishery (BLL), which targets large coastal sharks, as well as discards from the pelagic longline fishery and BLL (**Tables 2.1 to 2.4**). The five CPUE series described in previous sections were used (values are shown in **Table 4.3**). The gear selectivities used in the analysis are the same as those used in the catch-free model. However, selectivity for age 0 fish was also used in this case since the model explicitly calculates the number of pups and fish of age 0 and also assumes that fish of age 0 could be vulnerable to fishing. The values of gear selectivity for fish of age 0 used are as follows: fish of age 0 are assumed to be fully selected (selectivity =1) by the gear used in the directed bottom longline shark fishery and the gear that corresponds to the VIMS CPUE. Selectivity for fish of age 0 was assumed to be equal to 0.5 for the pelagic longline fishery, while in the case of the recreational fishery the selectivity was calculated using the same formula that we used to calculate the selectivity for fish of age 1 or older for that fishery.

4.1.2.2.3. Prior probability distributions, alternative hypotheses, and performance indicators

For the calculations with the ASM, the virgin biomass of fish of age 1 or older and the pup survival at low population density were assumed to be estimated input parameters. A uniform on log prior probability density function (pdf) (limits: 10^5 kg – 10^9 kg) and a lognormal pdf (LN(-0.241, 0.294^2); limits: 0.25 – 0.98) were used for the virgin biomass and pup survival at low population density, respectively. Non-informative priors were used for σ_i and q_i (see Eq. 4.3). The values of those two parameters were found analytically following the procedure described in section 4.1.1.1.

Inverse CV weighting was used for the calculations with the baseline model, but the baseline model was also run using equal CPUE weighting. The starting year for the calculations was assumed to be either 1960 or 1974. The model assumed virgin conditions for the population prior to the first year of calculations. Two different assumptions were used for the historical catches; they were treated as either estimated parameters or fixed values. In the former case, it was assumed that only the recreational fishery and the pelagic longline fishery (discards) contributed to the historical catches. The historical catches were also assumed to be the result of those two fisheries when the historical catches were treated as fixed input values. In this case, the catches from each of the two fisheries were set equal to 0 for the first year of the calculations and then increased linearly to a fixed value (100,000 Kg for the recreational fishery and 30,000 Kg for the pelagic longline fishery discards). Recent catches were assumed to be constant and equal to the values shown in Tables 2.1 to 2.4. Given the limited information about the degree of error in the catch data and to avoid complicating the calculations further it was assumed that recent catches are known without error.

4.1.2.2.4. Sensitivity analysis

In addition to the runs described above (baseline run and baseline run with equal weighting), a number of sensitivity runs were also performed. The baseline model was run using the alternative catch dataset described in section 4.1.1.6 to investigate how model predictions would be affected by the inclusion of that additional information. For the ASM, two cases were examined: catches were set equal to either the alternative catches, or twice the alternative catches. The model was also run with varying values of natural mortality to test the sensitivity of the model results to changes in the values of natural mortality. We considered two different scenarios: 1) the mortality of fish of age 1 or older was set equal to 0.238 (the highest mortality used in the baseline run), or 2) the mortality of fish of age 1 or older was set equal to 0.034 (the lowest mortality used in the baseline run). Since it is not clear whether the dusky shark has a biennial or triennial reproductive cycle, one sensitivity run assumed that only one third of the mature fish in each age class give birth in any given year.

4.1.3. Results

4.1.3.1. Bayesian Surplus Production Models

Baseline scenario

Although none of the three Bayesian surplus production models used is exactly the same, they all yielded generally similar results. The models predicted values of B_{2003} on the order of 0.7-2.8 x10^6 lb dw, K ranging from 8.8-17.1 x10^6 lb dw, and MSY ranging from 51,000-98,000 lb dw (**Table 4.4**). Biomass in 2003 was predicted to be about 1/6th that at carrying capacity (B_{2003}/K=0.16-0.17) with the BSP-spreadsheet and WinBUGS models, and less than 1/10th (B_{2003}/K=0.08) with the BSP model.

The predicted biomass trajectory at the mode of the posterior distribution for the BSP model showed a marked declining trend (**Figure 4.5**). The BSP model also indicated that current fishing mortality was above F at MSY and that current catch (for 2003) was slightly below the replacement yield (**Table 4.4**). The relative biomass trajectory showed a progressively more overfished status (below MSY) starting in 1991, while the relative fishing mortality trajectory showed overfishing had been occurring throughout the time period considered **(Figure 4.6**). BSP model fits to the CPUE series available were all declining and expected values tracked observed values rather well, except for the early years of the VIMS LL series (**Figure 4.7**).

The posterior distributions of r, B_{74}/K and C_0 obtained with the BSP-spreadsheet version were similar to their respective priors and the data supported relatively low values of K (**Figure 4.8**). Posteriors from the BSP-spreadsheet and WinBUGS models were similar (**Figure 4.8**). **Figure 4.9** shows the joint posterior distribution for K and r from the BSP-spreadsheet model. The predicted median biomass trajectory for the WinBUGS model also showed a marked declining trend (**Figure 4.10A**) and, as with the BSP model, the relative biomass trajectory showed a progressively more overfished status starting in 1991 **(Figure 4.10B**). The relative fishing mortality trajectory also showed overfishing had been occurring throughout the time period considered, except for the last year of data (**Figure 4.10C**). WinBUGS model fits to the CPUE series were similar to those obtained with the BSP model, all declining with expected values tracking observed values rather well, except for the early years of the VIMS LL series **(Figure 4.11**).

Although population projections with the BSP and BSP-spreadsheet version models differed somewhat, both models provided consistently pessimistic outlooks wherein the probability of the population biomass reaching B_{MSY} was 0 after 10, 20, and 30 years with a no-catch policy in the BSP model, and only 1% after 30 years with a no-catch policy with the BSP-spreadsheet model (**Table 4.4**).

Convergence diagnostics for the BSP model were satisfactory, with the ratio of the CV of the weights and the CV of the likelihood*priors <1 (0.79) and the maximum weight of any draw <0.5% (0.35%). The BSP-spreadsheet model convergence was also satisfactory, with the maximum parameter vector accounting for less than 0.5% of the total likelihood (0.31%). Convergence diagnostics for the WinBUGS model showed that there was good mixing of the two chains for most parameters, except for K. Autocorrelations for most parameters, except for B_{03}/K, also decreased after an initial lag and the Gelman-Rubin statistic indicated good convergence for all parameters of interest (the ratio of the width of the central 80% interval of the pooled runs and the average width of the 80% intervals within the individual runs converged to 1 and both the pooled and within interval widths stabilized; **Figure 4.12**). Cross-correlation matrices showed that some pairs of parameters had high correlations, as expected (K and MSY, K and B_{03}/K, and MSY and B_{03}/K), but in general most correlations between parameters were low, thus not providing strong evidence for slow convergence to the posterior distribution. The 0.975 quantile of the Brooks, Gelman and Rubin diagnostic was <1.2, indicating that the samples from most parameters arose from the stationary distribution. The p values of the Z-score in the Geweke convergence diagnostic were >0.05 for all parameters in chain 1, but <0.05 for K, MSY, and B_{03}/K in chain 2, indicating that there was evidence against convergence for those parameters. The Heidelberger and Welch halfwidth test indicated that all parameters had passed the test, whereas the stationarity test indicated that all parameters (except B_{03}/K in chain 1 and K, MSY, B_{2003}, and B_{03}/K in chain 2) had passed the test. The Raftery and Lewis convergence diagnostic indicated that the number of iterations needed to estimate the default 2.5th quantile with an accuracy of 0.005 and a probability of 0.95 was sufficient. This diagnostic also indicated that the number of iterations needed for each parameter was insufficient for B_{03}/K, K, and MSY for chain 1 and B_{03}/K and MSY for chain 2. The burn-in period was sufficient for all parameters in both chains, but the dependence factors for B_{2003}, B_{03}/K, K, and MSY were high (>5) for both chains, providing evidence against convergence and advising the use of a higher thinning rate.

Alternative scenarios

The sensitivity analyses that incorporated different weighting methods provided a slightly more optimistic outlook than the baseline scenario, especially weighting method 10, for which $B_{2003}/K=0.27$ (**Table 4.5**). For weighting methods 1 and 10, $F_{2003}/F_{MSY}<1$ and the current catch was below the replacement yield ($C_{2003}/R_y<1$). In all, the outlook was still very pessimistic, with a 23% probability of the stock reaching MSY after 30 years with a no-catch policy with method 10 (**Table 4.5**). Diagnostics indicated that all models converged, except for the ratio of the CV of the weights and the CV of the likelihood times the priors (1.48) with weighting method 1.

Changing the importance function from the priors to a multivariate t distribution, decreasing the value of K, considering an alternative catch series spanning back to 1960, or increasing the mean value of B_{74}/K to 1 had very little influence on results (**Table 4.6**). Each of these changes to the baseline scenario still predicted $B_{2003}/K=0.08$-0.09, $F_{2003}/F_{MSY}>1$ (especially with the alternative catch series scenario), and $C_{2003}/R_y<1$, except for the alternative catch series scenario. Except for the multivariate importance function scenario, all models converged and consistently predicted a 0% probability of the stock reaching MSY even after 30 years with a no-catch policy (**Table 4.6**).

Selective removal of CPUE series showed that no single series greatly affected the outcome, with $B_{2003}/K=0.08$, $F_{2003}/F_{MSY}>1$, and $C_{2003}/R_y<1$ (**Table 4.7**). Accordingly, all scenarios predicted a 0% probability of the stock reaching MSY even after 30 years with a no-catch policy (**Table 4.7**). Using commercial or recreational CPUE series only did not affect the outcome either, and using only the single fishery-independent CPUE series available (VIMS) yielded even more pessimistic results, with an estimated 97% depletion ($B_{2003}/K=0.03$) and no chance for recovery within the timeframe considered. Convergence diagnostics were all satisfactory (**Table 4.7**).

4.1.3.2. Age-Structured Catch-Free Model (ASCFM)

Baseline scenario

The estimates of current status suggest that B_{2003} is around 8% of virgin total biomass and SSB_{2003} is about 7% of virgin spawning (pupping) stock biomass. Estimates of current status relative to MSY values suggest that the stock is overfished ($SSB_{2003}/SSB_{MSY}=0.16$) and that overfishing is occurring ($F_{2003}/F_{MSY}=75$; **Table 4.8; Figure 4.13**). Although F_{2003} is 0.43, the overfishing estimate is so high because the estimate of F_{MSY} is 0.006.

$F_{\%SPR}$ is the fishing mortality rate that reduces a population to a given level of SPR. A range that is believed to be potentially sustainable for a wide range of fish stocks is $F_{30\%SPR}$ - $F_{40\%SPR}$. In the present assessment, the estimates are $F_{30\%SPR}$=0.048 and $F_{40\%SPR}$=0.036. Compared to these levels, F_{2003} is 9-12 times too large. In fact, for a long-lived, slow maturing species such as the dusky shark, even 40% SPR may not be sustainable—the model estimate of SPR_{MSY} for the base model assumptions is 86%. Further evidence of a very low resilience to exploitation is given by the estimate of maximum reproductive rate, α =1.35, which corresponds to a steepness of 0.25—in other words, the relationship between spawning stock and recruits is nearly linear, implying very little density dependence (see also similar results from section 3.7).

Both profile likelihoods and MCMC were performed for the baseline model to evaluate uncertainty in estimates of relative biomass in 1974 (B_{1974}/K), relative biomass in the current year (last year of data, B_{2003}/K), F_{2003}, F_{MSY}, and pup survival. Likelihood profiles for the base case indicated a slightly higher mode than the prior for pup survival but no difference for B_{1974}/K (**Figure 4.14**). The base case used inverse CV weighting and estimated a separate σ for each index. As a consequence of the tight CV on the B_{1974}/K prior compared to the other indices (CV=0.2), and the model estimating the smallest σ for that relative biomass index, the likelihood profile assigned all of the probability density to a very small interval around the prior mode of 0.83. The likelihood profiles for B_{2003} and F_{2003} show a bifurcation (two modes). The two posterior modes for F_{2003} are 0.82 and 0.39, with 0.39 having much greater probability (**Figure 4.14**). The model point estimate of F_{2003} (0.43; **Table 4.8**) is closer to the posterior mode with greatest probability. For B_{2003}, the two posterior modes are 0.07 and 0.11, with 0.11 having greater probability (**Figure 4.14**). The model point estimate for B_{2003} (0.08; **Table 4.8**) is closer to the posterior mode at 0.07, which has less probability than 0.11. To determine the impact of the weighting of B_{1974}/K on model results, likelihood profiles were also generated for the equal weighting sensitivity scenario (S1). In this case, the posterior for B_{1974}/K was more spread out, although the mode was still not very different from the prior (0.76 versus 0.83; **Figure 4.14**). The profile for B_{2003} and F_{2003} appeared smooth and unimodal, with the peak lining up with the base case peak for B_{2003} and between the two peaks of the base case for F_{2003}. The posterior for pup survival was nearly unchanged between the base case and S1, and both were not very different from the prior. F_{MSY} was only slightly different between the two cases.

Based on the results from likelihood profiling, MCMC was performed for both the base case and S1. Several initial runs were made to determine a chain length sufficient to reach the stationary distribution. The final MCMC results come from simulating two chains of initial length=2,500,000, which were thinned such that every 100th value was saved. From these 25,000 runs, iterations where the estimate of F_{MSY} hit the upper bound of 3 were dropped, and the first half of each chain was dropped for burn-in. The final number of iterations was around 10,000. For both the base model and the equal weight sensitivity scenario (S1), diagnostic output for B_{1974}/K suggested very high autocorrelation, even after a lag of 50. The cross-correlation matrix showed very high positive correlation between pup survival and F_{MSY}, which is not surprising. The Potential Scale Reduction Factor (Gelman and Rubin 1992) and the Corrected Scale Reduction Factor (Brooks and Gelman 1998) both indicate lack of convergence for B_{1974}/K, but there was no evidence that the other parameters had failed to converge. The modes for B_{2003} were smaller than those estimated by likelihood profile, while the modes for F_{2003} were between those estimated by likelihood profile (**Figure**

4.15). The distributions for F_{MSY} and pup survival were diffuse, but the posterior modes from likelihood profiling were bounded by the MCMC posteriors.

Alternative scenarios

S1. Equal weighting of all CPUE indices—The effect of changing the index weighting scheme from inverse CV to equal weighting altered how the model estimated the level of exploitation in the historic vs. the modern period. With equal weighting, the point in the relative biomass index (B_{1974}/K) had less influence, and so the model estimated that there was less exploitation in the historic period (B_{1974}/K=0.95, whereas the mean value of the prior was 0.85), and the biomass trajectory from 1960 to 1974 was nearly flat. In contrast, the F trajectory in the modern period was steeper than in the baseline case in order to fit the indices, all of which were declining. The final estimate of F was higher than in the baseline case (F_{2003} = 0.71 vs. 0.43), but there was almost twice as much spawning stock (SSB_{2003}/SSB_0 = 0.14). Nevertheless, the stock was still estimated to be overfished with overfishing occurring (**Table 4.8; Figure 4.16**).

S2. No relative biomass index—Repeating the base model run without including the relative biomass index led to virtually the same estimate of current status (SSB_{2003}= 8.1% of virgin size, F_{2003} = 0.42). As with the equal weighting sensitivity run (S1 above), the estimate of B_{1974}/K is somewhat larger than in the baseline case (B_{1974}/K=0.93). The estimates of pup survival, α, and steepness are very similar to those in the baseline case (**Table 4.8; Figure 4.17**). The stock was estimated to be overfished with overfishing occurring.

S3. No effort series—Ignoring the derived effort series did not affect the model estimates of current status (SSB_{2003}= 5% of virgin size, F_{2003} = 0.45). The biomass index, which has a relatively tight CV, drove the model to estimate a low constant total F in the historic period (F=0.027). In order to fit the declining indices in the modern period, the estimate of constant total F was about 0.5 (+/- annual deviation). This is an unrealistically sharp increase over one year, but there is little data in the historic period for the model to estimate anything other than light exploitation to match B_{1974}/K. As before, the conclusion about status is that the stock is overfished and overfishing is occurring (**Table 4.8; Figure 4.18**).

S4. No effort series, equal weighting of all CPUE indices—For this sensitivity trial, again the effort series was ignored, and all indices were given equal weight. As with sensitivity case 1, when equal weighting was applied to all indices, the model was not as constrained in estimating B_{1974}/K in the historic period. For this model, the estimate of B_{1974}/K is 0.98. Since total F is a constant in the historic period (1960-1973), the estimate of F is almost zero (1.4E-6). The decline suggested by the indices in the modern period forces the model to ramp up the estimate of constant F for 1974-2003 (F=0.69). As in sensitivity case 3, this is an unrealistically sharp increase over one year. The estimate of SSB_{2003}/SSB_0 was about the same as for the baseline case, while F_{2003}=0.51 is about 20% greater than in the baseline case. Again, the stock is overfished and overfishing is occurring (**Table 4.8; Figure 4.19**).

S5. No effort series, no relative biomass index, equal weighting of all CPUE indices—For this sensitivity trial, both the effort series and the relative biomass index were ignored. In addition, all 5 CPUE indices received equal weighting. Without the biomass index, there are no data in the historic period, so the model attempts to estimate a constant F that yields a level of depletion, and corresponding age structure, in 1974 that best fits the indices in the modern period. Solutions for this case included boundary values for one or more parameters, and are therefore to be viewed with some caution. Nevertheless, the results are very much in agreement with the others—i.e. that the stock is overfished and overfishing is occurring (**Table 4.8; Figure 4.20**).

S6. Constant M at lower limit of estimated range (M=0.03 for ages 1+)—This model followed the base case with the exception that natural mortality was fixed at 0.03 for all ages, giving a survival of 0.97. Such a high survival for ages 1 and older would suggest that sharks could be harvested considerably (SPR_{MSY}=0.27). This high survival also impacted estimates of maximum reproductive rate (α=22.37). The corresponding estimate of steepness (0.85) is very unrealistic for a species with this life history. Despite the high survival and high resilience implied by steepness, the model estimated that the stock is overfished (SSB_{2003}/SSB_{MSY}=0.15) and experiencing overfishing (F_{2003}/F_{MSY}=20.4) (**Table 4.8; Figure 4.21**).

S7. Constant M at upper limit of estimated range (M=0.10 for ages 1+)— The lowest reported value for survival was 0.79, which corresponds to an instantaneous natural mortality of M=0.236. An initial model run with this value for M did not lead to plausible estimates for maximum reproductive rate (α). The parameter α is related to steepness (h) by the relationship given in eq. (3.4).

The lower bound on h is 0.2, which translates to a lower bound on α of 1. By definition,

$$\alpha = \mathrm{e}^{-M_0} R_0 = \mathrm{e}^{(-M_0)} \sum_{age} fec_{age} \cdot mat_{age} \prod_{j=1}^{age-1} \mathrm{e}^{(-M_j)} \tag{4.38}$$

If the last age (A) is treated as a plus group, and if spawning (pupping) occurs after a fraction τ of the year has elapsed, then we have:

$$\alpha = \mathrm{e}^{(-M_0)} R_0 = \mathrm{e}^{(-M_0)} \sum_{age}^{A-1} fec_{age} \cdot mat_{age}\, \mathrm{e}^{(-M_\tau)} \prod_{j=1}^{age-1} \mathrm{e}^{(-M_j)} + fec_A mat_A\, \mathrm{e}^{(-M_\tau)} \left(\prod_{j=1}^{A-1} \mathrm{e}^{(-M_j)} \right)^{\frac{\mathrm{e}^{(-M_A)}}{(1-\mathrm{e}^{(-M_A)})}} \tag{4.39}$$

Given fec_{age} and mat_{age}, we can solve for either M_0 or M_j=M (constant adult survival) such that $\alpha \geq 1$. The value M=0.236 does not permit feasible solutions for pup survival (e^{-M_0}). For M≤0.12 it was possible to obtain solutions where $\alpha \geq 1$; we chose to fix M=0.10, giving a survival of 0.90 for ages 1+. The estimate of population status was similar to that in the baseline case: SSB_{2003}=7% of virgin size, SSB_{2003}/SSB_{MSY}=0.16, and

F_{2003}/F_{MSY}=12.5. The conclusion is therefore the same as that for all other model runs, i.e., that the stock is overfished and overfishing is occurring (**Table 4.8; Figure 4.22**).

Projections

The base model configuration and all sensitivity cases were projected to the year 2033 assuming F=0 (which implies complete compliance with the moratorium). Projections were made based on the estimated age structure in 2003. Estimates of total biomass, spawning stock biomass, and number in 2033 are reported in **Table 4.9** and **Figure 4.23**. The number in the population in 2033 increased in all cases; however, biomass and spawning stock biomass decreased slightly relative to 2003 except for the constant M cases (S6 and S7). Changes in age-structure, and the consequent change in weight of the plus group, account for this result. All projections indicate that the population is still in an overfished state in 2033.

4.1.3.3. Age-structured Model (ASM)

Baseline scenario

The value of at least one of the estimated input parameters at the mode of the joint posterior pdf was equal to either its upper or lower limit when the baseline model was run using 1960 as a starting year and assuming that historical catches were estimated parameters. The convergence of the baseline model was also problematic when a) the starting year was equal to 1974 and the historical catches were estimated parameters, b) the starting year was equal to 1960 and the historical catches were fixed input values, and c) the starting year was equal to 1974 and the historical catches were fixed input values. Further, runs using only subsets of the CPUE data listed in Table 4.3 showed that such convergence problems were not observed under case (c) when the LPL CPUE series was excluded from the calculations. The exclusion of a single CPUE series did not eliminate the convergence problems in any of the other cases examined. An example of the values of virgin biomass and pup survival at low population density at the mode of the joint posterior pdf that we got under case (c) for different combinations of the CPUE series is shown in **Table 4.10**.

The use of the equal CV weighting instead of the inverse CV weighting also solved the convergence problems for three out of the four cases discussed above (starting year equal to either 1960 or 1974 and fixed or estimated historical values). **Table 4.11** shows the values of some of the estimated parameters at the mode of the joint posterior pdf in each of the four cases. The results of the analysis for the baseline model are shown in **Table 4.12** and **Figures 4.24, 4.25,** and **4.26**. The model estimated that the current population is about 20% of its virgin size. It should also be noted that the uncertainty in the values of the estimated parameters is unrealistically small. The model was not able to replicate the large decline in population size indicated by the VIMS CPUE series, but fit well the remaining CPUE series (**Figure 4.25**).

Equal weighting

Results when the baseline run was repeated using equal CV weighting are shown in **Table 4.12** and **Figures 4.27, 4.28,** and **4.29**. The posterior pdfs in this case give higher probability to a broader range of values as shown in **Figure 4.27**. As a result, the CVs shown in **Table 4.12** are greater than those found under the previous run. The model also predicted a smaller decline in the population than that found under the baseline run. Year 2002 was used for the comparisons instead of the final year of the calculations (2003) because only two of the four catch data sets we used included catches for 2003, thus not allowing calculation of their contribution to the fishing effort.

Alternative catch series

The results of the runs with the two sets of alternative catches are also shown in **Table 4.12**. Due to the convergence problems we encountered with the inverse CV weighting method, these runs were done using equal CV weighting. By comparing the results of these two runs to each other, one realizes that the actual values of the estimated parameters under the run with the alternative catch 2 are approximately twice the values found under the run with the alternative catch 1. Furthermore, the relative values of the estimated parameters under the two runs are almost the same, which indicates that the relative values of the parameters of interest are not affected by the choice of the alternative data set. Such an observation is not surprising since the only difference between the two datasets is that the catches in the alternative catch 2 dataset are twice the catches in the alternative catch 1 dataset. Thus, although the actual values of the parameters of interest when the higher catches are used are different from the values obtained using the alternative catch 1 dataset, those differences disappear when the parameters of interest are calculated in relative values. Further, the model predictions about the status and productivity of the stock remain unchanged under both alternative catch scenarios. The use of the alternative catch datasets gave slightly more optimistic predictions about the status of the stock than the results of the baseline run with equal weighting.

Alternative natural mortality

The runs using the alternative values for mortality showed that the greater of the two values considered (mortality = 0.238) is not biologically acceptable (steepness of the Beverton-Holt stock recruitment becomes smaller than 0.20; see discussion in alternative scenario 7 of section 4.1.3.2). Therefore, only the results from the run with the smallest value for natural mortality (mortality =0.034) are considered (**Table 4.12**). In this case, it was possible to use inverse CV weighting in the analysis. The results under this run are more optimistic than the results under the baseline run, but are still less optimistic than those found in any of the other cases in which equal CV weighting was used instead of inverse CV weighting.

Triennial reproductive cycle

Under this scenario the model could not find a mode for the joint posterior pdf when the same assumptions as those in the baseline run were used for everything else but the length of the reproductive cycle. The model also converged to the minimum allowed value for the steepness of the Beverton-Holt stock recruitment function when the assumptions used were the same as those in the baseline with equal weighting run. The results of this run were very similar to those of the baseline run with equal CV weighting and a biennial reproductive cycle (**Table 4.12)**. The single main difference was in the predicted value of pup survival at low population density, which was much higher when considering a triennial cycle in order to compensate for the lower number of pups born per year when compared to a biennial cycle. This is probably the reason why the model converged to the minimum allowed value for steepness. Due to the convergence problems, this scenario was not considered in the rest of the analyses.

MSY calculations

The values of MSY, relative current exploitation, and relative stock biomass at MSY at the mode of the joint posterior pdf for each of the scenarios considered are shown in **Table 4.13**. The MSY calculation results showed that the population can sustain only very small rates of exploitation and that the current exploitation (2002) is much higher than the exploitation at MSY. The MSY predicted under the baseline scenario was the lowest of any run. With the exception of the run for which low natural mortality was assumed, all the runs gave values for the relative size of the stock at MSY above 0.7 and predicted that the exploitation in 2002 was at least 20 times higher than the exploitation at MSY. The use of the low mortality assumption resulted in much more optimistic results than those found under any of the other runs. Particularly, the model predicted that the current (2002) exploitation is only about twice the level that leads to MSY while the modal value for MSY is much higher than the value for MSY found under any of the other runs considered. The relative size of the population at MSY is also much smaller under the run in which the low mortality assumption was used than those predicted under the other sensitivity scenarios considered (**Table 4.13**).

Projections

The status of the population in 30 years was also calculated for each of the runs considered assuming that no exploitation was taking place after 2003 (**Table 4.14**). In all cases, the model predicted that the population in 30 years would be greater than the population in 2003. However, the increase of the population was very small in four out of the five alternative scenarios examined. Population size in 2033 ranged from 0.24 to 0.53 of the virgin population size (mean value, in numbers) and from 0.22 to 0.44 (in biomass). **Figure 4.30** also presents the changes in population size over the years for two of the scenarios considered: the baseline scenario and the low natural mortality scenario. These two scenarios correspond to the most pessimistic and more optimistic case with regard to the model predictions for the size of the population in 2003, respectively. According to the baseline scenario, the size of the population could continue to decrease for several years even without any exploitation. These results indicate that it will take many years for the population to recover even if exploitation becomes zero and highlight the low recovery potential of the population, which makes it susceptible to even small levels of exploitation.

5. DISCUSSION AND CONCLUSIONS

5.1. Catches, average size, and catch rates

Commercial landings reported in the general canvass data identified the mid-Atlantic region as the main landing area for dusky sharks, whereas catches reported in the coastal fisheries logbook program showed the Gulf of Mexico was the main area where dusky sharks had been caught commercially during 1991-2003. All landings/catches showed decreasing trends since the early-mid 90's, however. The presence of dusky sharks in commercial and recreational landings since 2001, after the designation as a prohibited species had gone into effect, is worrisome but can also be attributed, at least in part, to identification problems. For example, some commercial fishermen and seafood dealers may misidentify some sharks as dusky sharks, which then would be recorded as such in logbooks or dealer reports. Also, in the recreational fishery, the expansion factors used in the MRFSS may result in a large number of dusky sharks based on the incorrect identification of a few individuals. Indeed, use of the "catch-free" model in this assessment was due to the uncertainty in the magnitude of the catches.

Examination of trends in average size suggests that the stock of dusky sharks is heavily exploited. Four of the five time series examined showed statistically significant decreasing trends in average weight, with several subsets of the series showing even more significant decreasing trends, while none of the subsets that showed increasing tendencies were statistically significant. Size data from the BLLOP, VIMS LL, LPS, and dealer weighout all indicated that the majority of animals caught were immature, with the two first datasets showing high proportions of age-0 and juvenile individuals as obtained from the age-length key derived. According to the BLLOP, the majority of catches corresponded to immature individuals off North Carolina during summer and winter (which prompted NMFS to institute a time-area closure). Based on results from elasticity analysis, the juvenile stage of dusky sharks may be particularly important to population growth.

Catch rate analysis also yielded decreasing trends. Of the five CPUE series examined (all of which were statistically standardized with GLMs), three showed highly significant ($P<0.001$) negative trends and two slightly decreasing, non-significant trends. The BLLOP series showed a significantly ($P<0.05$) increasing trend in 2000-2003 as did the VIMS series for 1989-2003. The LPS and LPL series showed overall declines of 59% and 74%, respectively, from beginning to end of the time series, and the VIMS series showed a 94% decline from 1979 to 2003. It must be noted, however, that in our analysis of the LPL data set we did not account for changes in reporting that may have occurred owing to confusion on the part of fishers as to what logbook program to report to (see Burgess et al. 2005a,b and Baum et al. 2005 for a discussion). We also did not account for regulatory changes, such as the implementation of the HMS FMP in 1993 or the designation of dusky shark as a prohibited species in 1999, in our analysis of the LPS data set, although the large decline in CPUE occurred before the implementation of the HMS FMP in 1993. However, considering that the LPS data include total catch (kept and released fish), it is expected that the regulatory changes would have minimal effect on this series, unless fishers are making significant changes to targeting methodology (away from dusky sharks, but within the indicated "shark" target category) that cannot be discerned from the data collected during the interviews.

The decline in dusky shark catch rates for the LPL series reported here for the period 1992-2003 is very similar to that reported for the Gulf of Mexico from the 1950s (1954-1957) to the 1990s (1995-1999) using fishery-independent and observer data from the pelagic longline fishery (Baum and Myers 2004). The decline in dusky shark catch rates reported herein for the GLM-standardized VIMS series is also similar to previously reported un-standardized values (e.g., Romine 2004). Sheperd and Myers (unpublished data) found even more accentuated declines in a meta-analysis of multiple relative abundance series (mostly bottom trawl surveys), with a meta-analytic estimate of absolute decline of 99% since 1970.

5.2. Population Ecology and Stock Status

Simulation of population growth rates based on the biological information available for the dusky shark in the northwest Atlantic Ocean resulted in very low values (<3% yr^{-1}) as has been found in previous deterministic and stochastic studies (Cortés 1998, 2002; Smith et al. 1998; Simpfendorfer 1999; Romine 2004). This is hardly surprising given the biology of this species, which is characterized by very late age at first reproduction (~20 years), high longevity (> 40 years), and very limited reproductive potential, which result in low population growth rates and long generation times (30 years). The resulting elasticity profile is also characteristic of "slow" sharks (Cortés 2002), wherein juvenile survival is the main contributor to population growth.

Using density-independent theory and no explicit timeframe, Simpfendorfer (1999) and Cortés (1999) found that low exploitation levels of age-0 dusky sharks off southwestern Australia and sandbar sharks (*Carcharhinus plumbeus*) in the northwestern Atlantic, respectively, could be sustainable provided no other life stages were exploited. Low contribution of age-0 survival to population growth rates is a general prediction of elasticity analysis for "slow" vertebrate species, but does not necessarily mean that age-0 individuals can be exploited persistently. At a minimum, the effects of such continued removals should be monitored for at least one generation to allow time for propagation through all age classes of the population.

The various stock assessment methodologies used to estimate present (for 2003) stock status were all consistent in showing large depletions with respect to virgin (unexploited) levels. The vast majority of biomass dynamic models all predicted depletions >80% of virgin biomass. Results were largely insensitive to the CPUE time series used, changes to prior distributions, catch series considered, form and structural assumptions of the biomass dynamic models fitted, importance function used for Bayesian estimation (priors vs. multivariate t), and method for numerical integration (SIR vs. MCMC). The method used to weight the CPUE indices had a larger effect, but did not alter conclusions. Examination of the prior-posterior plots showed that the data were uninformative in general probably because of the one-way trip pattern of the time series (Hilborn and Walters 1992), and that the data favored a somewhat smaller posterior of r than the prior. The stochastic life table exercise was intended to produce an informative prior for r to use in the surplus production models because we suspected that the time series data were probably uninformative with respect to r owing to a lack of contrast in the data (i.e., a lack of an increasing pattern resulting from different levels of exploitation). Thus, using an informative prior for r based on life table modelling was intended to inform the model about values of this parameter that are biologically sound. We conducted a (post-hoc) sensitivity analysis doubling the mean value of r with respect to the baseline case, but the one-way trip pattern did not vary.

Depletions estimated through the age-structured catch-free model (ASCFM) were of similar magnitude to those from the biomass dynamic models, lending further credibility to the overall results. For the catch-free model, although a variety of model parameterizations were evaluated, and current estimates of status showed some sensitivity to the model assumptions, all outcomes were consistent in that the stock is overfished with overfishing occurring. Regardless of the assumptions about derived effort and the relative biomass in 1974, or the weighting of indices, all models estimated that the stock is overexploited. This consistent result is most likely driven by the declining trend in the five CPUE indices included in the model. In all, current SSB and total biomass values estimated with the catch-free model did not exceed 14% and 13% of virgin biomass, respectively, with most scenarios yielding values below 9% and 8%, respectively. It is also important to remember that if the stock was not at virgin conditions in 1960, the model results based on this assumption would likely be overestimating current status, i.e., depletions would be larger.

The age-structured model (ASM) generally provided the less pessimistic results, although the baseline scenario with inverse CV weighting estimated depletions of about 80% with respect to virgin biomass or numbers and the alternative scenario with low natural mortality also estimated depletions of 75% of the virgin level. The baseline scenario with equal CV weighting and the two alternative catch scenarios considered were less pessimistic and estimated depletions of slightly less than two thirds of the virgin level.

In general, population projections (even with a no-catch policy) consistently predicted pessimistic outlooks, especially with surplus production modeling. In only one case with the age-structured model, did population abundance (in numbers) exceed 50% of virgin levels after 30 years, although this was a sensitivity case with constant low mortality ($M=0.03$ for all ages), which implied $B_{MSY}/B_{virgin}=0.28$, quite a low value for this type of life-history.

The multiple indicators of fishing impact and vulnerability to exploitation used in this assessment provide a consistent picture for dusky sharks in the northwestern Atlantic Ocean. Decreasing temporal trends in mean size of catch and catch rates, together with decreasing biomass and increasing fishing mortality rates derived from the multiple stock assessment methodologies used, all indicate that the stock considered has been very heavily exploited. In addition, biological indicators such as late age at maturity and first reproduction, very limited reproductive potential, and high longevity—which translate into very low population growth rates and elasticity patterns characteristic of very vulnerable populations—also indicate that dusky sharks are particularly vulnerable to exploitation. The low value of steepness (0.29) and high inflection point of the population growth curve (0.72) further indicate that present stock size may be even farther away from MSY levels than predicted with traditional surplus production theory (where MSY is reached at 0.5K). However, results from the ASCFM suggest that the spawning stock biomass at MSY (SSB_{MSY}/SSB_0; **Table 4.8**) may be reached at values close to 50% of K, whereas the ASM results estimated values close to K. In all, more work to elucidate the differences in B_{MSY} among model predictions is needed.

According to IUCN Red List criteria, a taxon is "Critically Endangered" if there has been a population reduction of at least 80% over the last 10 years or three generations, whichever is longer. In our models we assumed that the stock was essentially unexploited in 1960; three generations (~90 years) from 2003 would correspond to 1913, a date that precedes the fishery for shark liver and hence, the stock of dusky sharks would have been virgin (see section 4.1.2.1.4). Thus, according to IUCN criteria, the U.S. Atlantic and Gulf of Mexico stock of dusky shark would be classified as Critically Endangered.

From a management perspective, the dusky shark is already a prohibited species and a time-area closure was designated off North Carolina to protect the juvenile stages of this species and sandbar shark while in their nursery areas. The high hooking mortality of immature dusky sharks in longlines (69-79%; Romine 2004) implies that there will still be some level of mortality associated with the incidental catch of this species over its range. The high value of dusky shark fins in the international trade is also an incentive for continued finning of this species.

It appears that the pronounced decline in dusky shark abundance was largely caused by declines in the late 1970s and during the 1980s, but most CPUE series in the 1990s show either a more stable or unclear trend. In particular, the BLLOP and VIMS series show some signs of recovery after lows in 2000 and 1997, respectively. Recent evidence from the VIMS survey further confirms that relative abundance of dusky sharks (mostly juveniles) may still be increasing (J. Musick, VIMS, pers. comm.). Results from the NEFSC shark surveys also appear to show an increase in the nominal CPUE of dusky sharks since 1996 (NEFSC, pers. comm.). Recent anecdotal information from a commercial longline fisherman also indicates large catches of adult dusky sharks off the east coast of Florida in the early fall of 2005 (R. Hudson, Directed Shark Fisheries, pers. comm.). However, it is hard to reconcile these recent increasing trends with the level of catches and the biology of this species. The more stable trends in CPUE since the 1990s correspond to some of the highest catches. The more recent increase (since 2000) could be attributed to the ban on catches of dusky sharks, but that would imply a stock that responds more rapidly to reductions in F than what its biology indicates. In all, despite these recent signs of potential recovery, there is little doubt that the dusky shark stock in the U.S. Atlantic and Gulf of Mexico has been severely depleted with respect to virgin levels.

5.3. Research Recommendations and Considerations for Future Assessments

Future research and assessment recommendations include, but are not limited to: better species identification, consideration of alternative catch scenarios (especially estimation of commercial catches and discards prior to 1990), quantification of MRFSS B2 (released alive) catches and post-release hooking mortality, derivation of selectivity patterns, use of mark-recapture data as an alternative method to estimate exploitation rates, use of surplus production models that do not assume a symmetrical production curve, and exploration of alternative approaches to modeling effort by fishery sector (or derivation of a composite effort series) with the catch-free assessment methodology.

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Appendix 1

Calculation of gear selectivity

Given the lack of studies on gear selectivity and the limited data available, a simple approach was used to calculate gear selectivity. The approach assumes that the population declines exponentially with age and that the fishing and natural mortalities are the same for all age groups. Thus, the number of fish at age a, will be:

$$N_a = N_0 e^{-(F+M)a} \tag{A.1}$$

The catch from age group a will be equal to:

$$C_a = s_a E N_a = s_a E N_0 e^{-(F+M)a} \tag{A.2}$$

where s_a denotes gear selectivity at age a and E is the exploitation rate.

If there is an age a_1 above which selectivity is equal to 1 (fish are fully selected), then the above equation becomes:

$$C_a = E N_0 e^{-(F+M)a} \quad \text{for a>a}_1 \tag{A.3}$$

and the total catch for the given period will be:

$$C_{tot} = E N_0 \sum_{a=0}^{a_{\max}} s_a e^{-(F+M)a} \tag{A.4}$$

The ratio of the catch from an age class a to the total catches is:

$$\frac{C_a}{C_{tot}} = \frac{e^{-(F+M)a}}{\sum_{a=0}^{a_{\max}} s_a e^{-(F+M)a}} = const \times e^{-(F+M)a} \quad \text{for a>a}_1 \tag{A.5}$$

Thus, the logarithm of the relative catch at age is linearly related to age:

$$\ln P_a = \ln \frac{C_a}{C_{tot}} = -(F+M)a + \ln(cons) = -Za + const \tag{A.6}$$

Using the catch at age information available for the fully selected age classes we can calculate the intercept and slope of this line. Once the intercept and slope have been found, we can use equation (A.6) to predict the relative catch at age for ages $a<a_1$ in the case in which those ages were fully selected. The ratio of the predicted relative catches for each of those ages, $P_{a,pred}$, to the observed relative catches, $P_{a,obs}$, could be used as an approximation of the gear selectivity for each of the non-fully selected age classes.

The approach presented here is very simple and needs to be used with caution, especially in cases in which fishing and natural mortalities vary considerably with age (see a relevant discussion in Quinn and Deriso, pp. 318-322). This method also assumes that fishing mortality is much smaller than natural mortality and that the population is at equilibrium. One important consideration of this type of analysis is which ages to use in the regression (fully selected age classes). Usually, this decision is made by plotting the catch curves and choosing the classes which appear to support a decline with age. For the gears considered in our analysis, the following age classes were assumed to be fully selected:

BLLOP: ages 11 to 25
VIMS: ages 5 to 12
LPS: ages 4 to 13
Weighout: ages 5 to 12

The decline in gear selectivity for fish of age smaller than the first age class which was considered fully selected was assumed to be described by a logistic curve. We also accounted for the fact that the representation of very old fish in the catch-at-age data was very low by assuming that selectivity declines slowly with age after it reaches its maximum. A double logistic curve was chosen to describe the trends in gear selectivity. The selectivity curves calculated for each gear are shown in **Figures 2.21** and **2.22**.

Table 2.1. Dusky shark commercial landings (pounds dressed weight) from four data collection programs: Canvass southeast, Quota monitoring data, Coastal logbook program, and Canvass northeast (dealer weighout).

Year	Canvass SE	QMD	Coastal Log	Canvass NE	Total
1982				40	40
1983				11	11
1984					0
1985	4,963				4,963
1986					0
1987	83			11	94
1988	1,691			135	1,826
1989	994			529	1,523
1990	39,951			922	40,873
1991	33,138		300	709	33,847
1992	141,730	2,318	56,674	1,114	142,844
1993	60,526	2,752	12,687	37,773	98,299
1994	86,074	31,348	6,896	36,442	122,516
1995	99,039	327,560	3,664	57,454	385,014
1996	94,189	270,626	174,345	44,612	315,238
1997	36,303	73,250	55,114	25,238	98,488
1998	43,278	79,206	53,902	21,214	100,420
1999	70,060	58,568	92,649	45,419	138,068
2000	24,828	80,208	22,797	127,290	207,498
2001	145	145	2,756	815	3,571
2002	4,173	1,139	12,552	4,605	17,157
2003	8,106	282	12,501		12,501

2003 data from Canvass NE not yet available at the time of this writing.
Total landings are the sum of the Canvass NE column and the maximum of the Canvass SE, QMD, or Coastal Log columns.

Table 2.2. Dusky shark recreational landings (numbers and pounds dressed weight) from three data collection programs: MRFSS, Headboat, and TXPWD surveys.

	MRFSS		Headboat		TXPWD		Total	
Year	numbers	weight	numbers	weight	numbers	weight	numbers	weight
1981	36,325	492,802					36,325	492,802
1982	9,023	122,410					9,023	122,410
1983	21,324	289,291					21,324	289,291
1984	30,505	413,845					30,505	413,845
1985	15,194	206,129					15,194	206,129
1986	20,215	274,246	149	1,533	448	2,946	20,812	278,726
1987	26,059	353,529	123	1,266	57	375	26,239	355,169
1988	14,845	201,394	105	1,081	117	769	15,067	203,244
1989	11,944	162,038	155	1,595	0	0	12,099	163,633
1990	10,333	140,182	38	391	0	0	10,371	140,573
1991	13,384	181,574	89	916	0	0	13,473	182,489
1992	27,885	378,301	392	4,034	0	0	28,277	382,335
1993	3,233	43,860	457	4,703	0	0	3,690	48,563
1994	9,284	125,951	191	1,966	0	0	9,475	127,917
1995	7,932	107,609	223	2,295	16	105	8,171	110,009
1996	14,958	202,927	355	3,653	0	0	15,313	206,580
1997	13,258	179,864	250	2,573	36	237	13,544	182,674
1998	4,336	58,824	163	1,677	0	0	4,499	60,502
1999	5,186	70,356	384	3,952	0	0	5,570	74,307
2000	2,226	30,199	16	165	43	283	2,285	30,646
2001	5,548	75,267	27	278	0	0	5,575	75,545
2002	962	13,051					962	13,051

Landings in weight were obtained by multiplying numbers by average weight for all years combined (due to very small sample sizes in some individual years) for each of the three surveys.
Data for 2002 are only from MRFSS; Headboat and TXPWD were not yet available.

Table 2.3. Dusky shark commercial discards (pounds dressed weight) from two data sources: Large Pelagic Logbook (i.e., dead discards estimated from the pelagic longline logbook and observer reports from that fishery) and Bottom longline observers (BLLOP).

Year	Large Pelagic Logbook	Bottom longline Observers	Total
1992	98,890	8,943	107,833
1993	51,800	3,819	55,619
1994	390,119	5,431	395,550
1995	45,313	20,669	65,982
1996	21,258	17,077	38,334
1997	39,899	4,622	44,521
1998	54,671	4,998	59,669
1999	17,002	5,846	22,849
2000	42,744	5,061	47,805
2001	4,187	174	4,361
2002	0	792	792
2003	0	789	789

Discard estimates from the bottom longline fishery obtained by multiplying the maximum of three commercial landings estimates (Canvass SE, QMD, and Coastal logbook; see Table 2.1) by an average discard rate of 6.31% observed during 1993-2004.

Table 2.4. Dusky shark total catches (pounds dressed weight).

Year	Commercial	Recreational	Discards	Total
1981		492,802		492,802
1982	40	122,410		122,451
1983	11	289,291		289,303
1984	0	413,845		413,845
1985	4,963	206,129		211,092
1986	0	278,726		278,726
1987	94	355,169		355,263
1988	1,826	203,244		205,070
1989	1,523	163,633		165,156
1990	40,873	140,573		181,447
1991	33,847	182,489		216,336
1992	142,844	382,335	107,833	633,011
1993	98,299	48,563	55,619	202,482
1994	122,516	127,917	395,550	645,983
1995	385,014	110,009	65,982	561,006
1996	315,238	206,580	38,334	560,153
1997	98,488	182,674	44,521	325,683
1998	100,420	60,502	59,669	220,590
1999	138,068	74,307	22,849	235,224
2000	207,498	30,646	47,805	285,949
2001	3,571	75,545	4,361	83,477
2002	17,157	13,051	792	31,000
2003	12,501		789	13,290

Table 2.5. Percentage of dusky shark commercial landings by region and year for all gear combined (general canvass data).

	Region		
Year	Gulf of Mexico	Mid Atlantic	South Atlantic
1988	0.00	100.00	0.00
1989	0.00	97.65	2.35
1990	0.00	100.00	0.00
1991	3.22	94.46	2.32
1992	1.61	78.00	20.39
1993	1.70	61.04	37.25
1994	6.90	41.18	51.92
1995	17.93	23.70	58.37
1996	31.57	17.59	50.37
1997	25.34	17.19	55.91
1998	15.53	3.45	68.84
1999	8.26	39.32	49.35
2000	1.12	83.68	15.20
2001	0.00	84.90	15.10
2002	0.80	52.45	46.75
2003	0.00	37.97	62.03

Table 2.6. Percentage of dusky shark commercial landings by region and gear for all years combined. (Years listed under each region indicate those used in the summary calculation; source: general canvass)

	Region		
Gear	Gulf of Mexico (1991 - 2004)	Mid Atlantic (1988 - 2002)	South Atlantic (1989 - 2003)
Diving	0.00	0.00	0.00
Gillnets	0.03	39.30	13.80
Lines	14.83	0.58	1.62
Longlines	85.13	54.44	76.52
Other	0.02	0.03	7.04
Other nets	0.00	0.03	0.02
Other trawl	0.00	0.00	0.00
Otter trawl	0.00	3.29	0.78
Pots & traps	0.00	0.00	0.00
Purse seine	0.00	0.03	0.00
Unknown	0.00	2.30	0.22

Table 2.7. Percentage of dusky shark commercial landings by region and year for all gear combined (source: coastal fisheries logbook).

	Region		
Year	Gulf of Mexico	Mid Atlantic	South Atlantic
1991	100.00	0.00	0.00
1992	95.01	0.00	4.99
1993	97.23	0.00	2.77
1994	49.46	13.12	37.41
1995	49.18	0.00	50.82
1996	42.47	20.15	37.38
1997	30.82	30.49	38.69
1998	20.89	13.17	65.94
1999	50.69	13.26	36.05
2000	22.33	5.07	72.60
2001	89.30	1.63	9.07
2002	78.94	7.30	13.76
2003	50.37	41.68	7.95

Table 2.8. Percentage of dusky shark commercial landings by region and gear for all years combined, 1991-2003 (source: coastal fisheries logbook).

	Region		
Gear	Gulf of Mexico	Mid Atlantic	South Atlantic
Bottom longline	97.42	54.84	92.62
Buoy lines	0.01	0.00	0.00
Diving	0.00	0.00	0.00
Electric reel	1.34	0.00	0.19
Handline	1.18	4.88	5.29
Gillnets	0.00	40.28	1.60
Traps	0.02	0.00	0.00
Trolling	0.03	0.00	0.29

Table 2.9. Results of linear regressions applied to several time series of average length and weight for dusky shark.

Survey	Years	Length			Weight		
		R^2	Pr > F	Trend	R^2	Pr > F	Trend
BLLOP	1994-2003	0.35	0.07	decreasing	0.41	0.046 *	decreasing
	1994 (-2000)	0.46	0.045 *	decreasing	0.61	0.012 *	decreasing
	1994-1998	0.96	0.003 **	decreasing	0.95	0.004 **	decreasing
	1998-2000	0.92	0.18	increasing	0.91	0.2	increasing
	2000-2003	0.56	0.25	decreasing	0.68	0.17	decreasing
MRFSS	1981-2001	0.34	0.011 *	decreasing	0.58	0.012 *	decreasing
	All but 1981	0.48	0.002 **	decreasing	0.66	0.004 **	decreasing
	1983-1992	0.61	0.008 **	decreasing	0.53	0.018 *	decreasing
	1994-2001	0.11	0.81	increasing	0.05	0.91	increasing
VIMS	1974-2003	0.17	0.044 *	decreasing	0.18	0.039 *	decreasing
	1974-1987	0.14	0.225	increasing	0.03	0.572	increasing
	1990-2003	0.08	0.37	decreasing	0.13	0.255	decreasing
LPS	1985-1998	0.43	0.015 *	decreasing	0.67	0.001 ***	decreasing
	1985-1993	0.28	0.14	decreasing	0.71	0.004 **	decreasing
	1995-1998	0.31	0.447	increasing	0.19	0.565	increasing
WEIGHOUT	1988-2003				0.04	0.47	decrease
	1988-1993				0.56	0.085	increase
	1993-2003				0.48	0.017 *	decrease

Lengths used were fork length (in cm) for the BLLOP and VIMS and total lengths (in cm) for the MRFSS and LPS; weights were pounds dressed weight except for the LPS (kg whole weight).
* denotes significance at the 5% level, ** at the 1% level, and *** at the 0.1% level.

Table 2.10. Deviance analysis tables showing the stepwise procedure used to develop the catch rate model for dusky shark in the **BLLOP**. Proportion positive assumed a binomial error distribution, whereas positive catch rates assumed a Poisson distribution. Effort defined as the product of the number of hooks per set, miles of longline per set, and soak time of set in hours.

BLLOP

Proportion positive

Factors	d.f.	Deviance	Deviance/df	% Reduction in deviance/df	% Difference	L	Chi Square	Pr>Chi Square
NULL	1107	1252.683	1.1316			-626.342		
AREA	1105	973.0561	0.8806	22.18	22.18	-486.528	279.63	<0.0001
BAIT TYPE	1100	1161.6036	1.056	6.68		-580.802	90.5	<0.0001
YEAR	1098	1201.83	1.0946	3.27		-600.915	50.85	<0.0001
HOOK TYPE	1097	1209.7762	1.102	2.62		-604.888	42.32	<0.0001
SEASON	1104	1236.3971	1.1199	1.03		-618.199	16.29	0.001
TEMPERATURE	932	1066.3105	1.1441	-1.10		-533.155	49.68	<0.0001
TIME SET START	1106	1252.5227	1.1325	-0.08		-626.261	0.16	0.6888
DEPTH	1106	1252.4282	1.1324	-0.07		-626.214	0.25	0.6136
AREA+								
YEAR	1096	940.5267	0.8581	24.17	1.99	-470.263	32.53	0.0002
BAIT TYPE	1098	943.707	0.8595	24.05		-471.854	27.3	0.0001
HOOK TYPE	1095	945.6566	0.8636	23.68		-472.828	25.35	0.0026
SEASON	1102	960.59	0.8717	22.97		-480.29	12.47	0.0059
TEMPERATURE	930	853.2006	0.917	18.96		-426.6	12.06	0.0005
AREA + YEAR								
BAIT TYPE	1089	917.5062	0.8425	25.55	1.38	-458.753	21.75	0.0013
HOOK TYPE	1086	922.8297	0.8498	24.90	0.73	-461.415	16.42	0.0585
SEASON	1093	930.7602	0.8516	24.74	0.57	-465.38	9.77	0.0207
AREA*YEAR	1080	922.535	0.8542	24.51	0.34	-461.268	17.99	0.3244
TEMPERATURE	921	835.8276	0.9075	19.80	-4.37	-417.914	8.81	0.003

FINAL MODEL RESULTS

Factors	Akaike's information criterion	Schwarz's Bayesian criterion	-2 Res L	Significance (Pr>Chi square) of theType 3 test of fixed effects for each individual factor: AREA	YEAR	BAIT TYPE
AREA+YEAR+ BAIT TYPE	5668	5673	5666	<0.0001	0.0052	0.0063

Positive catches

Factors	d.f.	Deviance	Deviance/df	% Reduction in deviance/df	% Difference	L	Chi Square	Pr>Chi Square
NULL	269	3851.1758	14.3166			775.3622		
AREA	267	2382.3389	8.9226	37.68	37.68	1509.781	1468.84	<0.0001
TEMPERATURE	256	3193.8307	12.4759	12.86		1070.031	547.34	<0.0001
YEAR	260	3294.4407	12.6709	11.50		1053.73	556.74	<0.0001
BAIT TYPE	263	3395.0957	12.909	9.83		1003.402	456.4	<0.0001
SEASON	266	3618.9216	13.605	4.97		891.4893	232.25	<0.0001
HOOK TYPE	262	3666.8929	13.9958	2.24		867.5036	184.64	<0.0001
TIME SET START	268	3809.1727	14.2133	0.72		796.3637	42	<0.0001
DEPTH	268	3843.0897	14.3399	-0.16		779.4052	8.09	0.0045
AREA+								
YEAR	258	2012.7435	7.8013	45.51	7.83	1694.578	369.6	<0.0001
SEASON	264	2108.02	7.9849	44.23		1646.94	274.32	<0.0001
TEMPERATURE	254	2112.709	8.3178	41.90		1610.592	242.31	<0.0001
BAIT TYPE	261	2247.6524	8.6117	39.85		1577.124	137.17	<0.0001
HOOK TYPE	260	2266.3241	8.7166	39.12		1567.788	118.50	<0.0001

Table 2.10. (continued)

AREA + YEAR								
SEASON	255	1723.1686	6.7575	52.80	7.29	1839.366	289.57	<0.0001
TEMPERATURE	245	1709.8571	6.9790	51.25		1812.018	274.76	<0.0001
BAIT TYPE	252	1909.436	7.5771	47.07		1746.232	106.15	<0.0001
HOOK TYPE	251	1997.39	7.957	44.42		1702.255	18.19	0.0111
AREA+YEAR+SEASON								
BAIT TYPE	249	1615.4905	6.4879	54.68	1.88	1893.205	110.09	<0.0001
TEMPERATURE	242	1631.3977	6.7413	52.91	0.11	1851.248	58.35	<0.0001
SEASON*YEAR	244	1663	6.8176	52.38	-0.42	1869	59.68	<0.0001
HOOK TYPE	248	1704.1977	6.8718	52.00	-0.80	1848.851	21.38	0.0032
AREA*YEAR	240	1664.4968	6.9354	51.56	-1.24	1868.702	58.67	<0.0001

FINAL MODEL RESULTS

Factors	Akaike's information criterion	Schwarz's Bayesian criterion	-2 Res L	Significance (Pr>Chi square) of theType 3 test of fixed effects for each individual factor: AREA	YEAR	SEASON	BAIT TYPE
AREA+YEAR+SEASON+ BAIT TYPE	388	392	386	<0.0001	<0.0001	0.7211	<0.0001

% Difference: percent difference in deviance/df between the newly included factor and the previous factor entered into the model
L: log likelihood; Chi Square: Pearson Chi-square statistic; Pr>Chi Square: significance level of the Chi-square statistic

Table 2.11. Results of linear regressions applied to several standardized time series of catch rates for dusky shark.

Survey	Years	R^2	Pr > F	Trend
BLLOP	1994-2003	0.17	0.24	decreasing
	1994 - 1997	0.81	0.10	increasing
	1997-2000	0.76	0.13	decreasing
	2000-2003	0.91	0.045 *	increasing
	1994-2000	0.12	0.45	decreasing
VIMS	1974-2003	0.40	0.0004 ***	decreasing
	1974-1990	0.44	0.007 **	decreasing
	1990-2003	0.32	0.043 *	increasing
CFL	1996-2003	0.05	0.60	decreasing
LPS	1986-2003	0.72	<0.0001 ***	decrease
	1986-1995	0.76	0.001 ***	decrease
	1996-2001	0.92	0.002 **	decrease
	2001-2003	0.46	0.5250	increase
LPL	1992-2003	0.81	<0.0001 ***	decrease

* denotes significance at the 5% level, ** at the 1% level, and *** at the 0.1% level.

Table 2.12. Dusky sharks observed and proportion of positive sets by year for the five CPUE series examined.

Series name	Year	Observations	Proportion positive	
BLLOP	1994	72	0.297	
	1995	395	0.298	
	1996	221	0.336	
	1997	143	0.395	
	1998	316	0.283	
	1999	297	0.302	
	2000	10	0.094	
	2001	84	0.244	
	2002	50	0.104	
	2003	22	0.231	
	Total	1610	0.265	Overall
VIMS	1973	0	0.000	
	1974	7	0.154	
	1975	20	0.450	
	1976	7	0.143	
	1977	4	0.118	
	1978	10	0.500	
	1979	10	0.200	
	1980	117	0.282	
	1981	43	0.483	
	1982	3	0.250	
	1983	3	0.067	
	1984	6	0.077	
	1985	1	0.333	
	1986	0	0.000	
	1987	4	0.429	
	1988	0	0.000	
	1989	1	0.200	
	1990	3	0.070	
	1991	12	0.135	
	1992	2	0.061	
	1993	5	0.150	
	1994	0	0.000	
	1995	5	0.080	
	1996	25	0.235	

Table 2.12. (continued)

	1997	1	0.053	
	1998	7	0.091	
	1999	18	0.235	
	2000	28	0.353	
	2001	16	0.278	
	2002	37	0.333	
	2003	23	0.176	
	Total	418	0.191	Overall
CFL	1996	288	0.082	
	1997	109	0.038	
	1998	136	0.049	
	1999	182	0.063	
	2000	61	0.020	
	2001	9	0.003	
	2002	26	0.008	
	2003	12	0.005	
	Total	823	0.035	Overall
LPS	1986	908	0.164	
	1987	992	0.145	
	1988	452	0.058	
	1989	773	0.111	
	1990	936	0.107	
	1991	865	0.096	
	1992	783	0.034	
	1993	418	0.086	
	1994	334	0.051	
	1995	396	0.058	
	1996	187	0.070	
	1997	298	0.044	
	1998	134	0.075	
	1999	114	0.035	
	2000	216	0.037	
	2001	147	0.041	
	2002	162	0.037	
	2003	560	0.027	
	Total	8675	0.088	Overall
LPL	1992	15032	0.073	
	1993	14837	0.092	
	1994	15925	0.089	
	1995	16515	0.074	

Table 2.12. (continued)

1996	16186	0.067	
1997	14858	0.051	
1998	11922	0.047	
1999	11693	0.050	
2000	11508	0.047	
2001	10522	0.032	
2002	9542	0.024	
2003	9529	0.027	
Total	158069	0.060	Overall

Table 2.13. Deviance analysis tables showing the stepwise procedure used to develop the catch rate model for dusky shark in the **VIMS** survey. Proportion positive assumed a binomial error distribution, whereas positive catch rates assumed a Poisson distribution. Effort defined as hooks per set times hours fished.

VIMS

Proportion positive

Factors	d.f.	Deviance	Deviance/df	% Reduction in deviance/df	% Difference	L	Chi Square	Pr>Chi Square
NULL	698	699	1.0014			-626.342		
TEMPERATURE	725	493.8762	0.6812	31.98	31.98	-246.938	10.08	0.0015
AREA	693	484.6693	0.6994	30.16		-242.335	103.32	<0.0001
DEPTH	902	655.7197	0.727	27.40		-327.859	1.76	0.1846
YEAR	668	521.558	0.7808	22.03		-293.995	66.43	0.0001
SETSTART	797	639.3322	0.8022	19.89		-319.666	1.01	0.3148
SEASON	696	586.2235	0.8423	15.89		-293.112	1.77	0.4134
HOOK TYPE	262	54.5569	0.2082	79.21		-27.2785	Hessian not positive definite	
AREA+								
TEMPERATURE	720	431.7331	0.5996	40.12	8.15	-215.867	0.21	0.6488
SETSTART	792	542.715	0.6852	31.58	1.42	-271.358	0.28	0.5949
SEASON	691	483.38	0.6995	30.15	-0.01	-241.69	1.29	0.5252
YEAR	1096	940.5267	0.8581	14.31	-15.85	-215.508	Hessian not positive definite	
YEAR*SEASON	622	378.4435	0.6084	39.25	9.09	-189.221	Hessian not positive definite	
AREA*YEAR	567	359.9636	0.6349	36.60	6.44	-179.982	Hessian not positive definite	
AREA*SEASON	682	470.5686	0.69	31.10	0.94	-235.284	Hessian not positive definite	

FINAL MODEL RESULTS

Factors	Akaike's information criterion	Schwarz's Bayesian criterion	-2 Res L	Significance (Pr>Chi square) of theType 3 test of fixed effects for each individual factor: AREA	YEAR
AREA+YEAR	3502.2	3506.5	3500.2	<0.0001	0.4706
YEAR	3472.6	3477.1	3470.6		0.0025

Positive catches

Factors	d.f.	Deviance	Deviance/df	% Reduction in deviance/df	% Difference	L	Chi Square	Pr>Chi Square
NULL	101	513.1346	5.0805			125.1168		
YEAR	75	298.7009	3.9827	21.61	21.61	232.3337	214.43	<0.0001
DEPTH	104	452.8114	4.354	14.30		73.8209	1.84	0.1749
TEMPERATURE	77	349.2717	4.536	10.72		65.6979	1.11	0.2916
SETSTART	106	504.9734	4.7639	6.23		95.8478	4.64	0.0312
SEASON	99	492.9607	4.9794	1.99		135.2038	20.17	<0.0001
AREA	97	495.4015	5.1072	-0.53		133.9833	17.73	0.0014
HOOK TIPE	0	0	.	n/a		-3.000	0.03	0.9846
YEAR+								
SEASON	73	257.35	3.5254	30.61	9.00	253.01	41.35	<0.0001
SETSTART	80	300.05	3.7506	26.18	4.57	198.31	0.03	0.8695
AREA	72	296.6219	4.1197	18.91	-2.70	233.3732	2.08	0.5562
YEAR + SEASON								
YEAR*SEASON	56	181.1015	3.2340	36.34	5.74	291.1334	76.25	<0.0001
SEASON*AREA	66	236.0073	3.58	29.62	-27.03	263.6805	21.35	0.0033
AREA	70	254.9698	3.6424	28.31	-2.30	254.1992	2.38	0.4968
YEAR*AREA	64	246.9066	3.8579	24.06	-6.54	258.2308	10.45	0.3156

Table 2.13. (continued)

FINAL MODEL RESULTS					
	Akaike's information	Schwarz's Bayesian		Significance (Pr>Chi square) of theType 3 test of fixed effects for each individual factor	
Factors	criterion	criterion	-2 Res L	YEAR	SEASON
YEAR+SEASON	265.7	267.9	263.7	0.0043	0.0084

% Difference: percent difference in deviance/df between the newly included factor and the previous factor entered into the model
L: log likelihood; Chi Square: Pearson Chi-square statistic; Pr>Chi Square: significance level of the Chi-square statistic

Table 2.14. Summary table showing the statistically significant factors ($P<0.05$) used to develop the catch rate model for dusky shark in the **CFL**. Proportion of positive trips and the log-transformed positive catches are modeled separately. Catch rate is defined as weight of catch divided by the product of the number of hooks per set, miles of longline per set, and soak time of set in hours, multiplied by a factor of 1000.

CFL

Proportion of positive trips

Factors	Pr > F
YEAR	<0.0001
QUARTER	<0.0001
VESSEL	<0.0001

Positive catches

Factors	Pr > F
YEAR	0.05
REGION	<0.0001
QUARTER	0.0127

Table 2.15. Deviance analysis tables showing the stepwise procedure used to develop the catch rate model for dusky shark in the **LPS**. Proportion positive assumed a binomial error distribution, whereas positive catch rates assumed a Poisson distribution. Effort defined as 100 trips.

LPS

Proportion positive

Factors	d.f.	Deviance	Deviance/df	% Reduction in deviance/df	% Difference	L	Chi Square	Pr>Chi Square
NULL	8674	5180.5	0.5972			-2590.2		
STATE	8667	4793.2	0.5530	7.40	7.40	-2396.6	387.25	<0.000001
REGION	8673	4884.7	0.5632	5.69		-2442.4	295.76	<0.000001
YEAR	8657	4959.6	0.5729	4.07		-2479.8	220.91	<0.000001
INTERVIEW TYPE	8673	5128.2	0.5913	0.99		-2564.1	52.32	<0.000001
TOURNAMENT	8673	5153.4	0.5942	0.50		-2576.7	27.11	<0.000001
BOAT TYPE	8673	5172.8	0.5964	0.13		-2586.4	7.64	0.00570
MONTH	8671	5178.3	0.5972	0.00		-2589.1	2.19	0.53312
STATE+								
YEAR	8650	4596.5	0.5314	11.02	3.62	-2298.3	196.72	0.000001
INTERVIEW TYPE	8666	4740.0	0.547	8.41		-2370.0	53.24	<0.000001
MONTH	8664	4754.8	0.549	8.10		-2377.4	38.43	<0.000001
TOURNAMENT	8666	4768.5	0.550	7.85		-2384.2	24.75	<0.000001
BOAT TYPE	8666	4791.4	0.553	7.42		-2395.7	1.78	0.18226
REGION	8667	4793.2	0.553			-2396.6	0	
STATE + YEAR								
MONTH	8647	4567.8	0.5283	11.54	0.52	-2283.9	28.69	<0.000001
TOURNAMENT	8649	4575.8	0.5291	11.40	0.39	-2287.9	20.73	0.00001
INTERVIEW TYPE	8649	4575.9	0.5291	11.40	0.39	-2288.0	20.60	0.00001
BOAT TYPE	8649	4592.1	0.5309	11.10	0.08	-2296.0	4.41	0.03582
REGION	8650	4596.5	0.5314	11.02	0.00	-2298.3	196.72	<0.000001

FINAL MODEL RESULTS

Factors	Akaike's information criterion	Schwarz's Bayesian criterion	-2 Res L	Significance (Pr>Chi square) of theType 3 test of fixed effects for each individual factor: STATE	YEAR
STATE+YEAR	48438	48445	48436	<0.0001	<0.0001

Positive catches

Factors	d.f.	Deviance	Deviance/df	% Reduction in deviance/df	% Difference	L	Chi Square	Pr>Chi Square
NULL	765	905	1.1829			-678.6		
MONTH	762	856.9	1.1246	4.93	4.93	-654.6	48.01	<0.000001
INTERVIEW TYPE	764	887.2	1.1612	1.83		-669.7	17.78	0.00002
STATE	759	888.9	1.1711	1.00		-670.6	16.08	0.01332
TOURNAMENT	764	898.4	1.176	0.58		-675.4	6.51	0.01075
YEAR	748	883.8	1.1816	0.11		-668	21.15	0.21972
BOAT TYPE	764	903.0	1.1820	0.08		-677.7	1.92	0.16608
REGION	764	904.9	1.1844	-0.13		-678.6	0.04	0.84769
MONTH+								
STATE	756	838.4	1.1090	6.25	1.32	-645.3	18.53	0.00504
INTERVIEW TYPE	761	847.2	1.1133	5.88		-649.8	9.70	0.00184
REGION	761	854.5	1.1228	5.08		-653.4	2.46	0.11669
BOAT TYPE	761	855.3	1.1239	4.99		-653.8	1.64	0.20058
YEAR	745	837.5	1.1242	4.96		-644.9	19.43	0.30457
TOURNAMENT	761	856.4	1.1253	4.87		-654.3	0.56	0.45454

Table 2.15. (continued)

MONTH + STATE								
INTERVIEW TYPE	755	828.8	1.0978	7.19	0.95	-640.6	9.57	0.00198
BOAT TYPE	755	834.5	1.1053	6.56		-643.4	3.93	0.04737
YEAR	739	817.1	1.1057	6.53		-634.7	21.32	0.21241
REGION	756	838.4	1.1090	6.25		-645.3	0	.
TOURNAMENT	755	838.4	1.1105	6.12		-645.3	0	0.95150
MONTH + STATE + INTERVIEW TYPE								
YEAR	738	805.1	1.0909	7.78	0.58	-628.7	23.75	0.12633
BOAT TYPE	754	823.9	1.0928	7.62		-638.1	4.9	0.0268
REGION	755	828.8	1.0978	7.19		-640.6	0	.
TOURNAMENT	754	828.5	1.0988	7.11		-640.4	0.36	0.5476
MONTH + STATE + INTERVIEW TYPE + YEAR								
BOAT TYPE	737	800.2	1.0858	8.21	0.43	-626.2	4.87	0.02728
REGION	738	805.1	1.0909	7.78		-628.7	0	.
TOURNAMENT	737	804.2	1.0912	7.75		-628.2	0.88	0.34744

FINAL MODEL RESULTS

				Significance (Pr>Chi square) of theType 3 test of fixed effects for each individual factor			
Factors	**Akaike's information criterion**	**Schwarz's Bayesian criterion**	**-2 Res L**	**MONTH**	**STATE**	**INT. TYPE**	**YEAR**
MONTH+STATE+ INTERVIEW TYPE+YEAR	2291	2295	2289	<0.0001	0.0790	0.0122	0.7803

% Difference: percent difference in deviance/df between the newly included factor and the previous factor entered into the model;
L: log likelihood; Chi Square: Pearson Chi-square statistic; Pr>Chi Square: significance level of the Chi-square statistic

Table 2.16. Summary table showing the statistically significant factors (P<0.05) used to develop the catch rate model for dusky shark in the **LPL**. Proportion of positive trips and the log-transformed positive catches are modeled separately. Catch rate is defined as catch per 1000 hooks.

LPL

Proportion of positive trips

Factors	Pr > F
YEAR	0.0001
AREA	<0.0001
QUARTER	0.1542
GEAR TYPE	<0.0001
TARGET SPECIES	<0.0001
LIGHT STICKS	<0.0001

Positive catches

Factors	Pr > F
YEAR	<0.0001
AREA	<0.0001
QUARTER	0.0007
GEAR TYPE	<0.0001
TARGET SPECIES	<0.0001
LIGHT STICKS	<0.0001
TUNA CATCH RATE	<0.0001
SWORDFISH CATCH RATE	<0.0001

Table 2.17. Double logistic distributions fitted to age data of dusky sharks to describe the selectivity of hooks used in commercial and recreational fisheries and a fishery-independent survey.

Data set	Parameter estimates					Regression estimates	
	a_{50}	b	c_{50}	d	max. sel.	intercept	slope
BLLOP	4	1	32	4	0.994	1.7907	-0.0774
VIMS	2	1	28	5	0.980	2.1619	-0.2086
LPS	2	0.75	24	5	0.969	4.0288	-0.319
WEIGHOUT	2	0.6	28	5	0.987	3.099	-0.1642

a_{50} and b are median age and slope of the ascending limb of the double logistic equation, c_{50} and d are median age and slope of the descending limb of the double logistic equation; max. sel. is the maximum selectivity value of the double logistic curve; intercept and slope are the estimates from the linear regression between the natural logarithm of the observed age proportions and age used to calculate expected proportions at age.

Table 3.1. Life history parameter estimates for dusky sharks.

Parameter	Definition	Value		Units	Reference
		males	females		
K	Brody growth coefficient	0.038	0.039	yr^{-1}	Natanson et al. (1995)
Linf	Theoretical maximum length	373	349	cm fork length	Natanson et al. (1995)
t_0	Age at zero length	-6.28	-7.04	yr	Natanson et al. (1995)
t_{mat}	Median age at maturity	18	20	yr	This document
L_{mat}	Median length at maturity	224	226	cm fork length	This document
t_{max}	Lifespan	>25	>33	yr	Natanson et al. (1995)
L_{max}	Maximum observed length	299	308	cm fork length	Natanson et al. (1995) and other sources
L_0	Size at birth		68-81	cm fork length	Natanson et al. (1995)
	Reproductive frequency		2 or 3	yr	Branstetter and Burgess (1996), Branstetter and Musick (1996)
	Sex ratio at birth		1 to 1	dimensionless	
m_x	Mean number of pups		7.1	pups	A. Morgan (pers. comm.)
a	Scalar coefficient of weight on length	3.2415×10^{-5}	sexes combined	dimensionless	Kohler et al. (1995)
b	Power coefficient of weight on length	2.7862	sexes combined	dimensionless	Kohler et al. (1995)
M_0 range	Age-0 instantaneous natural mortality rate		0.020-0.248	yr^{-1}	This document
S_0 range	Age-0 annual survivorship		0.78-0.98	yr^{-1}	This document
$M_{1\text{-}mat}$ range	Age-1 to maturity M		0.020-0.223	yr^{-1}	This document
$S_{1\text{-}mat}$ range	Age-1 to maturity S		0.80-0.98	yr^{-1}	This document
M_{ad} range	Adult instantaneous natural mortality rate		0.020-0.105	yr^{-1}	This document
S_{ad} range	Adult annual survivorship		0.90-0.98	yr^{-1}	This document

Table 3.2. Statistical distributions used to describe vital rates and population parameter estimates for dusky sharks.

Parameter	Definition	Distribution used				Units
t_{max}	Lifespan	Custom (39,51)				yr
m_x	Mean number of pups	Lognormal (7.1,2.05,2,12)				pups
S_0	Age-0 annual survivorship	Custom (0.78,0.98)				yr^{-1}
$S_{1\text{-}mat}$	Age-1 to maturity S	Custom (0.80-0.90,0.98)				yr^{-1}
S_{ad}	Adult annual survivorship	Custom (0.90-0.92,0.98)				yr^{-1}
		Results				
		Mean	Median	LCL	UCL	
r	Intrinsic rate of population change	0.023	0.023	0.011	0.035	yr^{-1}
λ	Finite rate of population change	1.023	1.023	1.011	1.036	yr^{-1}
R_0	Net reproductive rate	1.97	1.93	1.37	2.80	pups
A	Mean age of parents of offspring in a stable age distribution	28.8	28.7	27.5	30.3	yr
T	Time required for the population to increase by R_0	29.2	29.1	27.8	30.9	yr
μ_1	Mean age of parents of offspring produced by a cohort over its lifetime	29.6	29.5	28.1	31.6	yr
E(fer)	Fertility elasticity (proportional matrix sensitivity)	3.4	3.4	3.2	3.5	dimensionless
E(juv)	Juvenile survival elasticity	65.5	65.5	61.3	69.7	dimensionless
E(ad)	Adult survival elasticity	31.1	31.1	27.0	35.3	dimensionless

Table 3.2. (continued).

z	Steepness of the stock-recruitment curve	0.29	0.29	0.22	0.39	dimensionless
R	Position of the inflection point of population growth curves	0.72	0.71	0.63	0.86	dimensionless
α	Pups per female over entire lifespan at low densities	1.69	1.64	1.1	2.54	pups

	Distribution fitted
r	Normal (0.02,0.01)
z	Gamma (0.05,0.01,48.44)

Custom indicates a linearly decreasing pdf, with the first value being the likeliest (a range is indicated when more than two ages are considered) and the second, the least likely; values for lognormal are mean, SD, minimum, and maximum; values for normal are mean and SD; values for gamma are location, scale, and shape. LCL and UCL are lower and upper confidence limits (taken as the 2.5th and 97.5th percentiles).

Table 4.1. Relative effort for fleets in the catch-free model (BLL = Directed Bottom-Longline shark fishery; REC = recreational shark fishery; PL = Pelagic Longline shark fishery).

YEAR	BLL	REC	PL
1960	0.001	0.001	0.077
1961	0.001	0.001	0.071
1962	0.002	0.002	0.164
1963	0.002	0.002	0.190
1964	0.003	0.003	0.323
1965	0.003	0.003	0.327
1966	0.001	0.001	0.147
1967	0.001	0.001	0.112
1968	0.002	0.002	0.152
1969	0.002	0.002	0.171
1970	0.091	0.072	0.213
1971	0.181	0.143	0.363
1972	0.270	0.213	0.245
1973	0.360	0.284	0.288
1974	0.449	0.354	0.416
1975	0.539	0.425	0.466
1976	0.628	0.495	0.480
1977	0.718	0.566	0.430
1978	0.807	0.636	0.348
1979	0.897	0.706	0.292
1980	0.986	0.777	0.337
1981	1.076	0.847	0.461
1982	1.166	0.918	0.495
1983	1.255	0.988	0.375
1984	1.345	1.059	0.973
1985	1.434	1.129	0.695
1986	1.524	1.200	1.116
1987	1.613	1.270	0.732
1988	1.703	1.341	0.880
1989	1.792	1.411	0.921
1990	1.884	1.476	1.047
1991	2.095	1.641	1.164
1992	2.227	1.744	1.237
1993	2.278	1.785	1.266
1994	2.478	1.941	1.377
1995	2.377	1.862	1.321
1996	2.442	1.913	1.357
1997	1.800	1.410	1.000
1998	2.254	1.766	1.252
1999	2.254	1.766	1.252
2000	2.254	1.766	1.252
2001	2.254	1.766	1.252
2002	2.254	1.766	1.252
2003	2.254	1.766	1.252

Table 4.2. Prior probablity distributions assigned to effort proportionality coefficients used in ASCFM.

Parameter	Prior	Lower Bound	Upper Bound
$p_{BLL,1}$	Uniform	1.00E-10	0.7
$p_{BLL,2}$ *	Lognormal median=0.03 CV=0.2	1.00E-06	0.25
$p_{REC,1}$	Uniform	1.00E-10	0.7
$p_{REC,2}$ *	Lognormal median=0.15 CV=0.35	1.00E-06	0.25
$p_{LPL,1}$ *	Normal mean=0.1 CV=0.5	1.00E-12	0.3
$p_{LPL,2}$ *	Lognormal median=1.2 CV=0.4	1.00E-12	2.5

* denotes that the prior is depicted in Figure 4.4

Table 4.3. CPUE series used in the analyses.

	CPUE 1		CPUE 2		CPUE 3		CPUE 4		CPUE 5	
Year	**VIMS**	**CV**	**LPS**	**CV**	**BLLOP**	**CV**	**CFL**	**CV**	**LPL**	**CV**
1974	2.197	1.401								
1975	3.332	0.698								
1976	4.152	1.749								
1977	0.24	4.384								
1978	1.664	1.6								
1979	3.93	1.423								
1980	2.588	0.471								
1981	1.457	0.63								
1982	0.227	3.278								
1983	0.533	3.294								
1984	0.379	2.917								
1985	0.609	3.528								
1986	-	-	1.98	0.165						
1987	1.209	1.652	2.165	0.161						
1988	-	-	1.476	0.443						
1989	0.186	7.245	1.787	0.233						
1990	0.038	8.281	1.365	0.23						
1991	0.211	2.208	1.507	0.234						
1992	0.013	17.581	0.478	0.644					1.816	1.269
1993	0.25	2.723	1.305	0.372					1.820	1.456
1994	-	-	0.544	0.797	1.007	0.28			1.158	0.918
1995	0.203	3.638	0.539	0.681	0.93	0.197			1.148	0.901
1996	0.59	1.025	0.942	0.722	1.404	0.175	0.986	0.589	1.053	0.797
1997	0.012	24.903	0.788	0.71	1.551	0.202	0.884	0.398	0.910	0.663
1998	0.132	3.702	0.584	1.029	1.231	0.224	1.244	0.409	0.907	0.647
1999	0.592	1.366	0.641	1.425	1.27	0.218	1.255	0.424	0.929	0.673
2000	0.777	1.006	0.496	1.186	0.162	0.854	1.276	0.414	0.669	0.432
2001	0.312	1.737	0.305	1.813	0.646	0.336	0.355	0.436	0.469	0.279
2002	0.929	0.827	0.594	1.287	0.829	0.351	1.415	0.462	0.370	0.199
2003	0.24	2.703	0.506	0.837	0.971	0.42	0.585	0.080	0.751	0.480

Table 4.4. Estimated expected values (EV) of the means and coefficients of variation (CV) of marginal posterior distributions for output parameters from three baseline Bayesian surplus production models: BSP, BSP-spreadsheet version, and WinBUGS BSP. Predictions of alternative harvesting policies from the first two forms of the model are also included. Biomass values are in lb dw.

	BSP		BSP-spreadsheet		WinBUGS BSP	
Parameter	**EV**	**CV**	**EV**	**CV**	**EV**	**CV**
K	8,818,289	0.18	10,853,103	0.22	17,060,000	0.34
r	0.023	0.01	0.020	0.40	0.023	0.01
C_0	161,609	0.87	310,391	0.20	307,500	0.19
B_{2003}	687,290	0.09	1,655,540	0.26	2,756,000	0.37
B_{2003}/K	0.08	0.18	0.16	0.31	0.17	0.35
MSY	50,661	0.18	52,274	0.38	98,130	0.34
B_{1974}	7,340,261	0.10	9,827,341	---	14,980,000	0.35
B_{2003}/ B_{1974}	0.09	0.12	0.17	---	0.18	---
F_{2003}/F_{MSY}	1.70	0.15	---	---	0.58	---
C_{2003}/R_y	0.92	0.10	---	---	---	---
Diagnostics						
%max weight	0.35%		0.31%		See text	
CV (wt) / CV (L*priors)	0.79					

Projections		BSP				BSP-spreadsheet[1]			
Horizon	**TAC[2]**	**B_{fin}/K[3]**	**$P(B_{fin}<0.2K)$**	**$P(B_{fin}>B_{msy})$**	**$P(B_{fin}>B_{2003})$**	**B_{fin}/K[3]**	**$P(B_{fin}<0.2K)$**	**$P(B_{fin}>B_{msy})$**	**$P(B_{fin}>B_{2003})$**
10-year	0	0.10	1.00	0.00	1.00	0.19	0.64	0.00	0.90
(2013)	1.0	0.08	1.00	0.00	0.85	0.19	0.65	0.00	0.91
20-year	0	0.12	1.00	0.00	1.00	0.22	0.43	0.00	0.99
(2023)	1.0	0.08	1.00	0.00	0.85	0.22	0.46	0.00	0.99
30-year	0	0.15	0.99	0.00	1.00	0.26	0.29	0.01	1.00
(2033)	1.0	0.09	1.00	0.00	0.85	0.25	0.29	0.02	1.00

[1] Projections include process error
[2] Total Allowable Catch policy option expressed as a proportion of the reported 2003 catch
[3] B_{fin}/K is the stock abundance in the final year of management (2013, 2023, or 2033) as a percentage of K

Table 4.5. Sensitivity analysis for dusky sharks using the BSP model with three different weighting methods. Estimated expected values (EV) of the means and coefficients of variation (CV) of marginal posterior distributions for output parameters are reported. Predictions of alternative harvesting policies are also included. Biomass values are in lb dw.

	Weighting method 1		Weighting method 6		Weighting method 10	
Parameter	**EV**	**CV**	**EV**	**CV**	**EV**	**CV**
K	12,776,691	0.24	9,737,201	0.21	14,600,143	2.46
r	0.023	0.01	0.023	0.01	0.023	0.01
C_0	441,145	0.65	259,771	0.84	303,052	0.80
B_{2003}	2,673,046	0.47	984,681	0.11	5,252,314	6.46
B_{2003}/K	0.21	0.33	0.10	0.22	0.27	0.47
MSY	73,432	0.24	55,933	0.21	83,933	2.46
B_{1974}	10,286,025	0.17	8,069,051	0.14	11,945,475	2.72
B_{2003}/ B_{1974}	0.26	0.30	0.12	0.16	0.32	0.43
F_{2003}/F_{MSY}	0.48	0.32	1.19	0.11	0.44	0.50
C_{2003}/R_y	0.31	0.30	0.67	0.10	0.29	5.16
Diagnostics						
%max weight	0.18%		0.28%		0.03%	
CV (wt) / CV (L*priors)	1.48		0.88		0.87	

Projections

		Weighting method 1				Weighting method 6			
Horizon	**TAC**[1]	B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$	B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$
10-year	0	0.25	0.27	0.01	1.00	0.15	1.00	0.00	1.00
(2013)	1.0	0.24	0.35	0.01	1.00	0.13	1.00	0.00	1.00
20-year	0	0.30	0.13	0.03	1.00	0.18	0.79	0.00	1.00
(2023)	1.0	0.27	0.21	0.01	1.00	0.15	0.99	0.00	1.00
30-year	0	0.34	0.05	0.07	1.00	0.22	0.15	0.00	1.00
(2033)	1.0	0.31	0.12	0.04	1.00	0.16	0.95	0.00	1.00

		Weighting method 10			
Horizon	**TAC**[1]	B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$
10-year	0	0.31	0.19	0.09	1.00
(2013)	1.0	0.30	0.23	0.08	1.00
20-year	0	0.36	0.09	0.14	1.00
(2023)	1.0	0.33	0.15	0.12	1.00
30-year	0	0.41	0.03	0.23	1.00
(2033)	1.0	0.37	0.09	0.17	1.00

[1] Total Allowable Catch policy option expressed as a proportion of the reported 2003 catch

[2] B_{fin}/K is the stock abundance in the final year of management (2013, 2023, or 2033) as a percentage of K

Table 4.6. Sensitivity analysis for dusky sharks using the BSP model with a multivariate importance function, decreasing the values of the prior for K, considering an alternative catch series, or changing the prior for B_{74}/K. Estimated expected values (EV) of the means and coefficients of variation (CV) of marginal posterior distributions for output parameters are reported. Predictions of alternative harvesting policies are also included. Biomass values are in lb dw.

	Multivariate IF		**Decreasing K**		**Alternative catch series**		**Changing B_{74}/K**	
Parameter	**EV**	**CV**	**EV**	**CV**	**EV**	**CV**	**EV**	**CV**
K	7,484,518	0.07	8,896,912	0.18	8,560,740	0.09	8,176,743	0.15
r	0.023	0.09	0.023	0.01	0.023	0.01	0.023	0.01
C_0	131,939	0.82	163,862	0.90	---	---	154,086	0.90
B_{2003}	698,586	0.09	687,015	0.09	775,750	0.09	690,404	0.09
B_{2003}/K	0.09	0.11	0.08	0.18	0.09	0.12	0.09	0.16
MSY	42,936	0.07	51,140	0.18	49,219	0.09	47,001	0.15
B_{1974}	7,469,064	0.07	7,335,217	0.10	7,510,513	0.06	7,431,248	0.10
B_{2003}/ B_{1974}	0.09	0.11	0.09	0.12	0.10	0.10	0.09	0.12
F_{2003}/F_{MSY}	1.67	0.10	1.70	0.10	4.36	0.09	1.69	0.10
C_{2003}/R_y	0.92	0.09	0.92	0.08	2.34	0.08	0.92	0.08
Diagnostics								
%max weight	22.8%		0.09%		0.24%		0.33%	
CV (wt) / CV (L*priors)	78.9		0.79		0.94		0.77	

Projections		**Multivariate Imp Func**				**Decreasing K**			
Horizon	**TAC**[1]	**B_{fin}/K^2**	**$P(B_{fin}<0.2K)$**	**$P(B_{fin}>B_{msy})$**	**$P(B_{fin}>B_{2003})$**	**B_{fin}/K^2**	**$P(B_{fin}<0.2K)$**	**$P(B_{fin}>B_{msy})$**	**$P(B_{fin}>B_{2003})$**
10-year	0	0.12	1.00	0.00	1.00	0.10	1.00	0.00	1.00
(2013)	1.0	0.10	1.00	0.00	0.85	0.08	1.00	0.00	0.85
20-year	0	0.14	1.00	0.00	1.00	0.12	1.00	0.00	1.00
(2023)	1.0	0.10	1.00	0.00	0.85	0.08	1.00	0.00	0.85
30-year	0	0.17	0.97	0.00	1.00	0.15	0.99	0.00	1.00
(2033)	1.0	0.10	1.00	0.00	0.85	0.09	1.00	0.00	0.85

		Alternative catch series				**Changing B_{74}/K**			
Horizon	**TAC**[1]	**B_{fin}/K^2**	**$P(B_{fin}<0.2K)$**	**$P(B_{fin}>B_{msy})$**	**$P(B_{fin}>B_{2003})$**	**B_{fin}/K^2**	**$P(B_{fin}<0.2K)$**	**$P(B_{fin}>B_{msy})$**	**$P(B_{fin}>B_{2003})$**
10-year	0	0.12	1.00	0.00	1.00	0.11	1.00	0.00	1.00
(2013)	1.0	0.10	1.00	0.00	0.99	0.09	1.00	0.00	0.84
20-year	0	0.14	1.00	0.00	1.00	0.13	1.00	0.00	1.00
(2023)	1.0	0.10	1.00	0.00	0.99	0.09	1.00	0.00	0.84
30-year	0	0.17	0.98	0.00	1.00	0.16	0.99	0.00	1.00
(2033)	1.0	0.11	1.00	0.00	0.99	0.09	1.00	0.00	0.84

[1] Total Allowable Catch policy option expressed as a proportion of the reported 2003 catch

[2] B_{fin}/K is the stock abundance in the final year of management (2013, 2023, or 2033) as a percentage of K

Table 4.7. Sensitivity analysis for dusky sharks using the BSP model when removing one CPUE series at a time. Estimated expected values (EV) of the means and coefficients of variation (CV) of marginal posterior distributions for output parameters are reported. Predictions of alternative harvesting policies are also included. Biomass values are in lb dw.

Parameter	Removing VIMS		Removing LPS		Removing BLLOP		Removing CFL	
	EV	CV	EV	CV	EV	CV	EV	CV
K	9,289,419	0.19	8,997,299	0.19	8,840,088	0.18	8,829,274	0.18
r	0.023	0.01	0.023	0.01	0.023	0.01	0.023	0.01
C_0	192,640	0.87	171,522	0.88	162,222	0.87	162,017	0.87
B_{2003}	711,238	0.08	670,852	0.11	670,165	0.09	681,837	0.09
B_{2003}/K	0.08	0.20	0.08	0.20	0.08	0.19	0.08	0.19
MSY	53,384	0.19	51,698	0.19	50,788	0.18	50,725	0.18
B_{1974}	7,467,877	0.12	7,352,445	0.11	7,323,583	0.10	7,335,600	0.10
B_{2003}/B_{1974}	0.10	0.13	0.09	0.13	0.09	0.12	0.09	0.12
F_{2003}/F_{MSY}	1.64	0.09	1.74	0.11	1.74	0.09	1.71	0.10
C_{2003}/R_y	0.89	0.08	0.94	0.10	0.94	0.09	0.93	0.09
Diagnostics								
%max weight	0.20%		0.23%		0.31%		0.32%	
CV (wt) / CV (L*priors)	0.77		0.79		0.79		0.79	

Projections Horizon	TAC[1]	Removing VIMS series B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$	Removing LPS series B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$
10-year	0	0.10	1.00	0.00	1.00	0.09	1.00	0.00	1.00
(2013)	1.0	0.08	1.00	0.00	0.93	0.08	1.00	0.00	0.75
20-year	0	0.12	1.00	0.00	1.00	0.12	1.00	0.00	1.00
(2023)	1.0	0.08	1.00	0.00	0.93	0.08	1.00	0.00	0.75
30-year	0	0.15	0.98	0.00	1.00	0.14	0.99	0.00	1.00
(2033)	1.0	0.09	1.00	0.00	0.93	0.08	1.00	0.00	0.75

Horizon	TAC[1]	Removing BLLOP series B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$	Removing CFL series B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$
10-year	0	0.10	1.00	0.00	1.00	0.10	1.00	0.00	1.00
(2013)	1.0	0.08	1.00	0.00	0.77	0.08	1.00	0.00	0.82
20-year	0	0.12	1.00	0.00	1.00	0.12	1.00	0.00	1.00
(2023)	1.0	0.08	1.00	0.00	0.77	0.08	1.00	0.00	0.82
30-year	0	0.14	0.99	0.00	1.00	0.15	0.99	0.00	1.00
(2033)	1.0	0.08	1.00	0.00	0.77	0.08	1.00	0.00	0.82

[1] Total Allowable Catch policy option expressed as a proportion of the reported 2003 catch

[2] B_{fin}/K is the stock abundance in the final year of management (2013, 2023, or 2033) as a percentage of K

Table 4.7. (continued) Sensitivity analysis for dusky sharks using the BSP model when removing one CPUE series at a time or considering commercial, recreational, or fishery-independent CPUE series only. Estimated expected values (EV) of the means and coefficients of variation (CV) of marginal posterior distributions for output parameters. Predictions of alternative harvesting policies are also included. Biomass values are in lb dw.

	Removing LPL		**Commercial series**		**Recreational series**		**F-I series**	
Parameter	**EV**	**CV**	**EV**	**CV**	**EV**	**CV**	**EV**	**CV**
K	8,809,235	0.18	9,567,914	0.20	9,288,098	0.19	8,618,833	0.19
r	0.023	0.01	0.023	0.01	0.023	0.01	0.023	0.01
C_0	159,998	0.87	209,324	0.86	189,404	0.88	175,348	0.84
B_{2003}	706,545	0.14	706,179	0.10	727,341	0.16	224,586	0.61
B_{2003}/K	0.08	0.21	0.08	0.21	0.08	0.25	0.03	0.61
MSY	50,608	0.18	54,992	0.20	53,373	0.19	49,551	0.19
B_{1974}	7,351,337	0.10	7,518,334	0.13	7,463,619	0.12	7,026,692	0.11
B_{2003}/B_{1974}	0.10	0.15	0.09	0.14	0.10	0.18	0.03	0.59
F_{2003}/F_{MSY}	1.67	0.14	1.65	0.10	1.64	0.18	6.78	0.49
C_{2003}/R_y	0.91	0.13	0.90	0.09	0.89	0.16	3.23	0.44
Diagnostics								
%max weight	0.25%		0.13%		0.11%		0.22%	
CV (wt) / CV (L*priors)	0.80		0.77		0.77		0.77	

Projections		**Removing LPL series**				**Commercial series only**			
Horizon	**TAC**[1]	B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$	B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$
10-year	0	0.10	1.00	0.00	1.00	0.09	1.00	0.00	1.00
(2013)	1.0	0.08	1.00	0.00	0.80	0.08	1.00	0.00	0.88
20-year	0	0.12	1.00	0.00	1.00	0.12	1.00	0.00	1.00
(2023)	1.0	0.09	1.00	0.00	0.80	0.08	1.00	0.00	0.88
30-year	0	0.15	0.94	0.00	1.00	0.14	0.99	0.00	1.00
(2033)	1.0	0.09	1.00	0.00	0.80	0.08	1.00	0.00	0.88

		Recreational series only				**F-I series only**			
Horizon	**TAC**[1]	B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$	B_{fin}/K[2]	$P(B_{fin}<0.2K)$	$P(B_{fin}>B_{msy})$	$P(B_{fin}>B_{2003})$
10-year	0	0.10	1.00	0.00	1.00	0.03	1.00	0.00	1.00
(2013)	1.0	0.08	1.00	0.00	0.82	0.02	1.00	0.00	0.02
20-year	0	0.12	1.00	0.00	1.00	0.04	1.00	0.00	1.00
(2023)	1.0	0.09	1.00	0.00	0.82	0.02	1.00	0.00	0.02
30-year	0	0.15	0.93	0.00	1.00	0.05	0.99	0.00	1.00
(2033)	1.0	0.09	1.00	0.00	0.82	0.01	1.00	0.00	0.02

[1] Total Allowable Catch policy option expressed as a proportion of the reported 2003 catch

[2] B_{fin}/K is the stock abundance in the final year of management (2013, 2023, or 2033) as a percentage of K

Table 4.8. Results from Age-Structured Catch-free Model (ASCFM) runs for the Base case (BASE) and all sensitivity cases (S1-S7). Estimates are reported for total relative biomass (B) and spawning stock biomass (SSB). F is the total fishing mortality rate that would be experienced by a fully selected fish. $*B_{1974}/B_0$ and $*B_{2003}/B_0$ are the predicted values for the relative biomass index, and were calculated with virgin population weight at age; all other biomass calculations are based on annual weight at age, which reflects the updated average age of the plus group. Reported values are the modes, with CVs in parentheses. Model specifications that differ from the base assumptions are underlined.

Estimates	**BASE**: CV weighting, Effort Series, Relative Biomass Index	**S1**: <u>Equal weighting</u>, Effort Series, Relative Biomass Index	**S2**: CV weighting, Effort Series, <u>No Relative Biomass Index</u>	**S3**: CV weighting, <u>No Effort Series</u>, Relative Biomass Index	**S4**: <u>Equal weighting, No Effort Series</u>, Relative Biomass Index	**S5**: <u>Equal weighting, No Effort Series, No Relative Biomass Index</u>	**S6**: same as BASE, except M=0.03 for ages 1+	**S7**: same as BASE, except M=0.10 for ages 1+
$*B_{2003}/B_0$	0.079 (0.32)	0.132 (0.80)	0.086	0.047 (0.23)	0.083 (0.58)	0.090	0.044 (0.20)	0.074 (0.26)
B_{2003}/B_0	0.080 (0.32)	0.133 (0.80)	0.088 (0.51)	0.048 (0.23)	0.084 (0.57)	0.094 (0.55)	0.044 (0.20)	0.075 (0.26)
SSB_{2003}/SSB_0	0.074 (0.34)	0.142 (0.81)	0.081 (0.50)	0.045 (0.27)	0.086 (0.60)	0.098 (0.61)	0.035 (0.20)	0.065 (0.28)
SSB_{MSY}/SSB_0	0.462 (0.82)	0.461 (0.96)	0.456 (0.87)	0.460 (0.78)	0.478 (1.72)	0.477 (1.64)	0.239 (0.07)	0.419 (0.37)
SSB_{2003}/SSB_{MSY}	0.161 (1.04)	0.308 (1.27)	0.177 (1.11)	0.097 (0.98)	0.180 (2.04)	0.205 (1.93)	0.148 (0.22)	0.156 (0.57)
$*B_{1974}/B_0$	0.83 (1.5E-4)	0.947 (0.78)	0.929	0.83 (3.6E-4)	0.980 (0.01)	1.000	0.83 (1.2E-4)	0.83 (1.4E-4)
SPR_{MSY}	0.861 (0.01)	0.860 (0.01)	0.843 (0.01)	0.854 (0.01)	0.920 (0.01)	0.916 (0.01)	0.273 (0.05)	0.714 (0.02)
F_{2003}	0.433 (0.35)	0.710 (0.48)	0.423 (0.39)	0.452 (0.30)	0.512 (0.34)	0.572 (0.38)	1.059 (0.22)	0.209 (0.32)
F_{MSY}	0.006 (0.06)	0.007 (0.06)	0.007 (0.06)	0.006 (0.06)	0.004 (0.07)	0.004 (0.12)	0.052 (0.04)	0.017 (0.06)
F_{2003}/F_{MSY}	75.02 (0.36)	102.02 (0.48)	64.345 (0.39)	74.136 (0.31)	143.76 (0.37)	146.39 (0.35)	20.413 (0.22)	12.508 (0.32)
pup-survival	0.804 (0.25)	0.804 (0.29)	0.839 (0.30)	0.817 (0.25)	0.705 (0.29)	0.710 (0.29)	0.692 (0.24)	0.803 (0.25)
α	1.350 (0.25)	1.350 (0.29)	1.408 (0.3)	1.371 (0.25)	1.182 (0.29)	1.192 (0.29)	22.370 (0.24)	1.972 (0.25)
steepness	0.252 (0.18)	0.252 (0.21)	0.260 (0.22)	0.255 (0.18)	0.228 (0.22)	0.230 (0.22)	0.848 (0.04)	0.330 (0.17)

B is total biomass
SSB is spawning stock biomass
α is maximum reproductive rate
Values boxed in yellow: sensitivities S2 and S5 did not use the relative biomass index; therefore these values were calculated from model estimates of the number at age in year (1974 or 2003) multiplied by the weight at age vector for 1960 to be comparable to the model-estimated values for the other runs. As these values were calculated from model output, no CV is given.

Table 4.9. Projections from Age-Structured Catch-free Model (ASCFM) runs with F=0 for the Base case (BASE) and all sensitivity cases (S1-S7). For each sensitivity case, input treatments different from base case assumptions are underlined. Estimates are reported for total relative biomass (B) and spawning stock biomass (SSB).

Estimates	**BASE:** CV weighting, Effort Series, Relative Biomass Index	**S1:** Equal weighting, Effort Series, Relative Biomass Index	**S2:** CV weighting, Effort Series, No Relative Biomass Index	**S3:** CV weighting, No Effort Series, Relative Biomass Index	**S4:** Equal weighting, No Effort Series, Relative Biomass Index	**S5:** Equal weighting, No Effort Series, No Relative Biomass Index	**S6:** same as BASE, except M=0.03 for ages 1+	**S7:** same as BASE, except M=0.10 for ages 1+
B/B_0 (2003)	0.082	0.136	0.091	0.046	0.084	0.068	0.046	0.075
B/B_0 (2033)	0.072	0.123	0.082	0.041	0.071	0.057	0.148	0.108
SSB/SSB_0 (2003)	0.074	0.142	0.081	0.042	0.087	0.061	0.035	0.065
SSB/SSB_0 (2033)	0.066	0.113	0.075	0.037	0.066	0.053	0.138	0.087
N/N_0 (2003)	0.075	0.098	0.086	0.042	0.057	0.061	0.061	0.086
N/N_0 (2033)	0.081	0.133	0.093	0.046	0.073	0.060	0.333	0.133

Table 4.10. Values of the two estimated input parameters at the mode of the joint posterior pdf for different combinations of CPUE series when historical catches are treated as fixed input values and the starting year of the calculations is 1974. Inverse CV weighting was used for the calculations.

Parameter	CPUE 1	CPUE 1+2	CPUE 1-3	CPUE 1-4	CPUE 1-5	CPUE 5
Virgin biomass (kg)	5,316,063	5,588,206	5,653,892	5,668,722	5,247,254	5,128,219
Pup survival at low population density	0.75	0.68	0.64	0.63	0.98	0.98

Table 4.11. Results of the baseline run (modal values) with equal CV weighting for four different combinations of the starting year of calculations and the way that historical catches are treated. Fixed catches: the historical catches are treated as fixed input parameters; estimated catches: the historical catches are treated as estimated parameters and prior distributions are used to describe their values (see text for more details); historical catch 1: catches attributed to the recreational fishery; historical catch 2: catches attributed to the pelagic longline fishery (discards).

	Starting year: 1974, fixed catches	Starting year: 1960, fixed catches*	Starting year: 1974, estimated catches	Starting year: 1960, estimated catches
Virgin Biomass (kg)	6,166,336	11,603,041	7,565,651	10,102,992
Pup survival at low population densities	0.74	0.58	0.74	0.71
N_{2003}/N_{virgin}	0.30	0.53	0.25	0.19
Historical catch 1	N/A	N/A	245,708	233,019
Historical catch 2	N/A	N/A	139,394	155,477

* This run converged to the minimum plausible value of the pup survival at low population density. This value is greater than the minimum limit for that parameter (0.25) but is equal to the minimum value that will not make the steepness for Beverton-Holt stock recruitment function fall bellow its minimum value (0.20; see text for further discussion).

Table 4.12. Mean value and CV of the estimated parameters based on the corresponding marginal posterior pdfs for the baseline model with inverse and equal CV weighting, and sensitivity runs with alternative catch scenarios and equal CV weighting, and low natural mortality with inverse CV weighting. Biomass values are in kg, numbers are individuals.

	Baseline Model		Baseline Model with equal CV weighting		Alternative catch 1 (equal weighting)		Alternative catch 2 (equal weighting)		Baseline with low mortality (inverse CV weighting)	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Virgin biomass	5,543,167	0.02	7,303,693	1.35	9,552,538	3.12	17,462,673	1.77	8236278	0.02
Pups survival	0.75	0.14	0.76	0.14	0.77	0.14	0.77	0.14	0.71	0.22
Virgin number of fish	116,123	0.02	148,547	1.35	194,286	3.12	355,167	1.77	105338	0.02
B_{2003}/B_{virgin}	0.21	0.05	0.36	0.21	0.37	0.30	0.37	0.29	0.25	0.05
N_{2003}/N_{virgin}	0.20	0.06	0.37	0.22	0.38	0.31	0.38	0.30	0.25	0.05
$Nmat_{2003}/Nmat_{vir}$	0.24	0.05	0.37	0.18	0.39	0.26	0.39	0.29	0.25	0.05

Table 4.13. Prediction of the model about the level of exploitation that the population can sustain for each of the scenarios considered. The results are given for the values of the input parameters at the mode of the joint posterior pdf. MSY values are in kg.

	MSY	B_{msy}/B_{vir}	$Expl_{2002}/Expl_{msy}$	$Expl_{msy}$
Baseline Model	152	0.96	1730	5.23E-5
Baseline Model with equal CV weighting	5,255	0.77	20.4	2.07E-3
Alternative catch 1 (equal weighting)	4,020	0.82	29.8	1.38E-3
Alternative catch 2 (equal weighting)	6,367	0.86	42.6	1.04E-3
Baseline with low mortality (inverse CV weighting)	55,519	0.28	1.92	5.12E-2

Table 4.14. Results of the projections for the baseline and sensitivity runs presented in Table 4.12. For comparison, the relative value of B_{MSY} (B_{MSY}/B_{virgin}) is shown in parentheses under the relative value of stock biomass in 2033.

	Baseline Model		Baseline Model with equal CV weighting		Alternative catch 1 (equal weighting)		Alternative catch 2 (equal weighting)		Baseline with low mortality (inverse CV weighting)	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
N_{2033}/N_{virgin}	0.24	0.10	0.40	0.21	0.42	0.27	0.42	0.27	0.53	0.03
B_{2033}/B_{virgin}	0.22 (0.96)	0.07	0.38 (0.77)	0.21	0.39 (0.82)	0.28	0.40 (0.86)	0.28	0.44 (0.28)	0.04
N_{2033}/N_{2003}	1.17	0.08	1.09	0.06	1.11	0.07	1.11	0.07	2.12	0.05
B_{2033}/B_{2003}	1.06	0.07	1.05	0.06	1.06	0.06	1.06	0.06	1.76	0.04

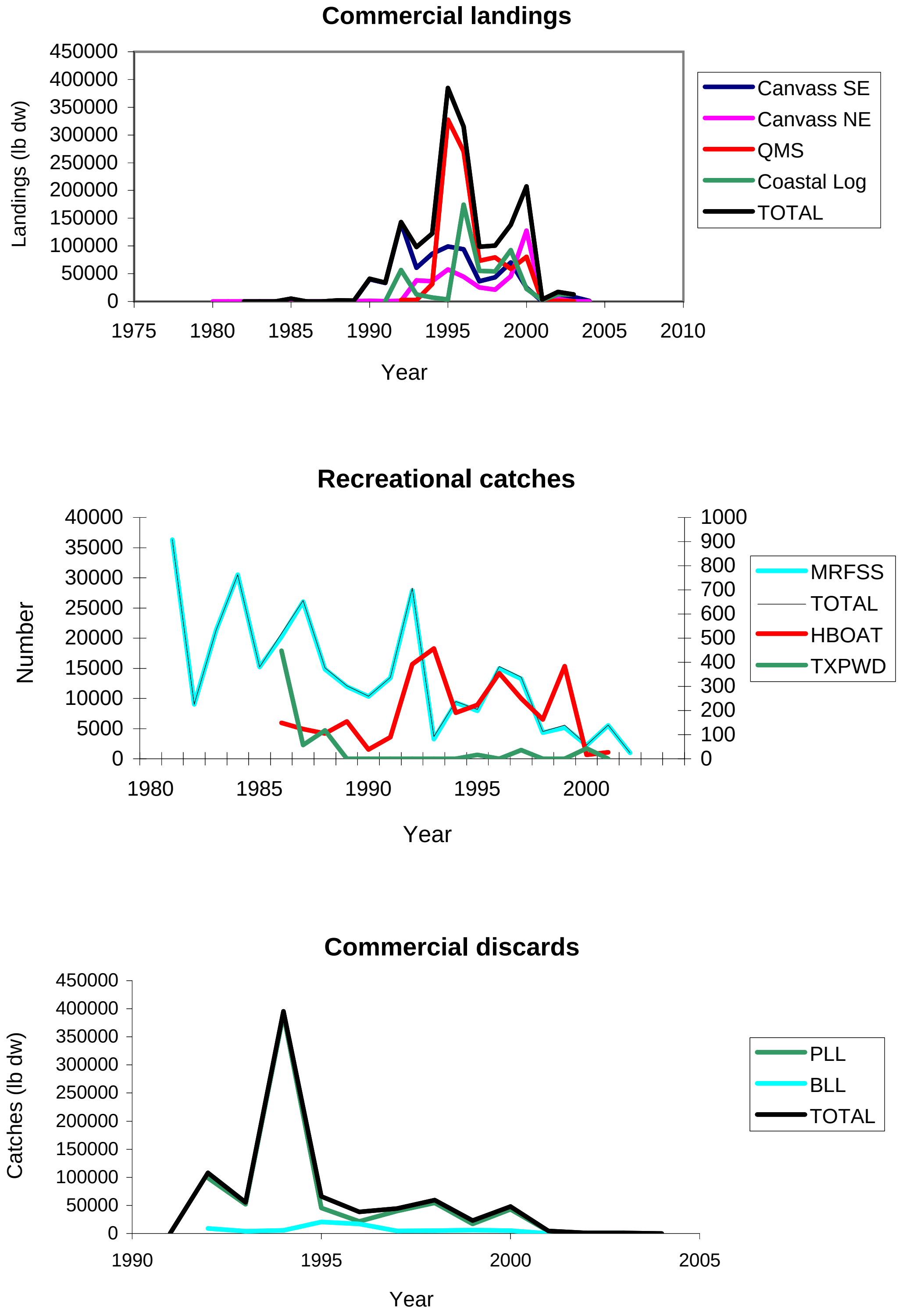


Figure 2.1. Commercial landings, recreational catches, and commercial discards of dusky sharks as reported in sources available. In the middle panel, the HBOAT and TXPWD series use the y-axis on the right of the plot.

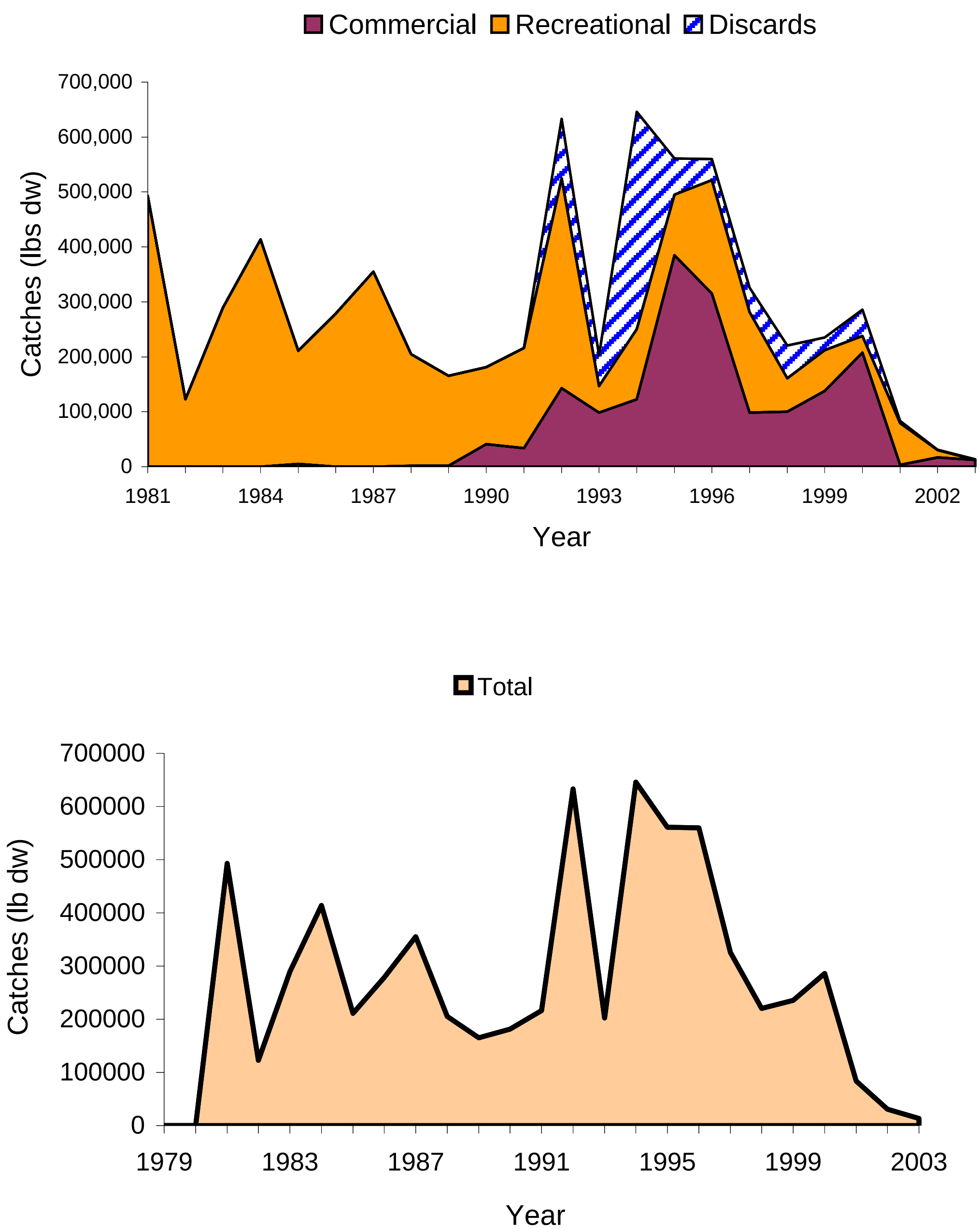


Figure 2.2. Total catches of dusky sharks. Top panel shows cumulative catches by sector.

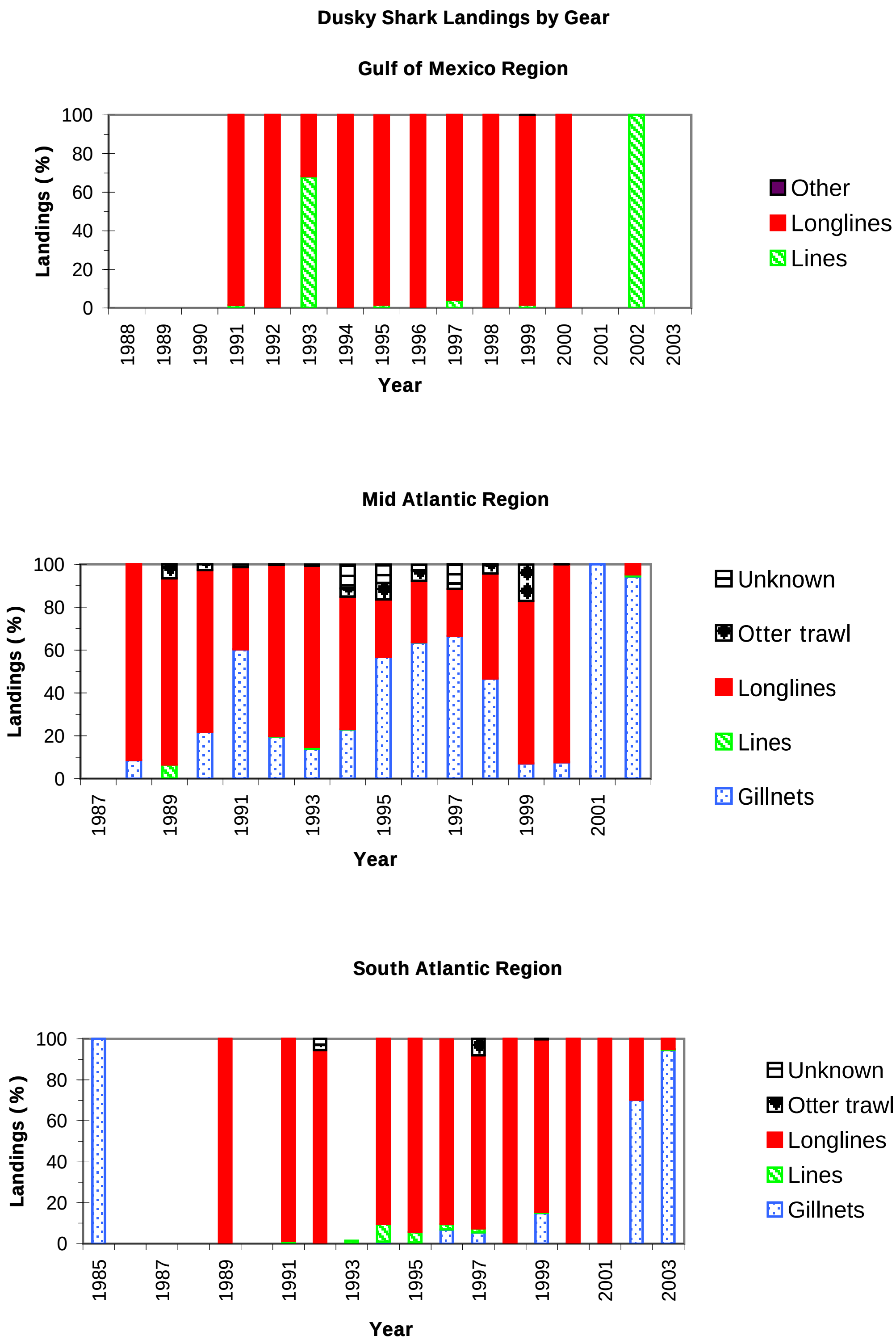


Figure 2.3. Commecial landings of dusky sharks by region and gear type obtained from the general canvass database.

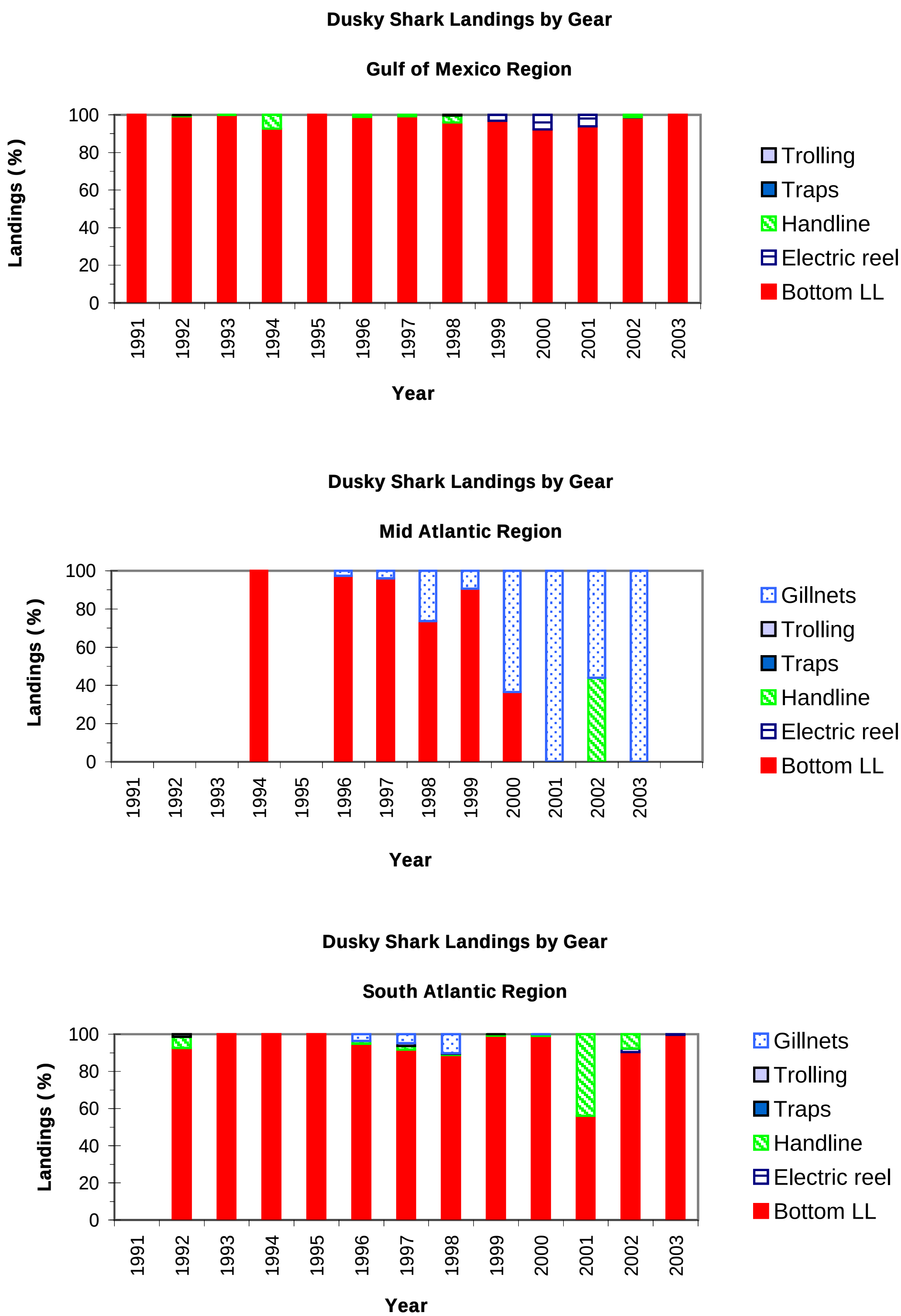


Figure 2.4. Commecial landings of dusky sharks by region and gear type obtained from the coastal fisheries logbook database.

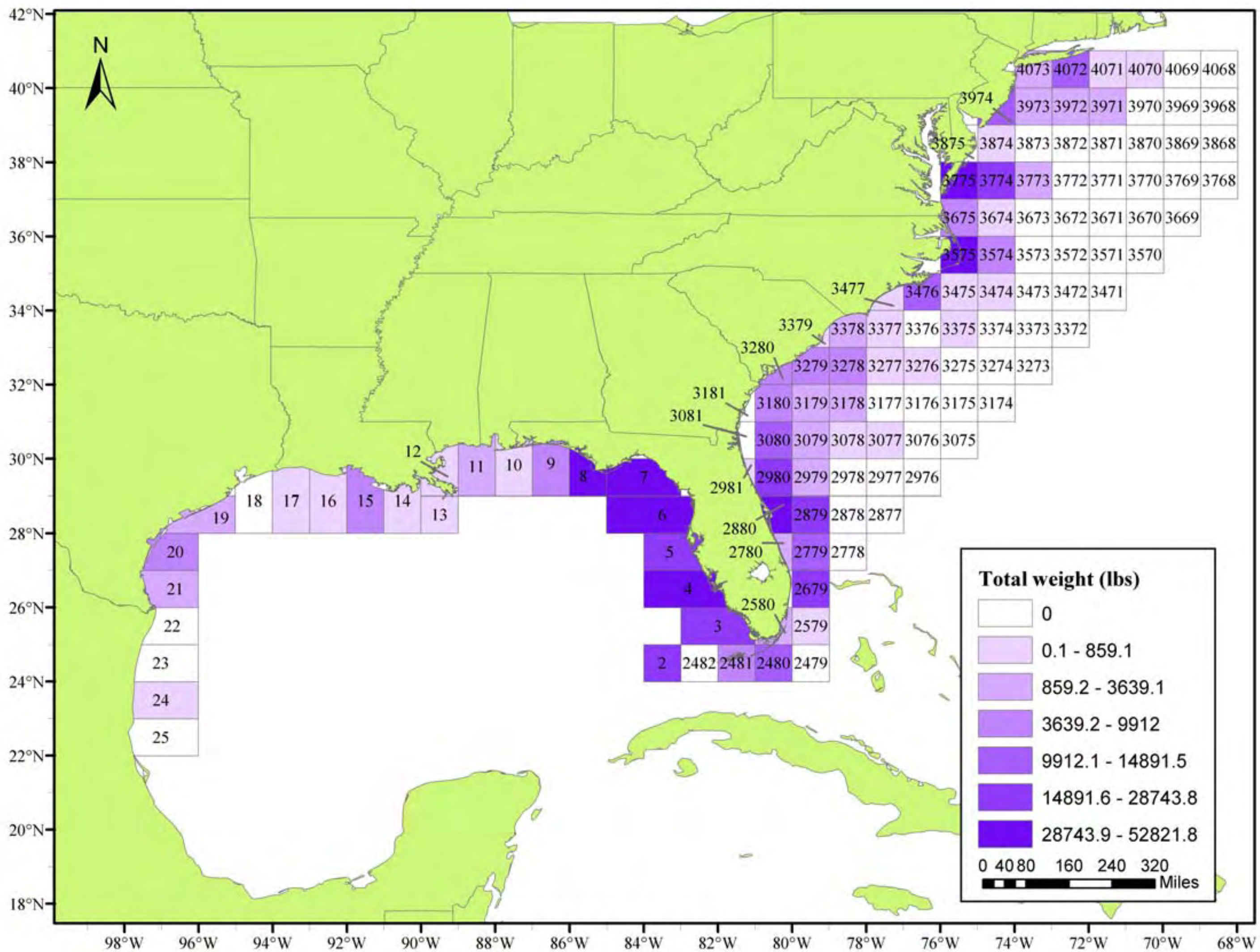


Figure 2.5. Statistical grid map of catches of dusky sharks off the U.S. east coast from the coastal fisheries logbook program, 1991-2003.

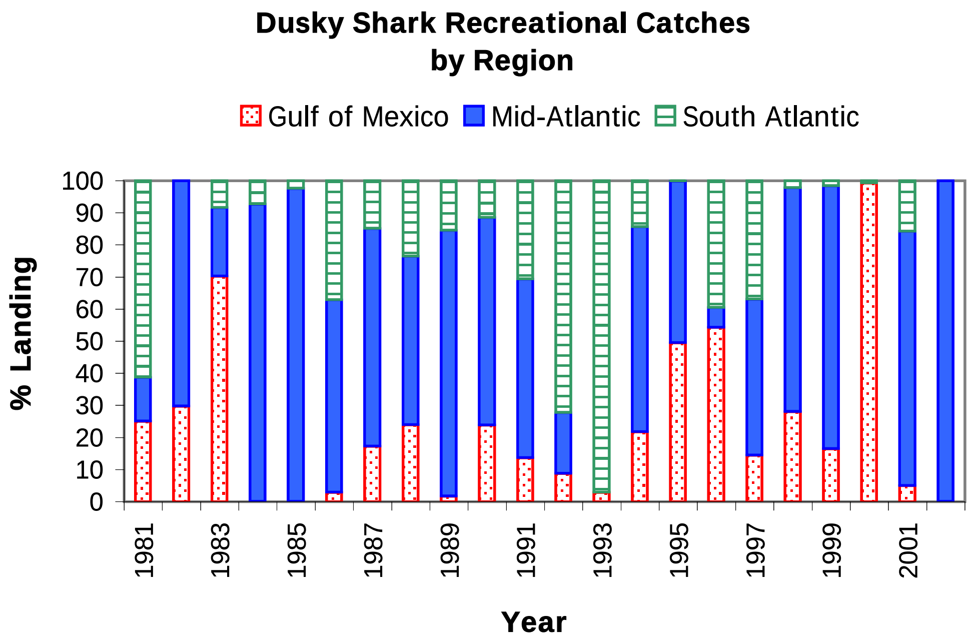
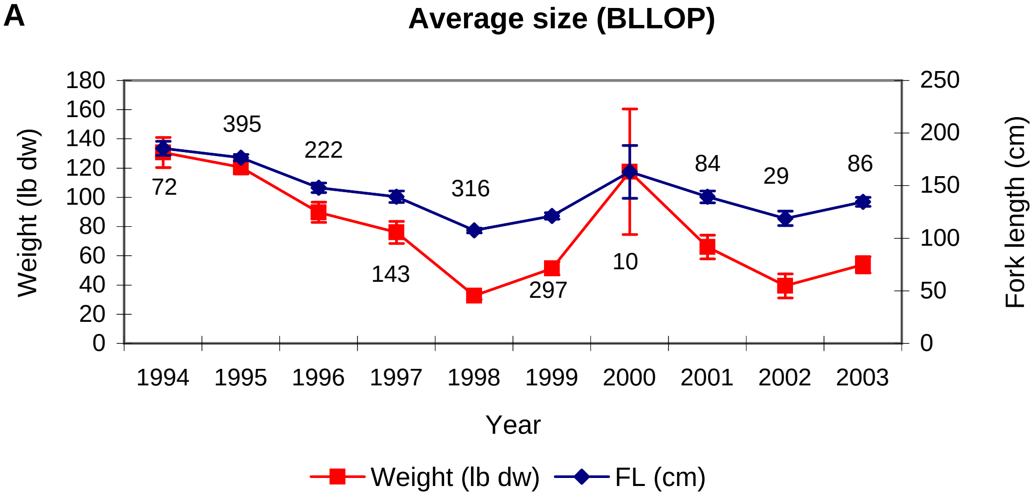


Figure 2.6. Recreational catches of dusky sharks by region obtained from the MRFSS, Headboat, and TXPWD surveys.

A



B

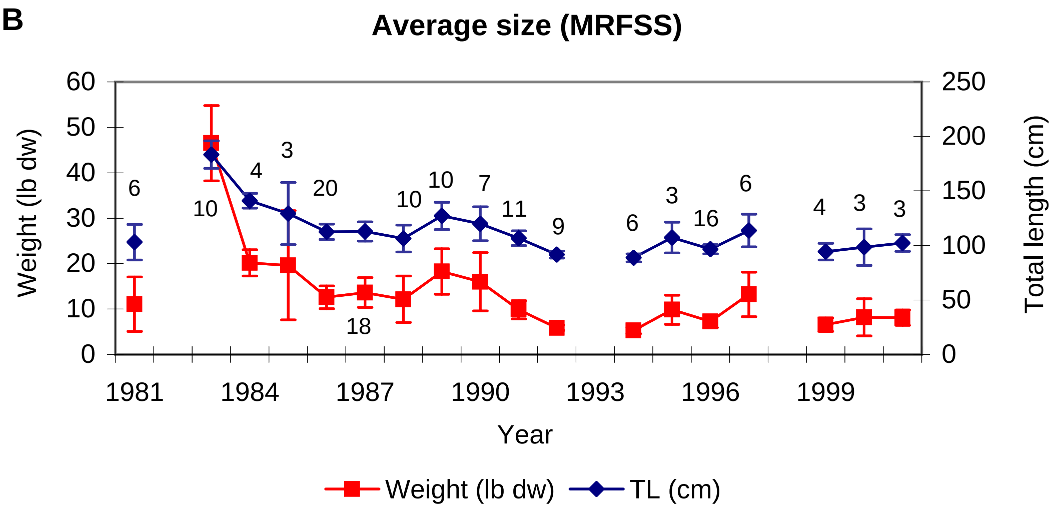
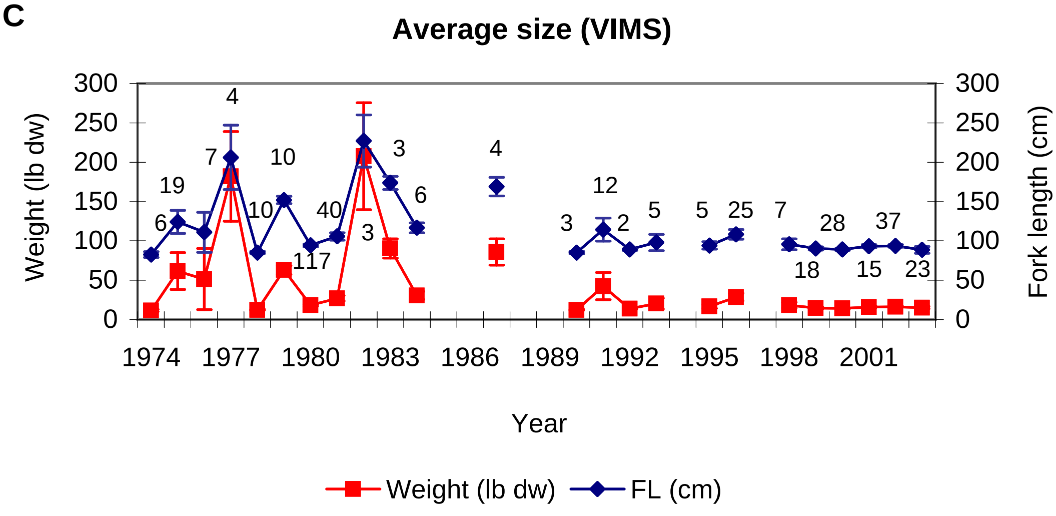


Figure 2.7. Average size (length and dressed weight) of dusky shark from the directed shark fishery bottom longline observer program (BLLOP; A) and MRFSS (B). Vertical bars are +/- 1 SE. Sample sizes for each year are indicated.

C



D

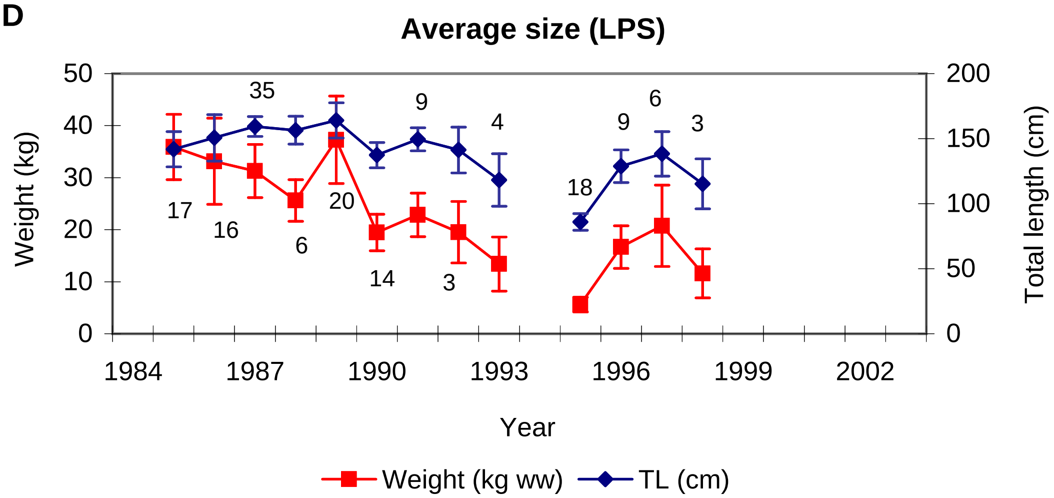


Figure 2.7 (continued). Average size (length and weight) of dusky shark from the Virginia Institute of Marine Science longline survey (VIMS; C) and the LPS recreational survey (D). Vertical bars are +/- 1 SE. Sample sizes for each year are indicated.

E

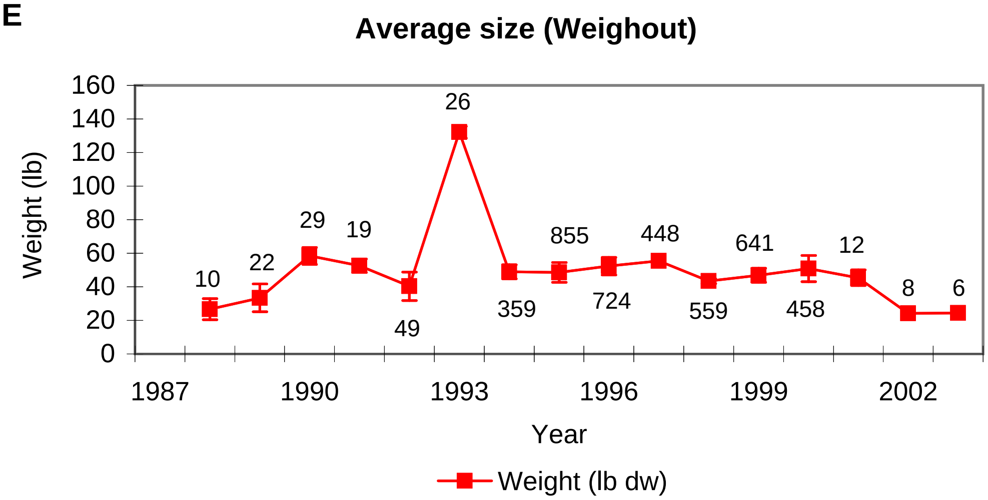


Figure 2.7 (continued). Average size (dressed weight) of dusky shark from dealer weighout data sheets (E) of U.S. pelagic longline fishermen targeting swordfish. Vertical bars are +/- 1 SE. Sample sizes for each year are indicated.

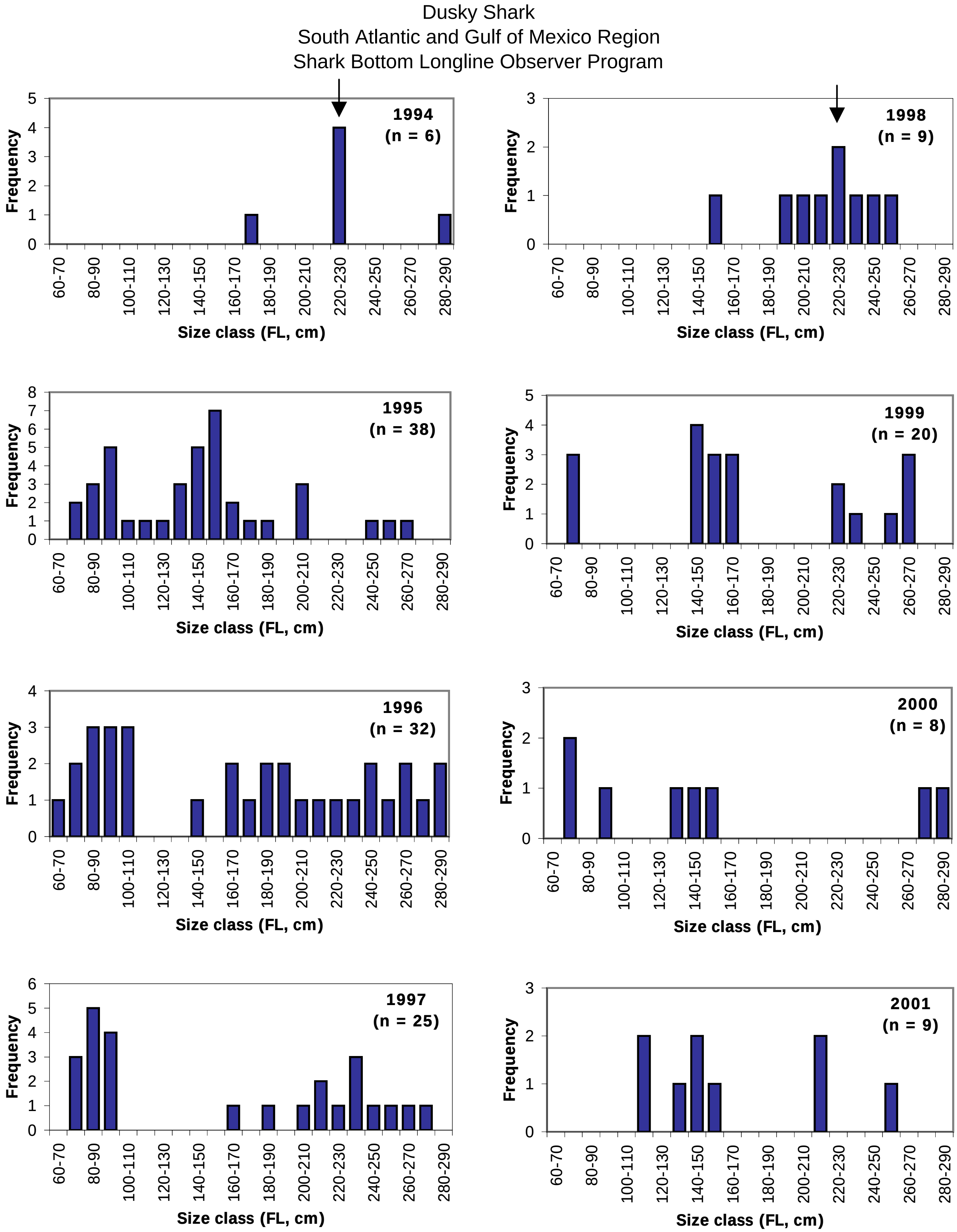
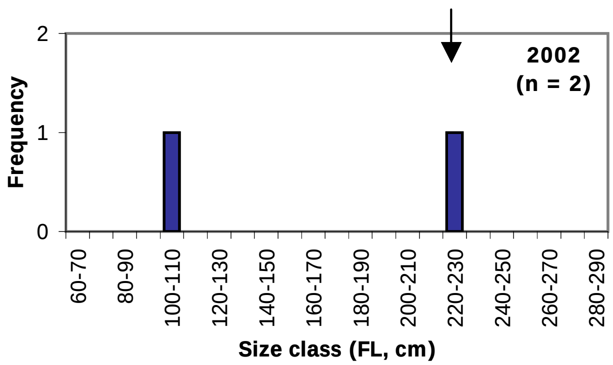


Figure 2.8. Length-frequency distributions for dusky sharks observed in the South Atlantic and Gulf of Mexico regions in the Shark Bottom Longline Observer Program. Note the different scales along the y-axis. Vertical arrows on the top panels indicate median size at maturity.

Dusky Shark
South Atlantic and Gulf of Mexico Region
Shark Bottom Longline Observer Program



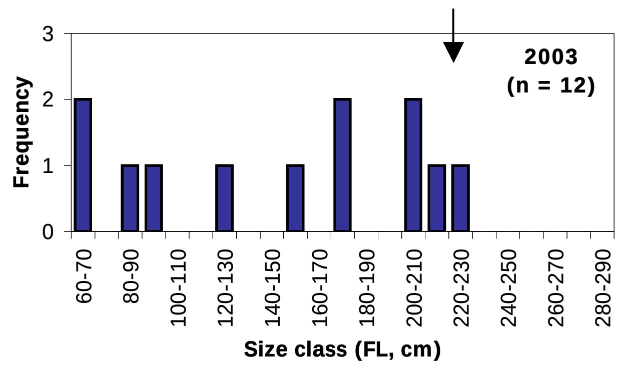


Figure 2.8. (continued)

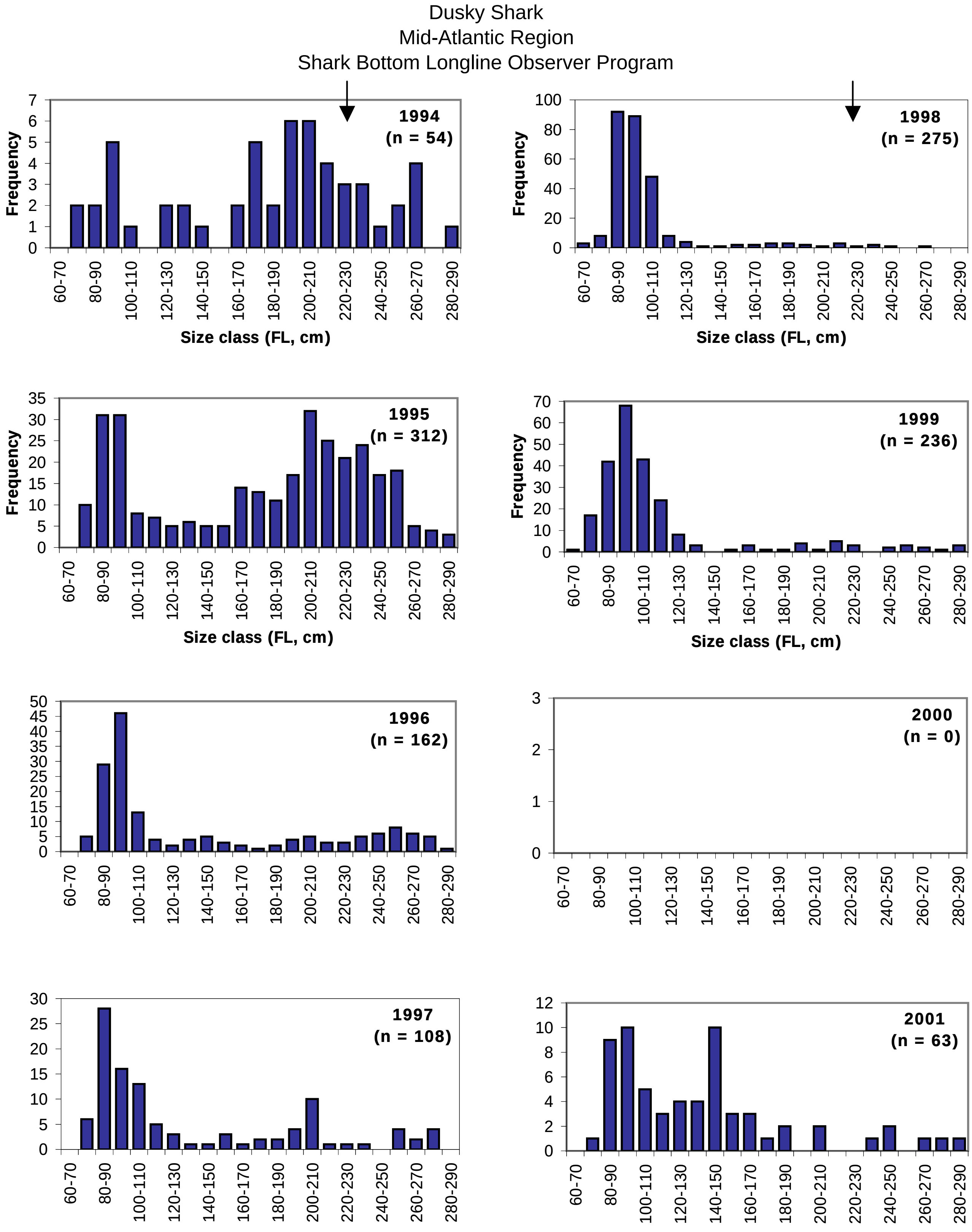


Figure 2.9. Length-frequency distributions for dusky sharks observed in the Mid Atlantic region in the Shark Bottom Longline Observer Program. Note the different scales along the y-axis. Vertical arrows on the top panels indicate median size at maturity.

Dusky Shark
Mid-Atlantic Region
Shark Bottom Longline Observer Program

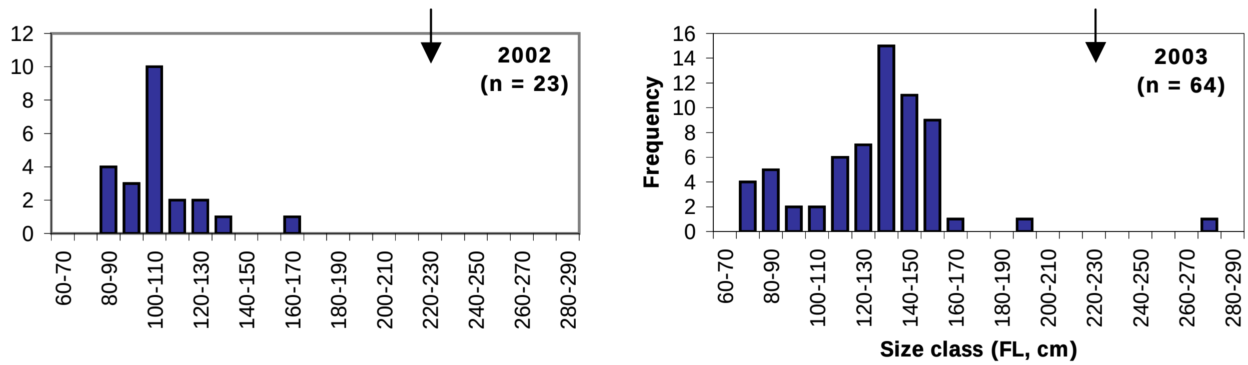


Figure 2.9. (continued)

Dusky Shark
All Areas Combined
Sharks Bottom Longline Observer Program

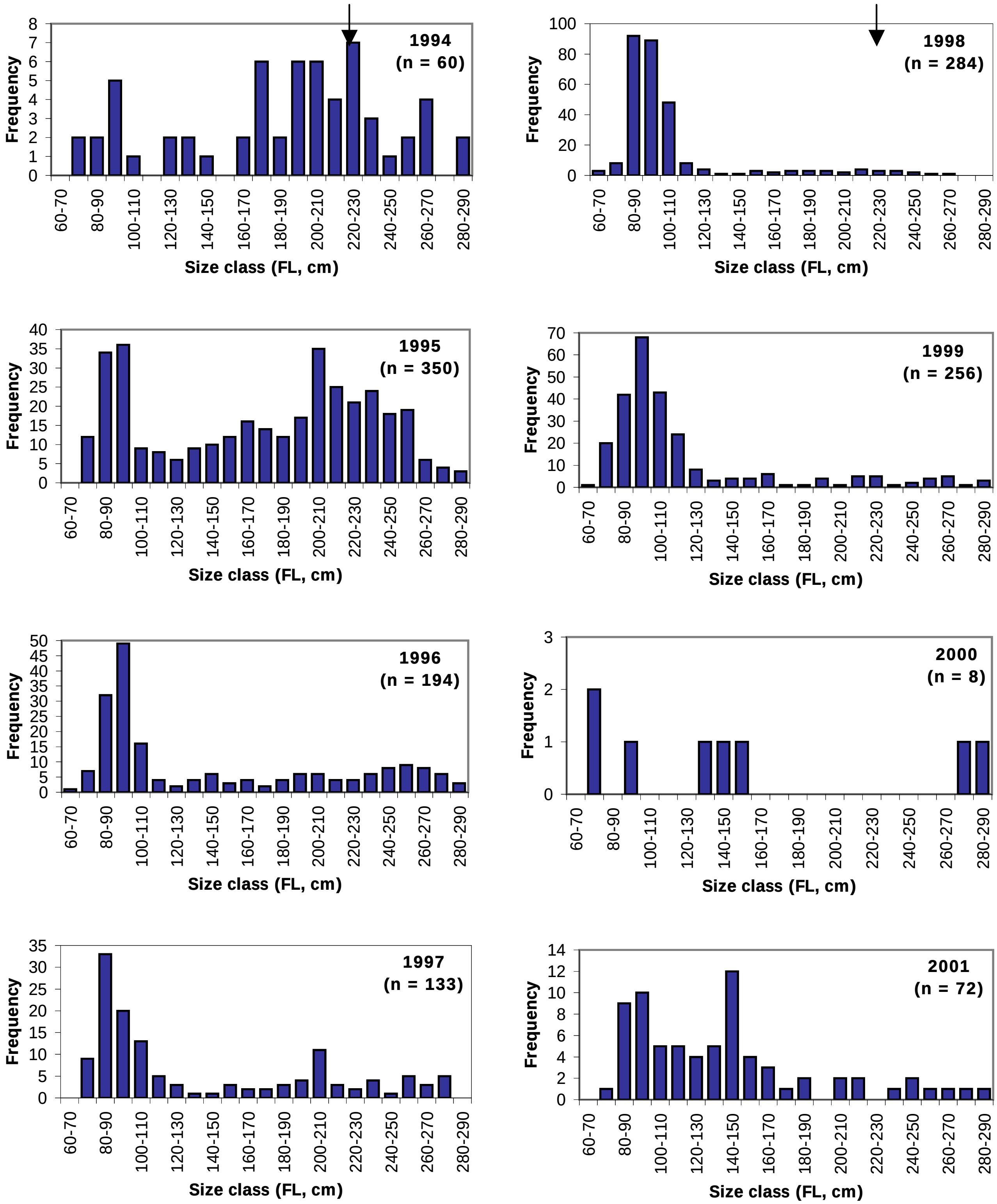


Figure 2.10. Length-frequency distributions for dusky sharks observed in all areas combined in the Shark Bottom Longline Observer Program. Note the different scales along the y-axis. Vertical arrows on the top panels indicate median size at maturity.

Dusky Shark
All Areas Combined
Sharks Bottom Longline Observer Program

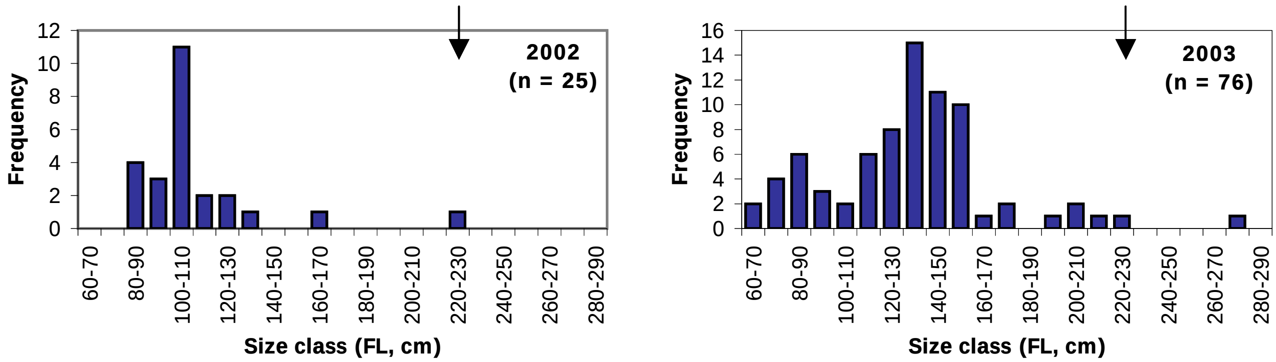


Figure 2.10. (continued)

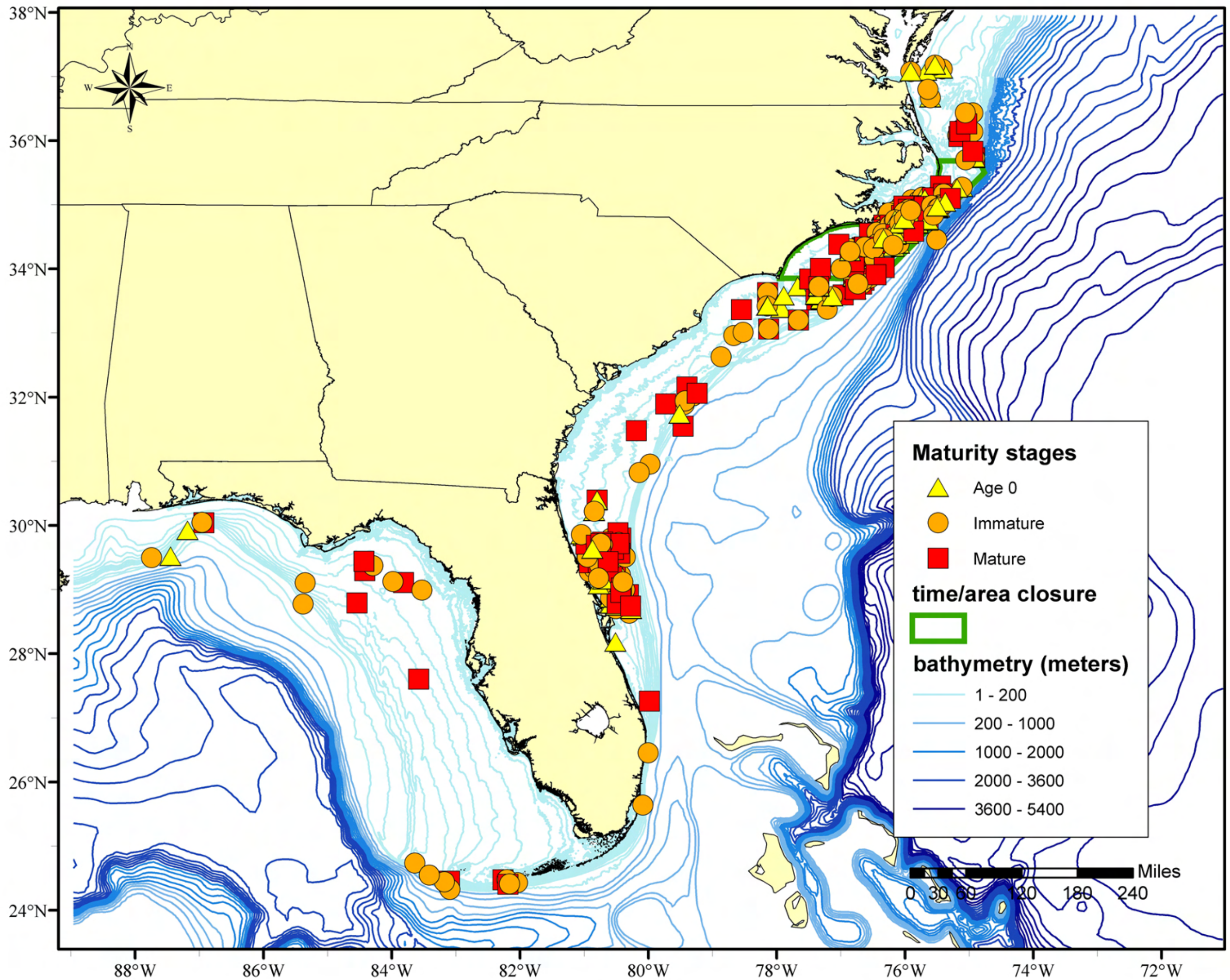


Figure 2.11. Dusky sharks reported off the U.S. east coast in the Bottom Longline Observer Program (BLLOP), 1994-2003. Maturity stage of individual animals and bathymetry associated with catches are indicated.

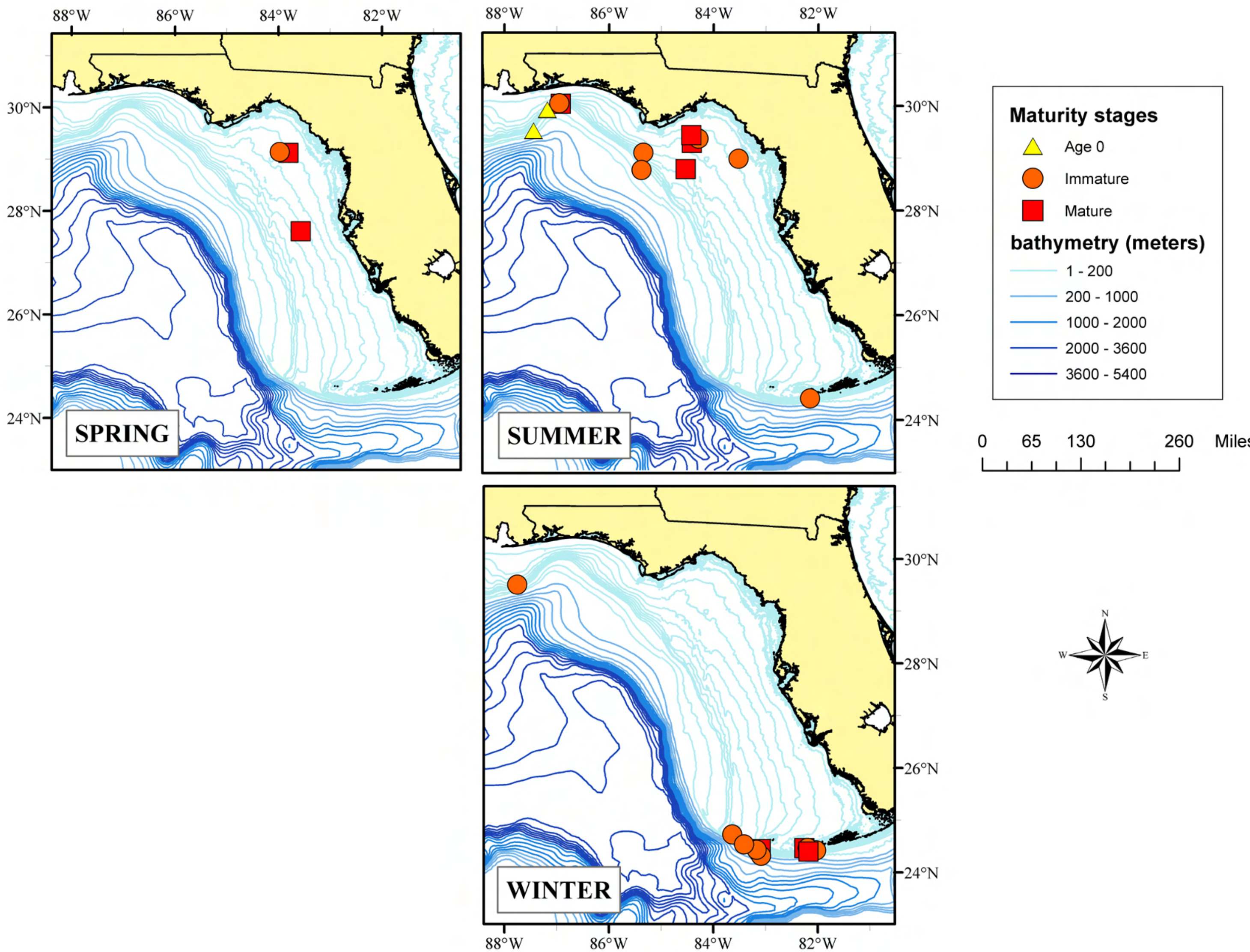


Figure 2.12. Dusky sharks reported off the U.S. Gulf of Mexico region (west coast of Florida) in the Bottom Longline Observer Program (BLLOP), 1994-2003. Maturity stage of individual animals and bathymetry associated with catches are indicated.

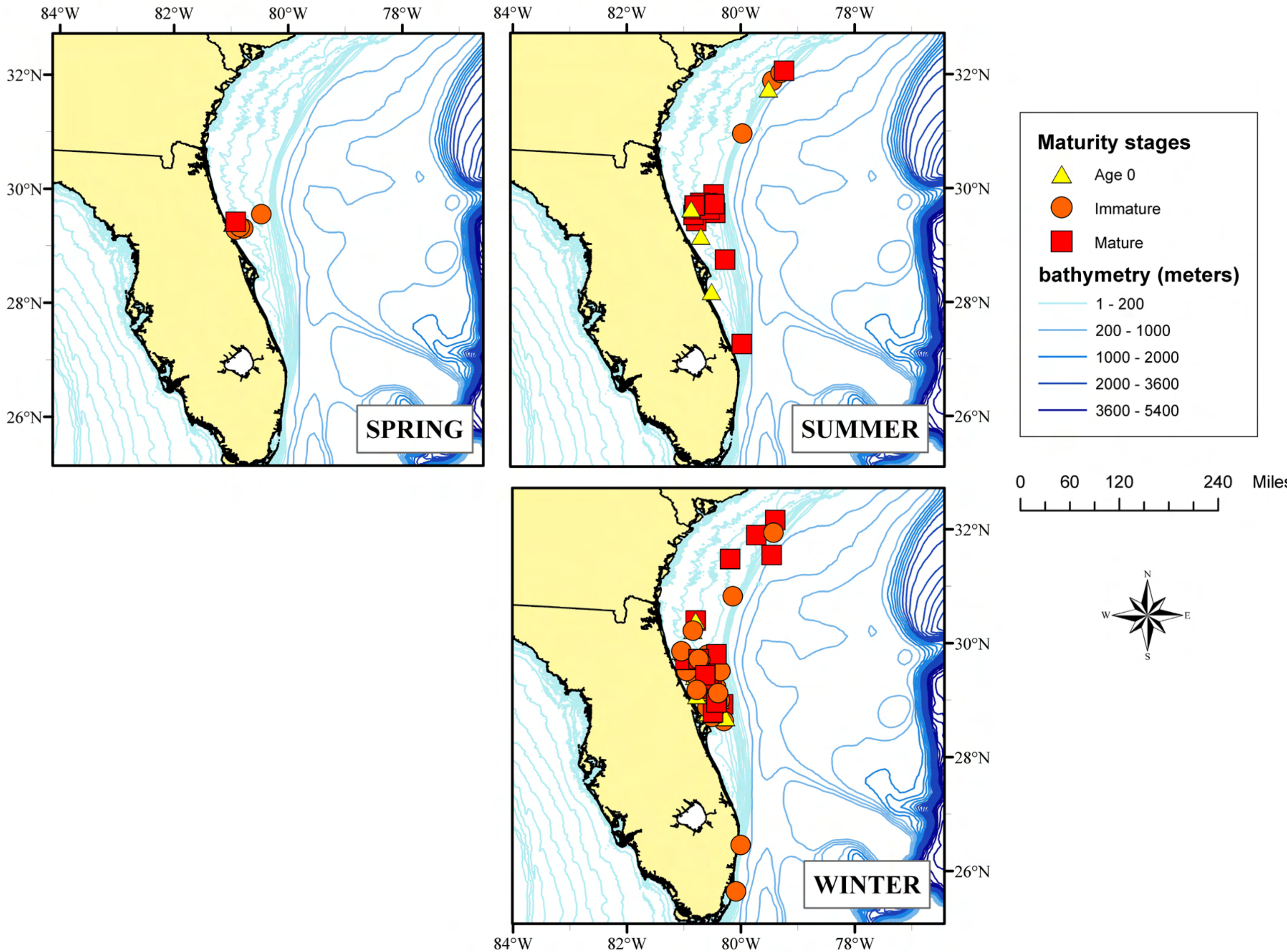


Figure 2.13. Dusky sharks reported off the U.S. South Atlantic region (east coast of Florida, Georgia and South Carolina) in the Bottom Longline Observer Program (BLLOP), 1994-2003. Maturity stage of individual animals and bathymetry associated with catches are indicated.

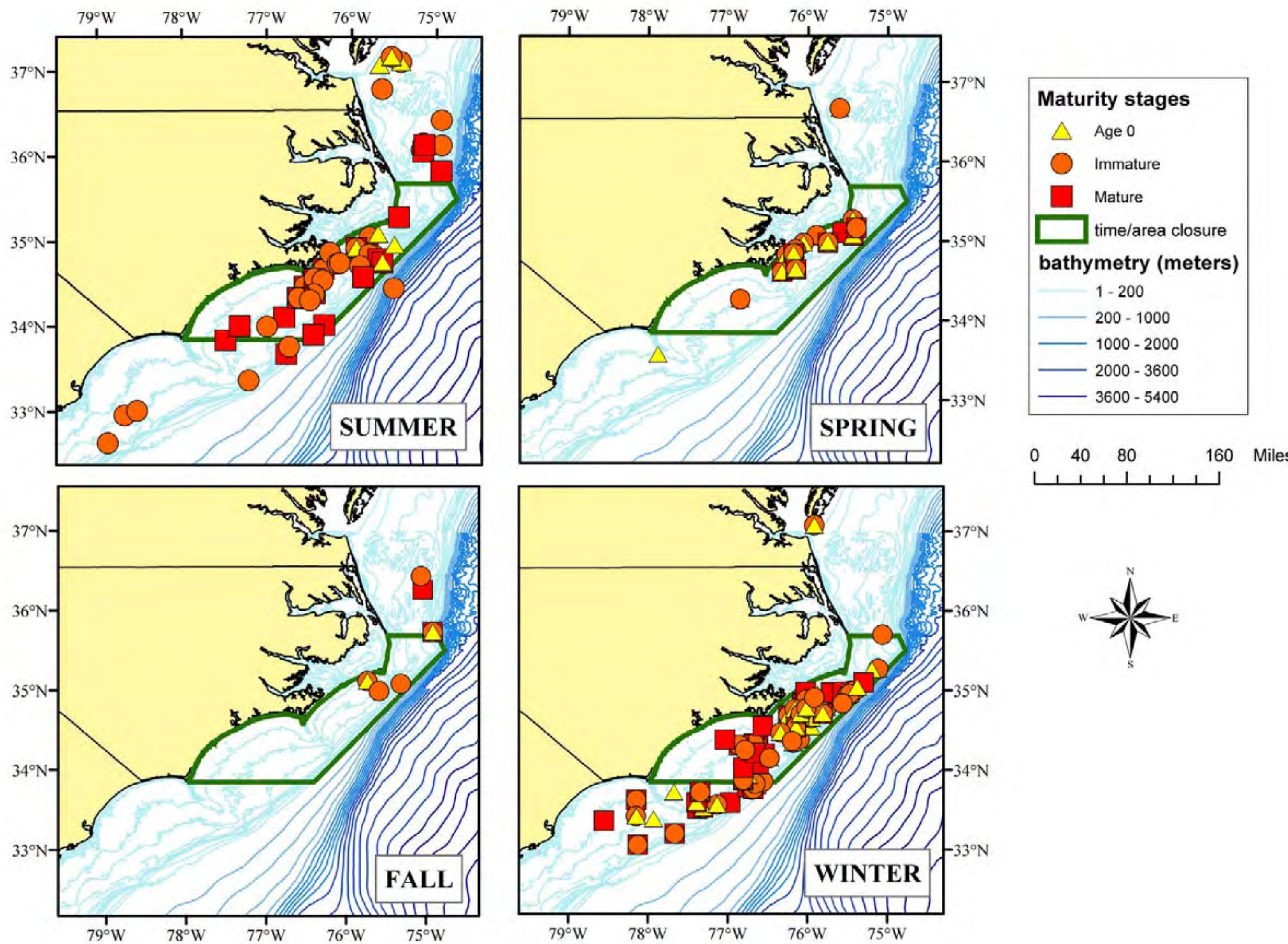


Figure 2.14. Dusky sharks reported off the U.S. mid-Atlantic region (South Carolina, North Carolina and Virginia) in the Bottom Longline Observer Program (BLLOP), 1994-2003. Maturity stage of individual animals, bathymetry associated with catches, and the time-area closure off North Carolina are indicated.

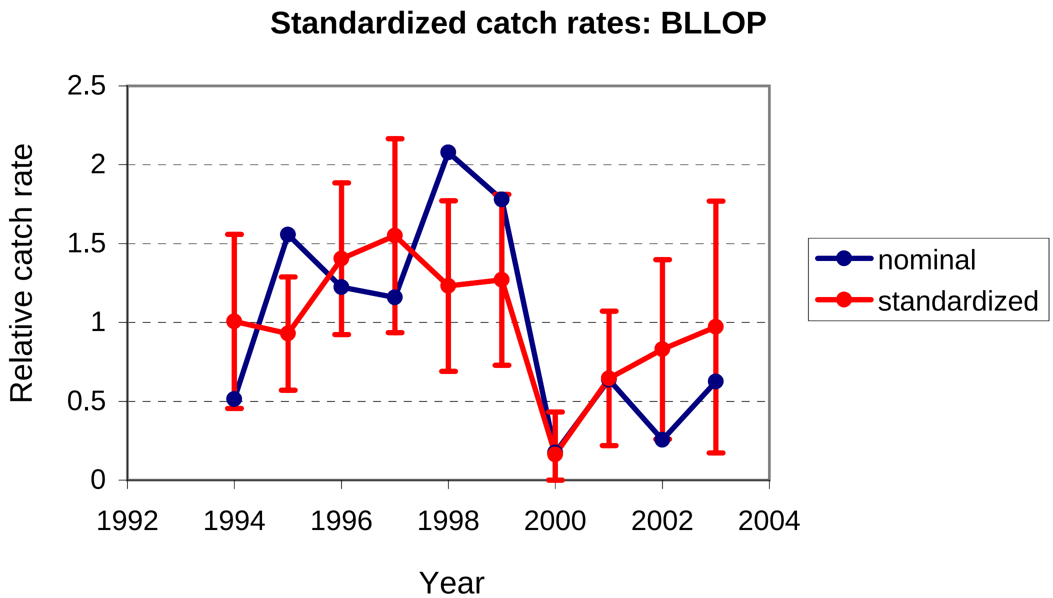
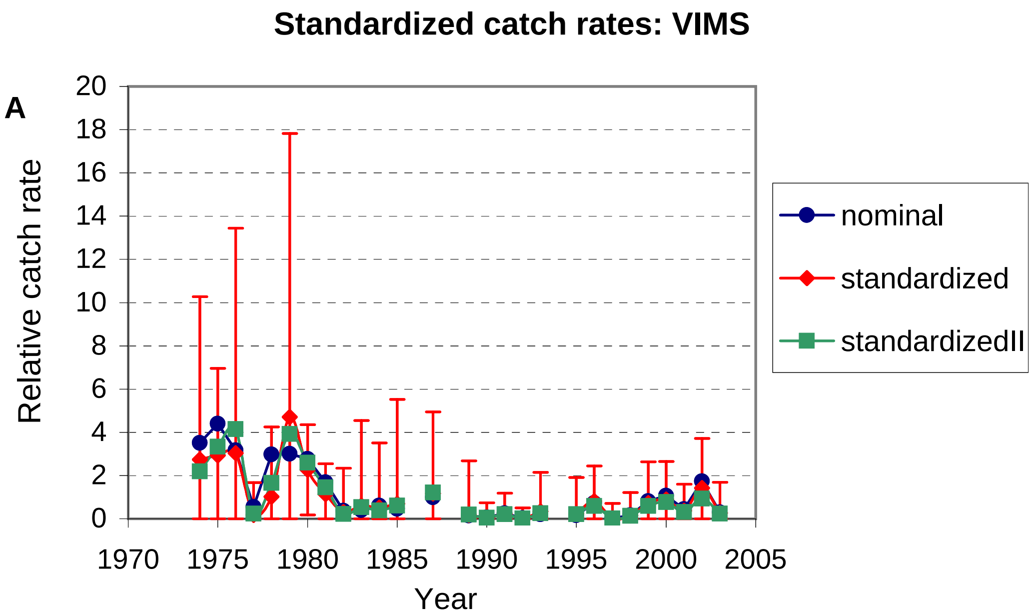


Figure 2.15. Relative abundance indices (nominal and GLM-standardized catch rates) for dusky shark from the **BLLOP**. CPUE is the number of sharks caught divided by the product of the number of hooks per set, soak time of set in hours, and miles of longline per set, multiplied by a factor of 1000. Vertical bars are 95% confidence limits.



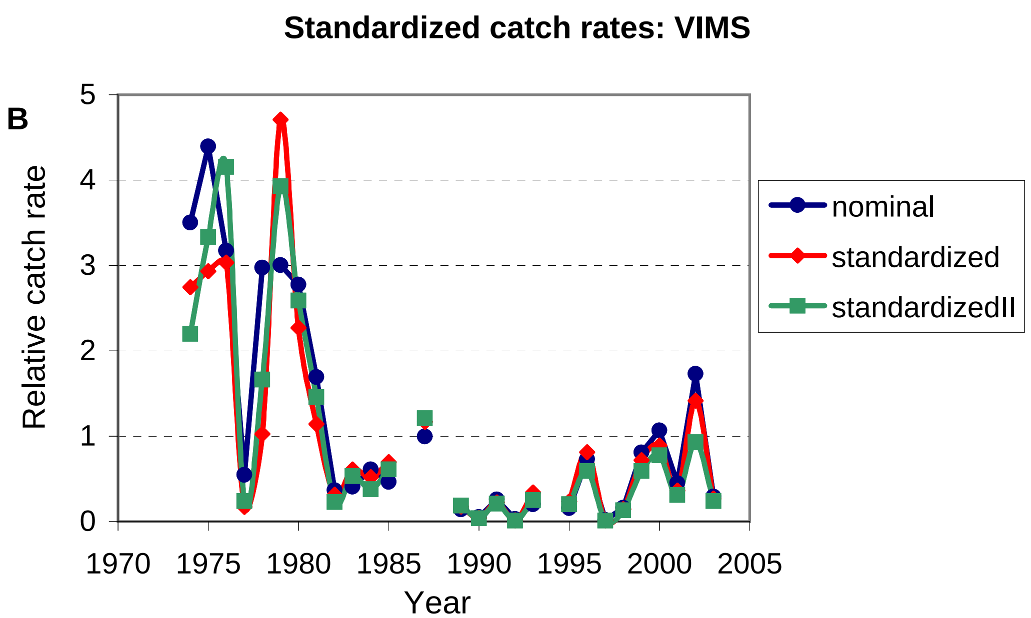


Figure 2.16. Relative abundance indices (nominal and GLM-standardized catch rates) for dusky shark from the **VIMS** survey. CPUE is the number of sharks caught divided by the number of hooks per set times soak time in hours. Vertical bars in (A) are 95% confidence limits for the "standardized" model, which included area+year in the proportion positive and year+season in the positive catches final mixed model; the "standardizedII model" (which included year and year+season in the final mixed models) is shown for comparison. Panel (B) is a detailed view without CLs.

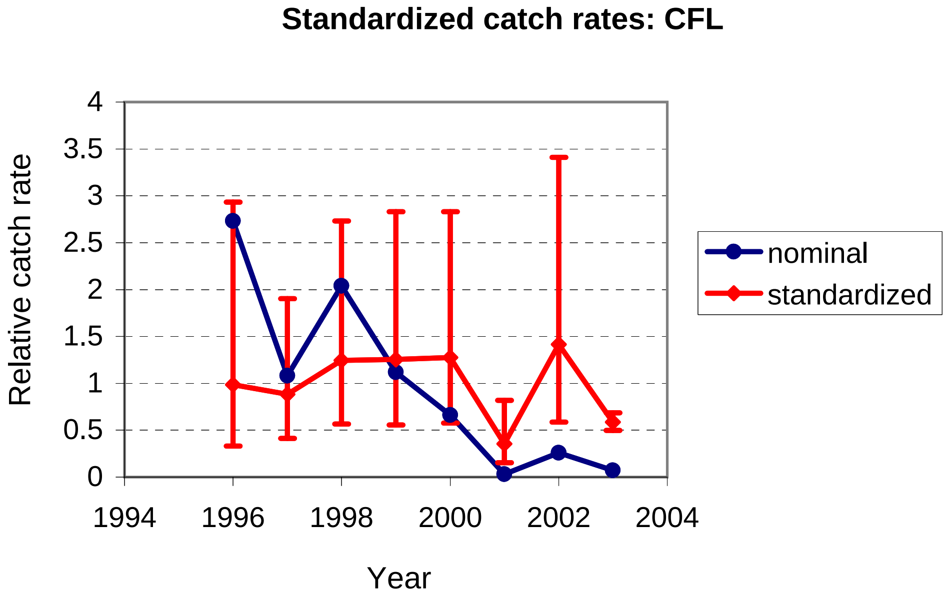


Figure 2.17. Relative abundance indices (nominal and GLM-standardized catch rates) for dusky shark from the **CFL**. CPUE is the weight of dusky sharks caught divided by the product of the number of hooks per set, soak time of set in hours, and miles of longline per set, multiplied by a factor of 1000. Vertical bars are approximate 95% confidence limits.

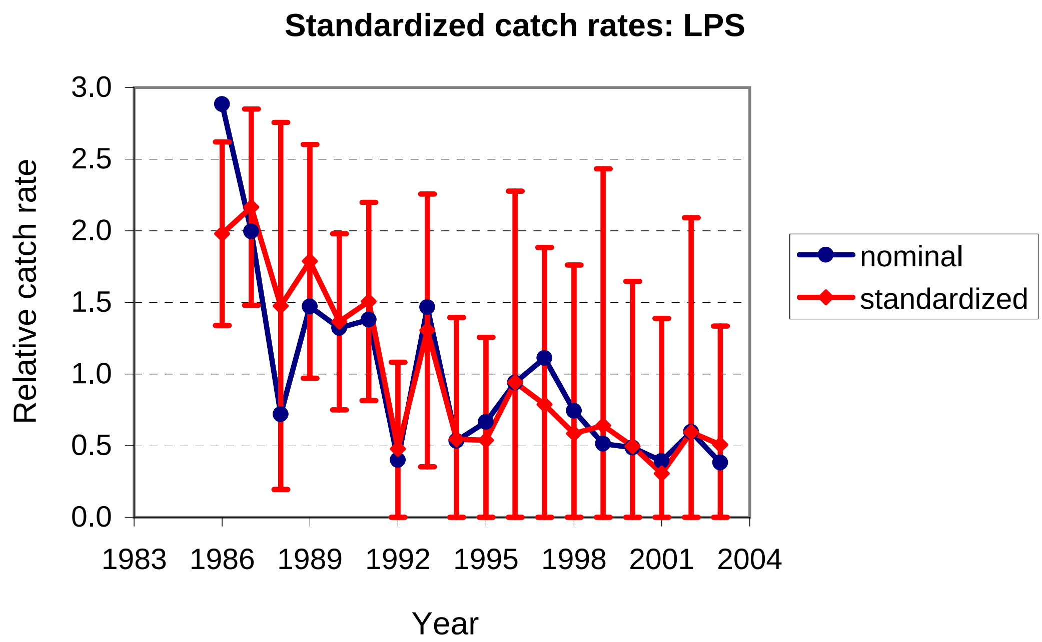


Figure 2.18. Relative abundance indices (nominal and GLM-standardized catch rates) for dusky shark from the **LPS**. CPUE is catch of dusky sharks in numbers per 100 trips. Vertical bars are 95% confidence limits.

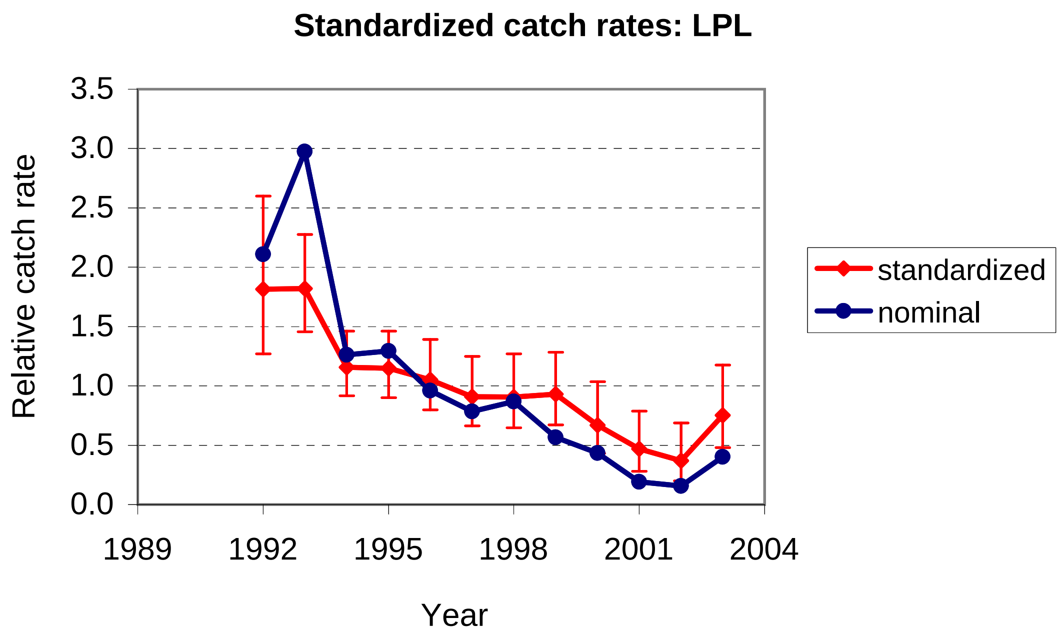


Figure 2.19. Relative abundance indices (nominal and GLM-standardized catch rates) for dusky shark from the **LPL**. CPUE is catch of dusky sharks in numbers per 1000 hooks. Vertical bars are approximate 95% confidence limits.

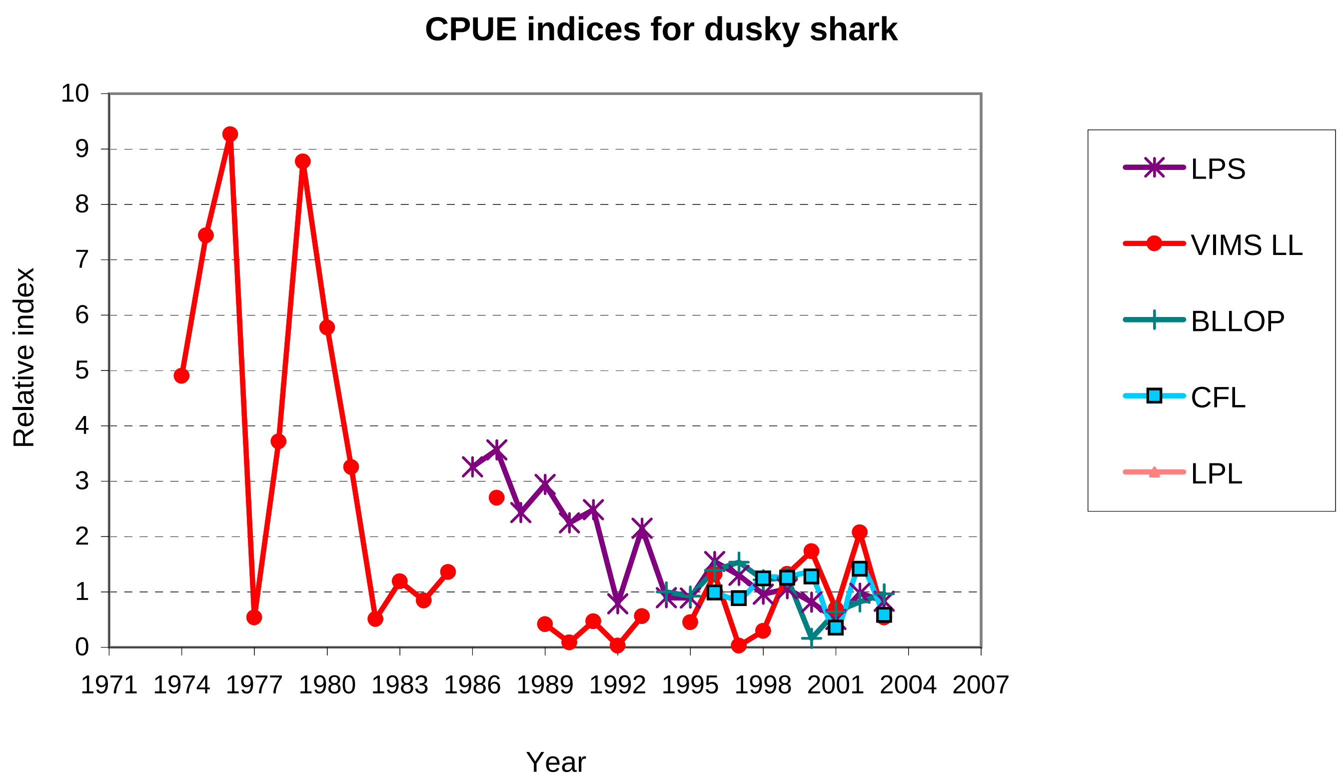


Figure 2.20. A combined view of relative abundance indices (all GLM-standardized) for dusky shark from five data sources. Series are scaled to the mean of their overlapping years (1996-2003).

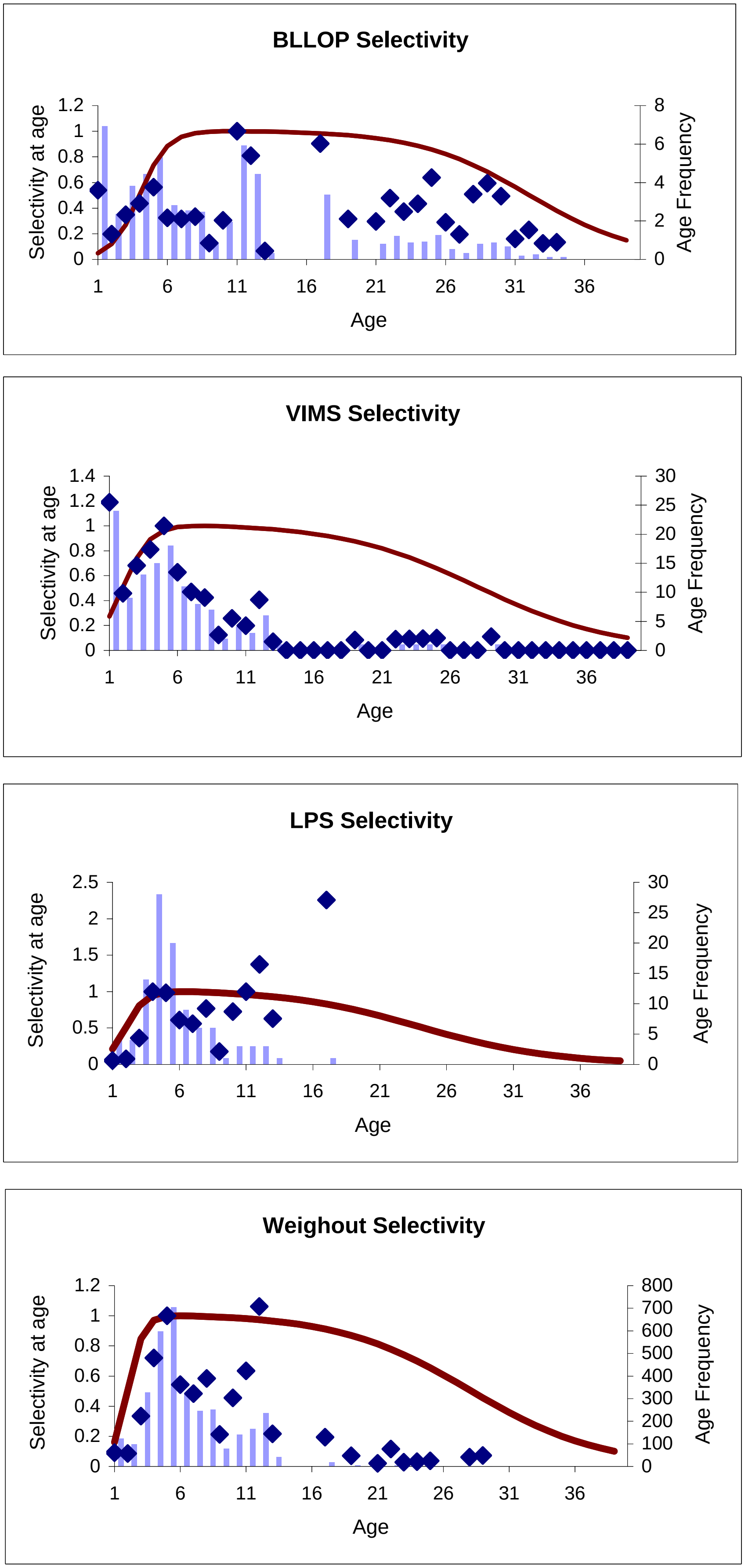


Figure 2.21. Double logistic selectivity curves fitted to age-frequency distributions of dusky sharks from multiple sources (BLLOP, VIMS, LPS, and weighout). Vertical bars are proportions at age (starting at age-1), diamonds are the normalised ratios of observed to expected proportions (see text for explanation).

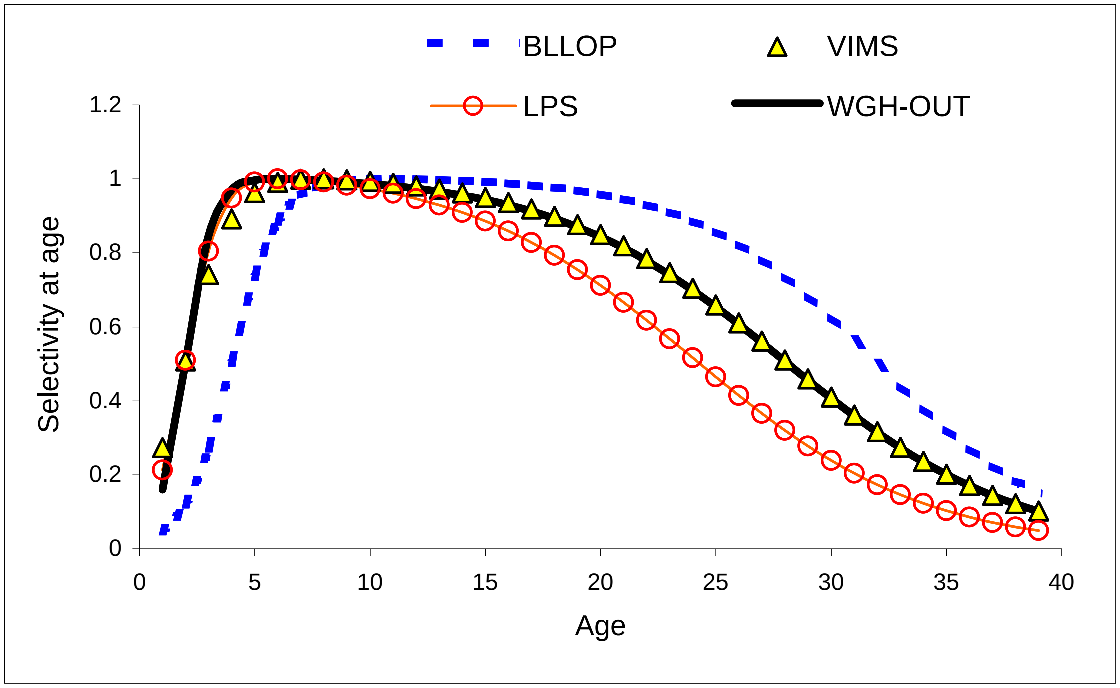


Figure 2.22. Combined view of the double logistic selectivity curves fitted to age-frequency distributions of dusky sharks from multiple sources (BLLOP, VIMS, LPS, and weighout).

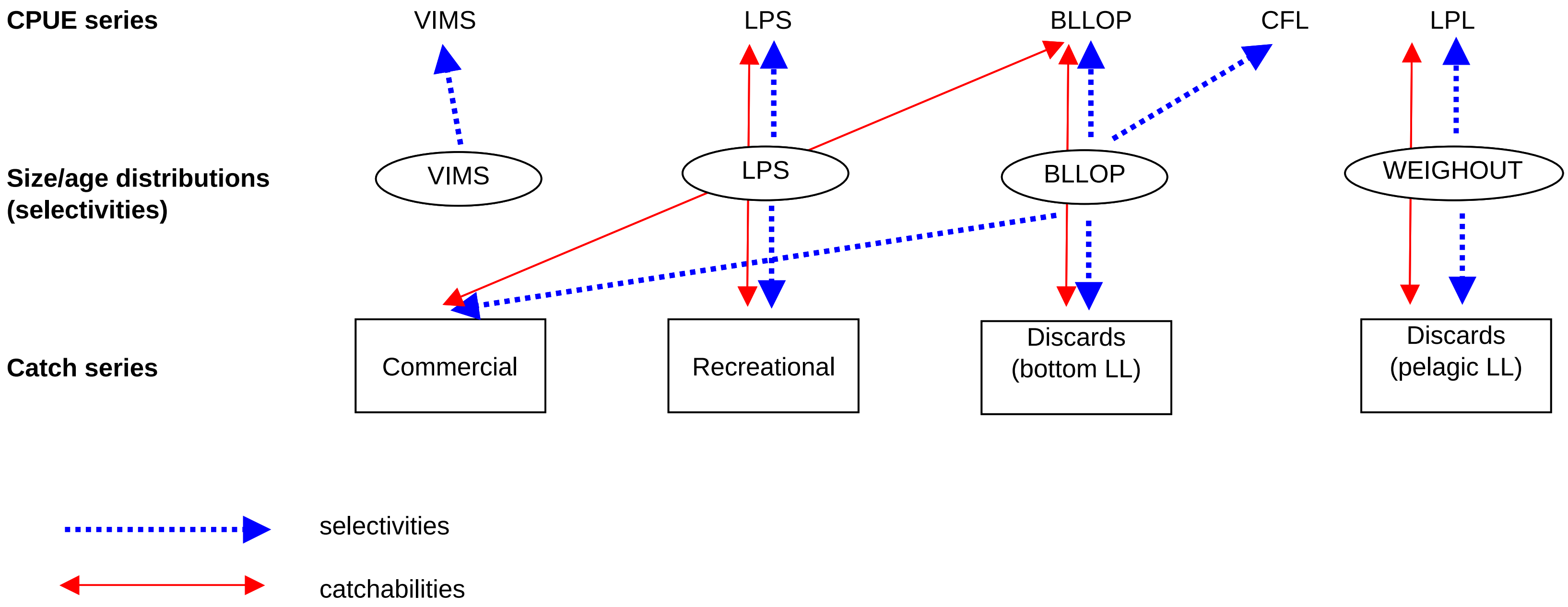
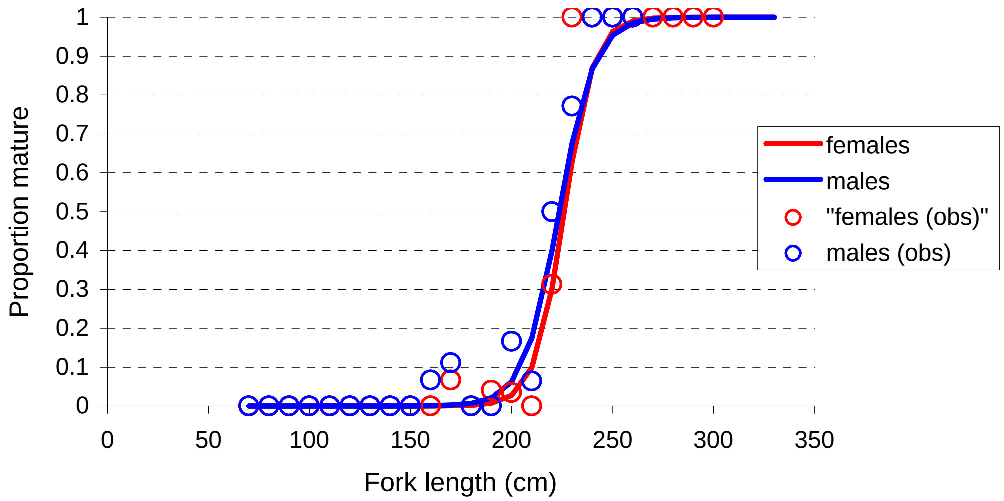


Figure 2.23. Schematic representation of the assumptions on selectivities and catchabilities for use in the catch-free and age-structured stock assessment models. Selectivities derived from the four age-frequency distributions available were applied to the five CPUE series and the four catch series available as indicated by the dotted blue arrows. CPUE and catch series linked by a solid red arrow were assumed to have the same catchability.

A



B

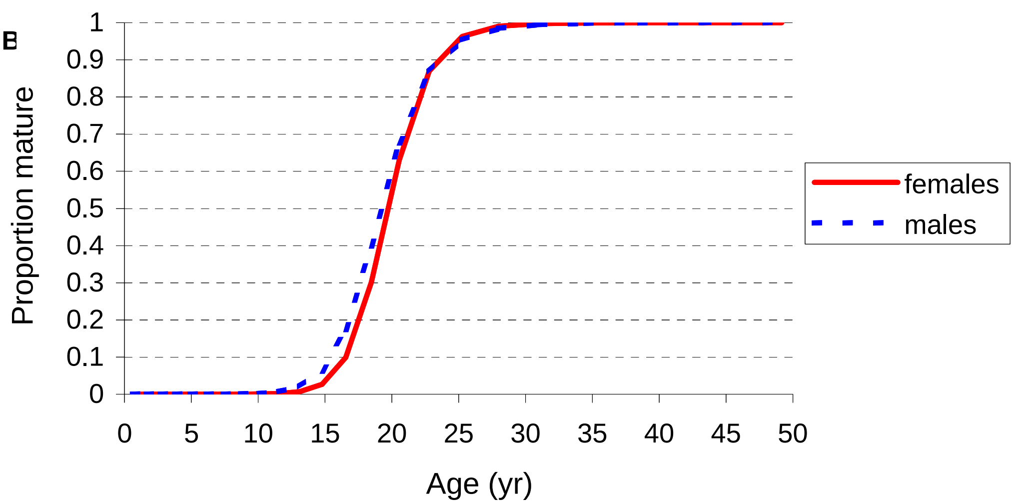


Figure 3.1. Maturity ogives in length (A) and age (B) for dusky shark. Observed proportion mature by length interval is also shown.

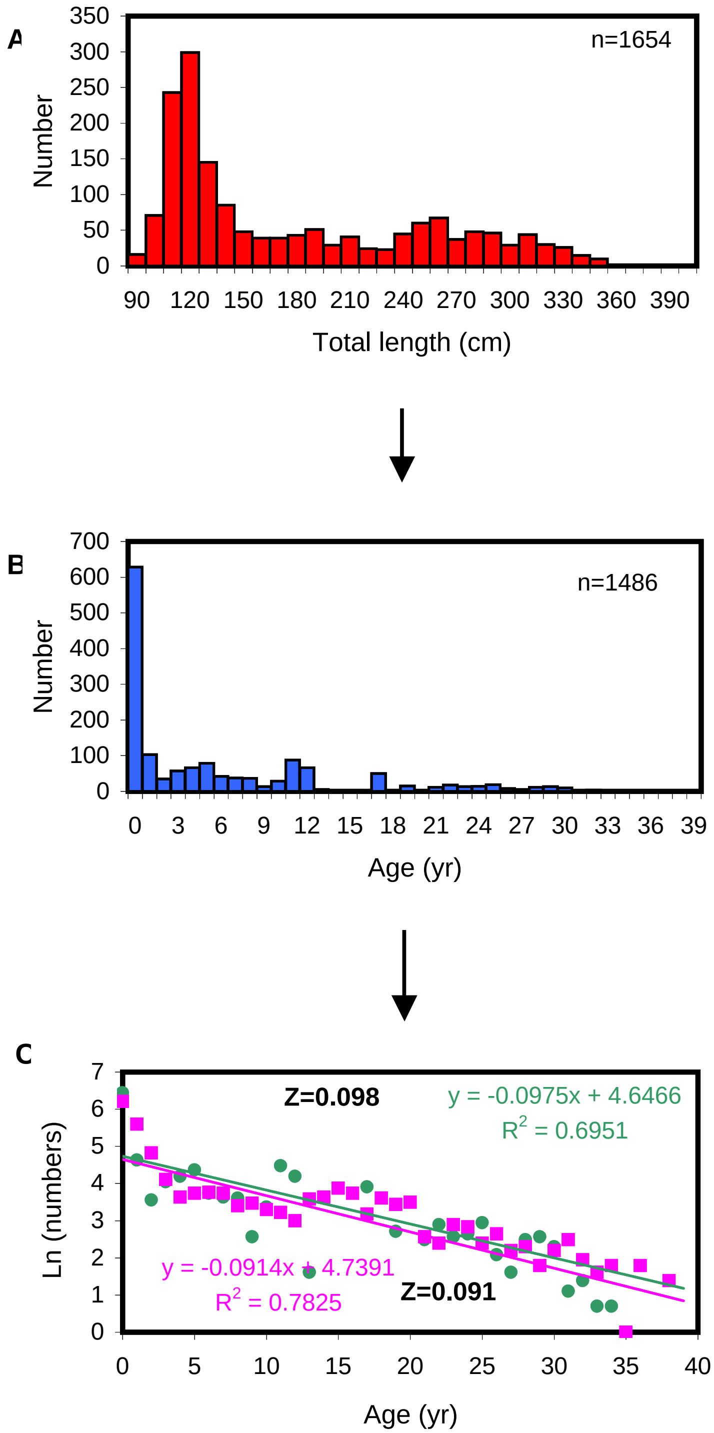


Figure 3.2. Estimation of Z (total instantaneous mortality rate) for dusky shark from the BLLOP using a catch curve (C, circles) constructed using numbers at age (B) obtained from an age-length key generated from the growth curves of Natanson et al. (1995). Also shown (C, squares) is a catch curve generated by back-transforming lengths into ages through the growth curves. (A) is the length-frequency distribution of total lengths from the BLLOP.

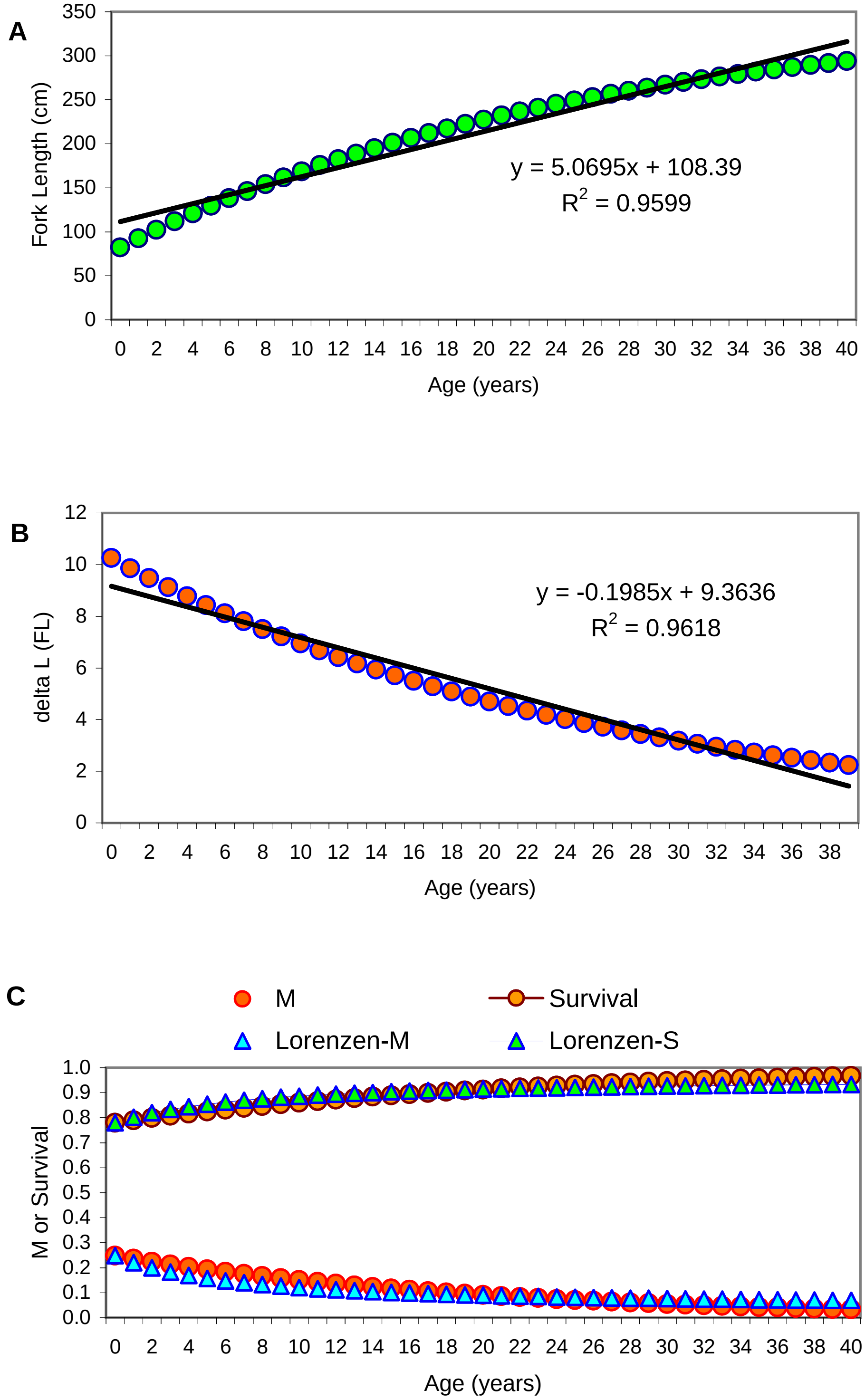


Figure 4.1. Von Bertalanffy growth curve showing minimum curvature (A), linear decrease in rate of change in FL with age (B), and natural mortality and survivorship values obtained with Lorenzen's (2000) method and when assuming a linear decrease in the rate of change in M. See text in section 4.1.2.1.3 for details.

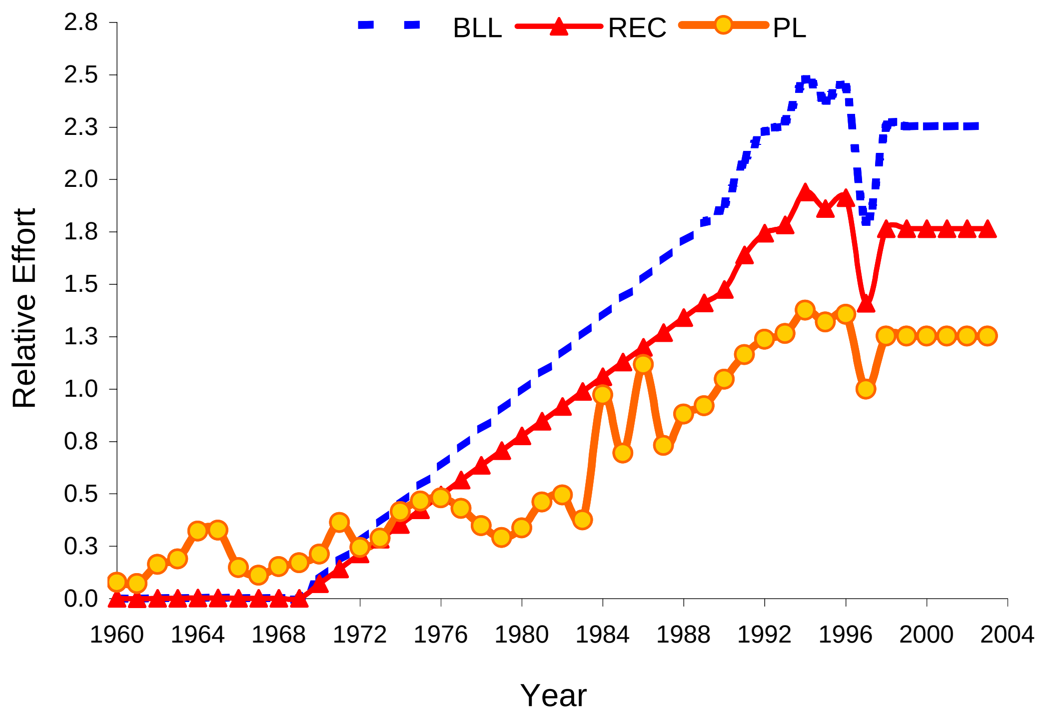


Figure 4.2. Relative effort for fleets in the catch-free model (BLL = Directed Bottom-Longline shark fishery; REC = recreational shark fishery; PL = Pelagic Longline shark fishery). See text for explanation on how series were derived.

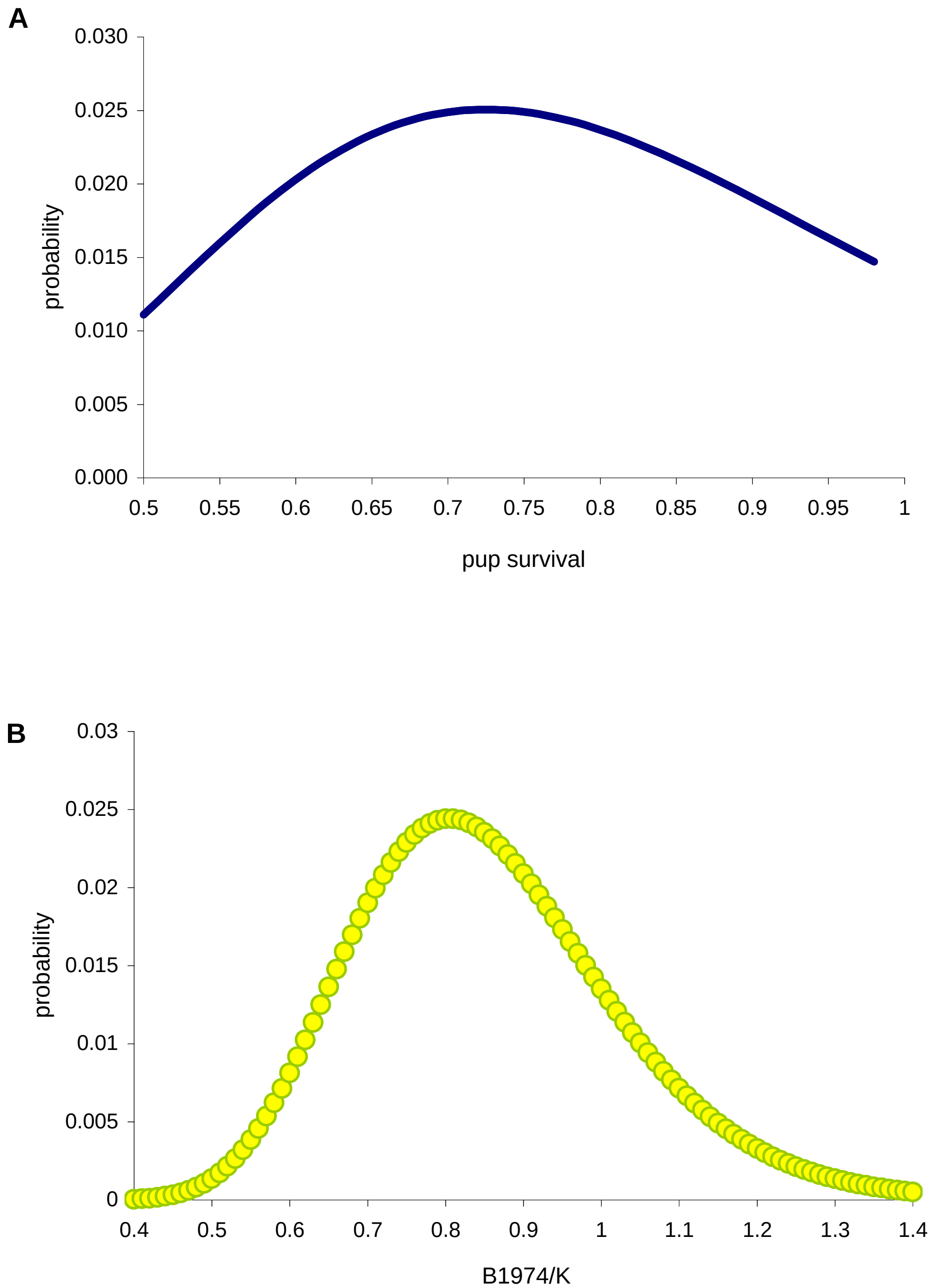


Figure 4.3. Prior probability distributions for pup survival (A) and B_{1974}/K (B) in the baseline scenario from the ASCFM.

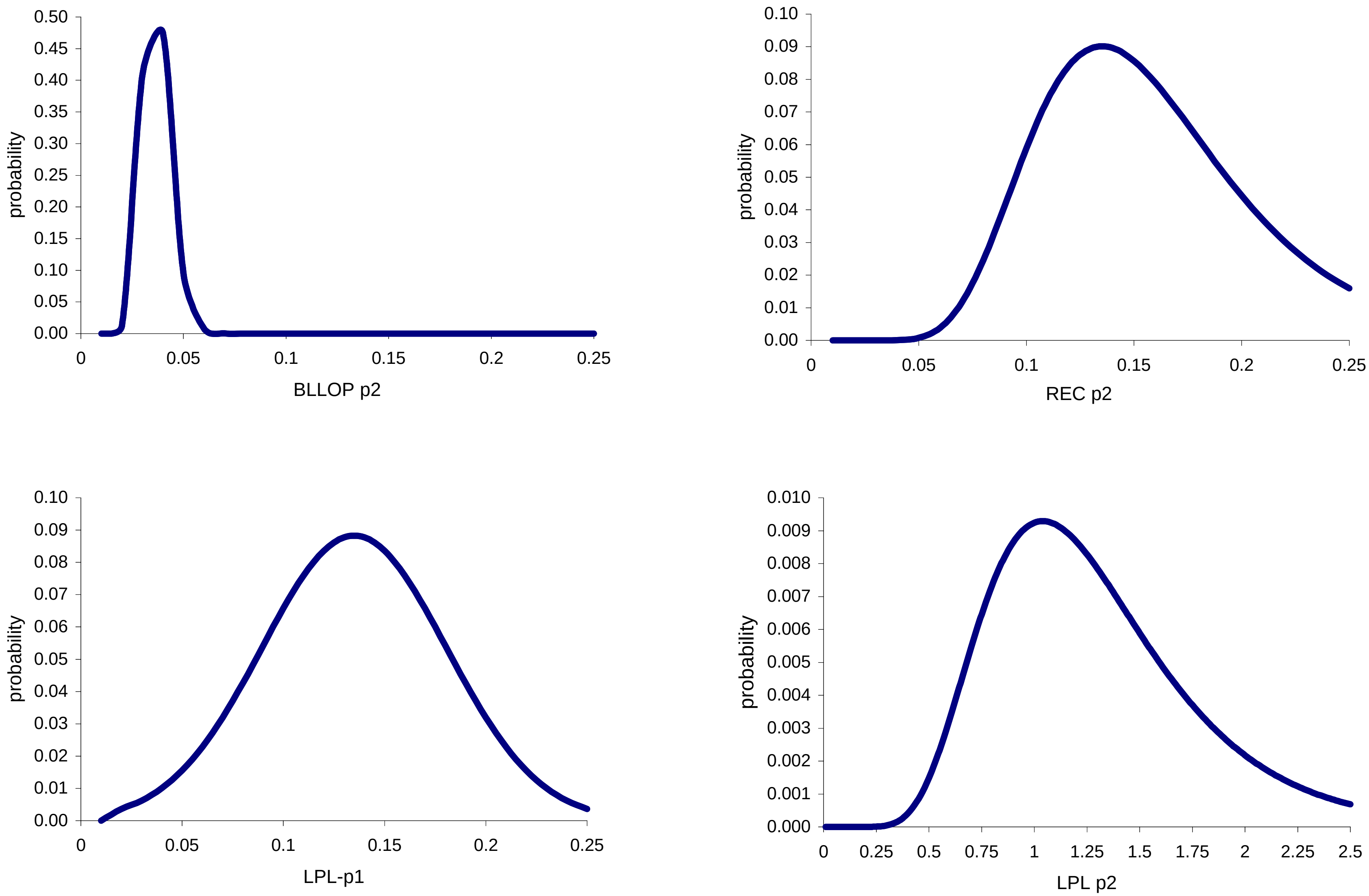


Figure 4.4. Prior probability distributions for effort proportionality coefficients (see text and Table 4.2 for details).

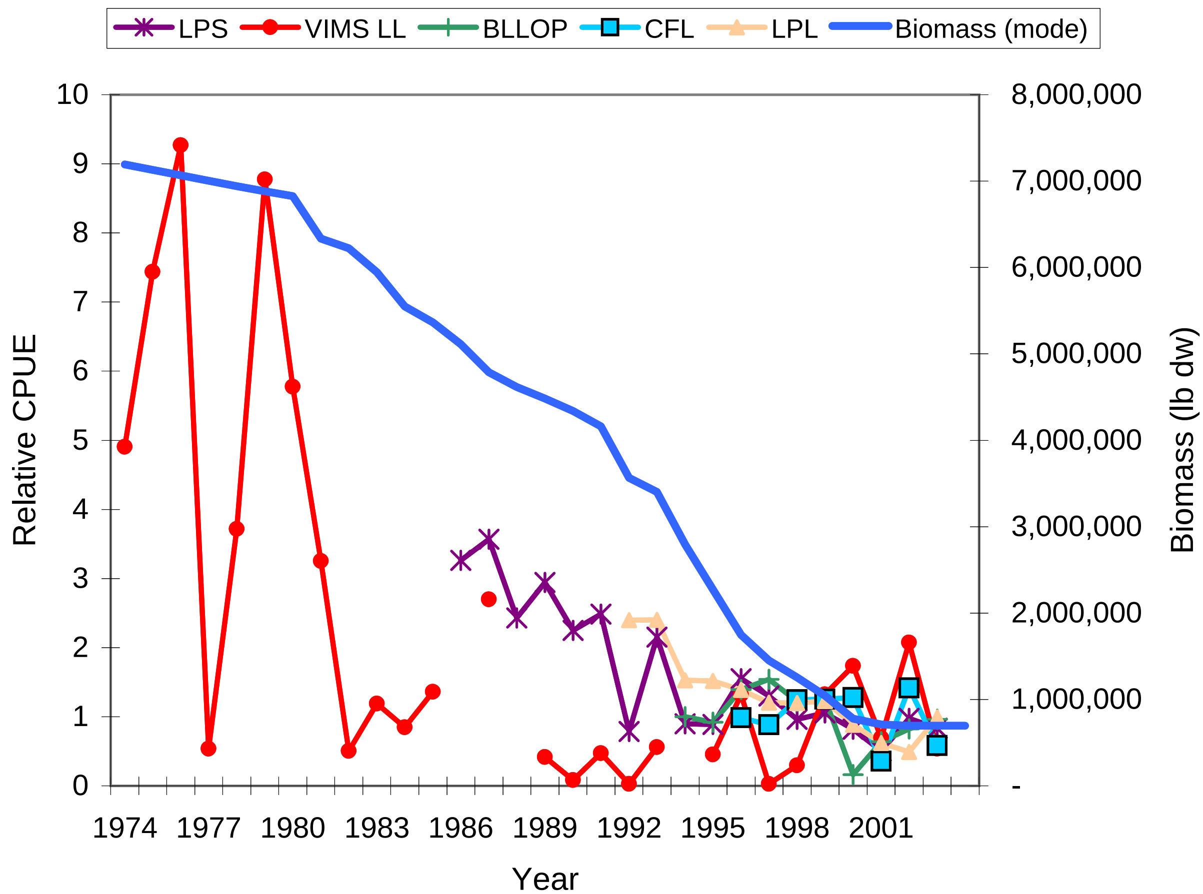


Figure 4.5. Predicted biomass trend at posterior mode of the BSP model fitted to the catch and CPUE data for the baseline scenario. CPUE series are scaled (divided by mean of the overlapping years among all series; 1996-2003).

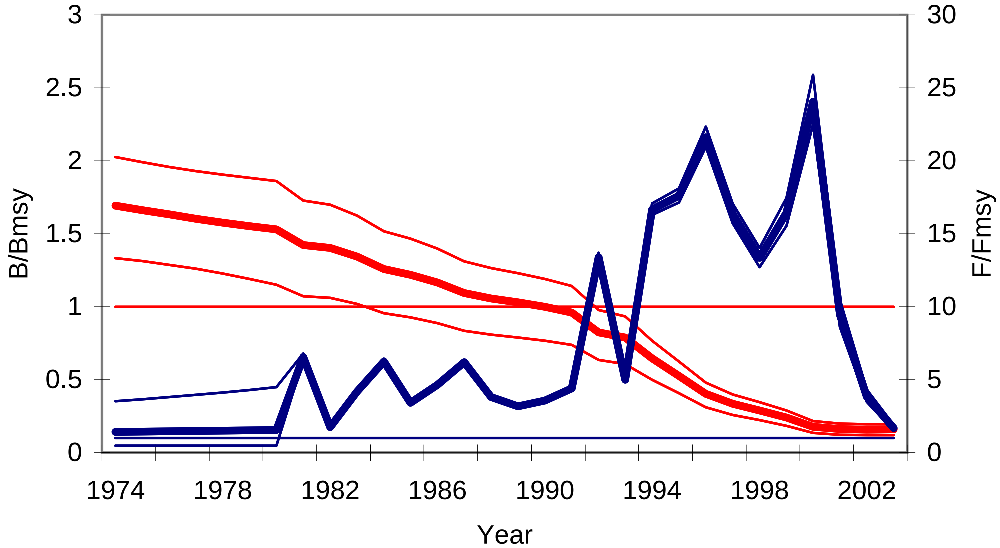


Figure 4.6. Estimated relative biomass and fishing mortality rate trajectories for dusky shark in the baseline scenario of the BSP. Values shown are medians and 80% probability intervals. Horizontal lines denote MSY levels.

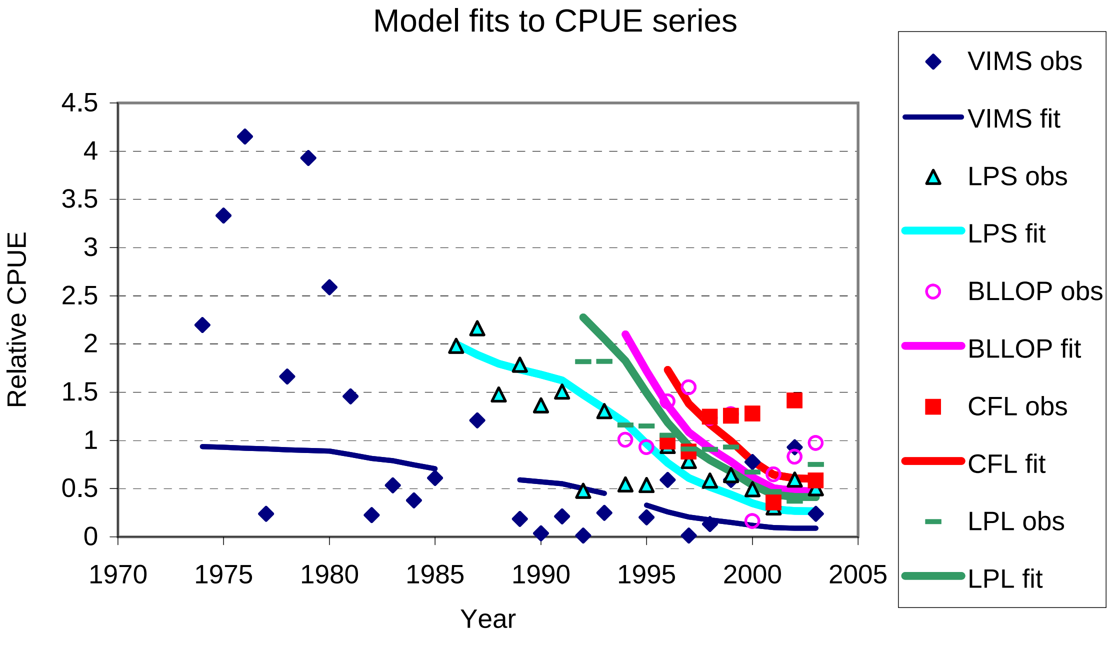


Figure 4.7. BSP model fits to the individual CPUE series in the baseline scenario for dusky shark.

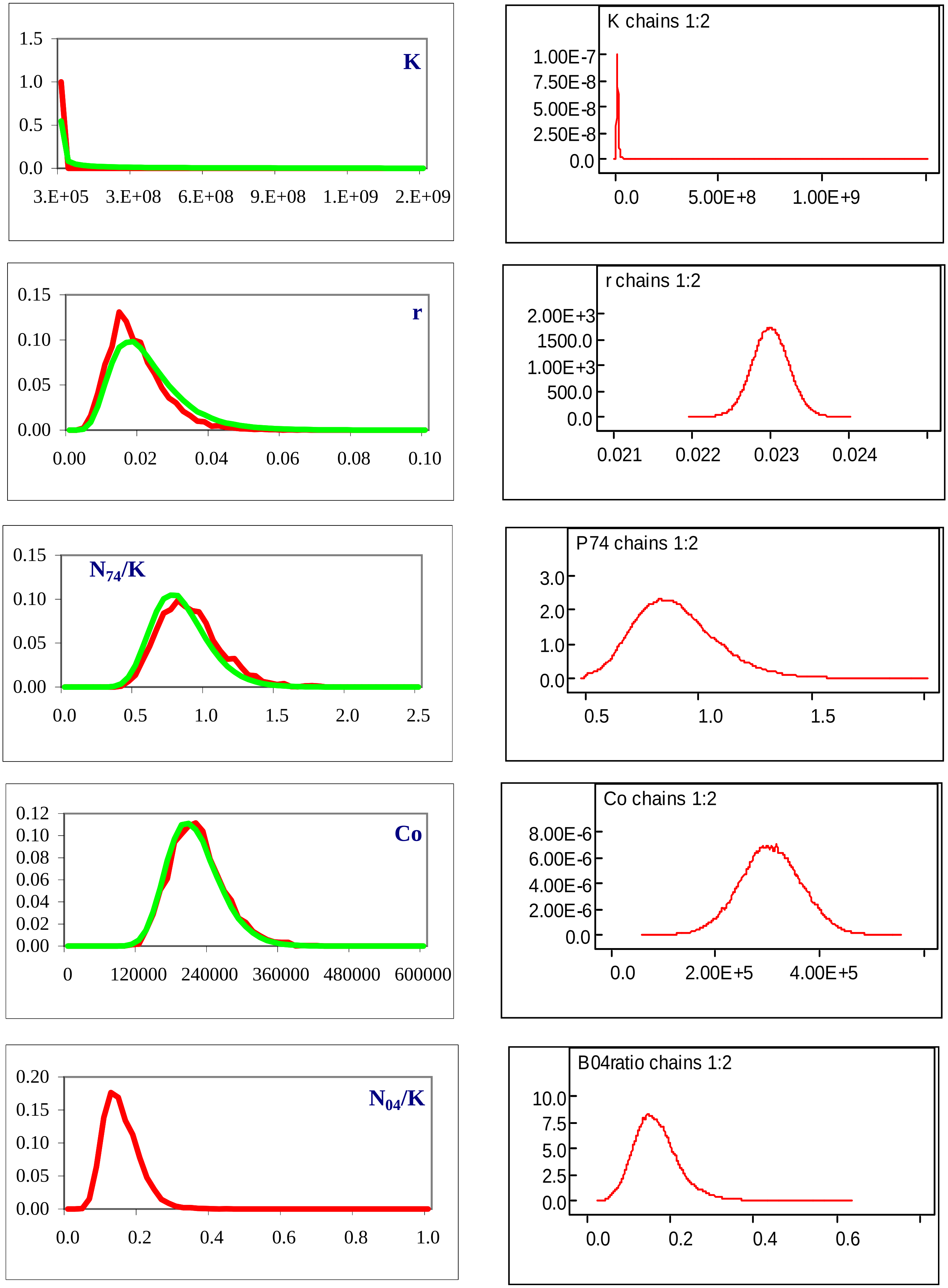


Figure 4.8. Prior (green) and posterior (red) distributions for several parameters of interest in the baseline scenario from the BSP model-spreadsheet version (left column) and WinBUGS model (right column).

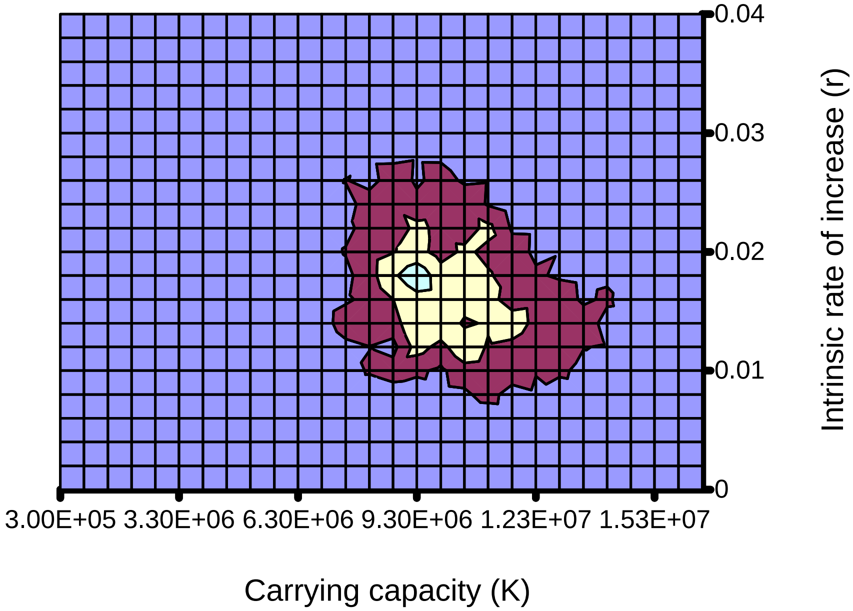


Figure 4.9. Joint posterior distribution for K and r from the BSP-spreadsheet version model baseline scenario. Smaller, inner concentric areas denote higher probability.

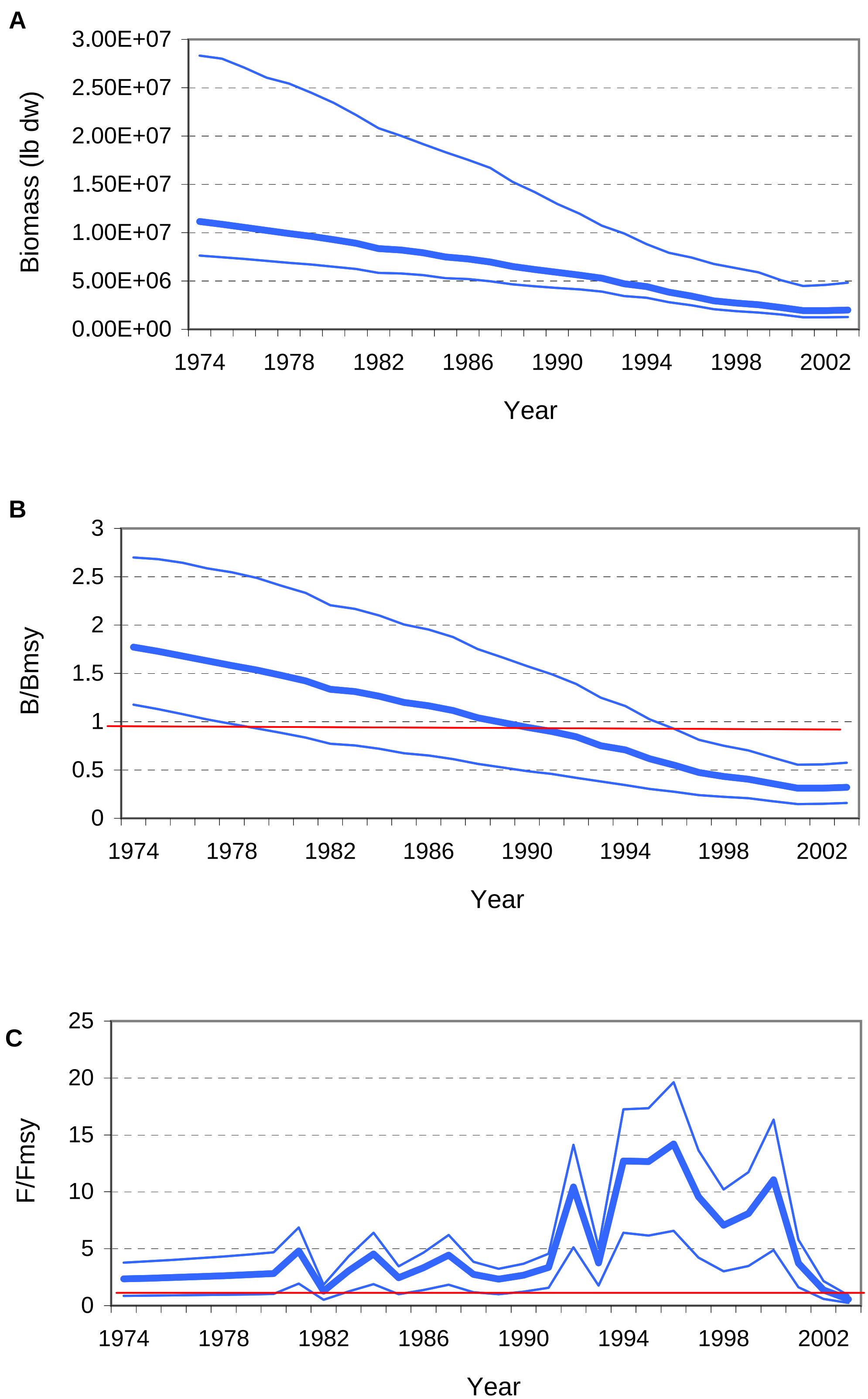


Figure 4.10. Estimated biomass (A) and relative biomass (B) and fishing mortality rate (C) trajectories for dusky shark in the baseline scenario of the WinBUGS BSP. Values shown are medians with 2.5th and 97.5th percentiles. Horizontal lines denote MSY levels.

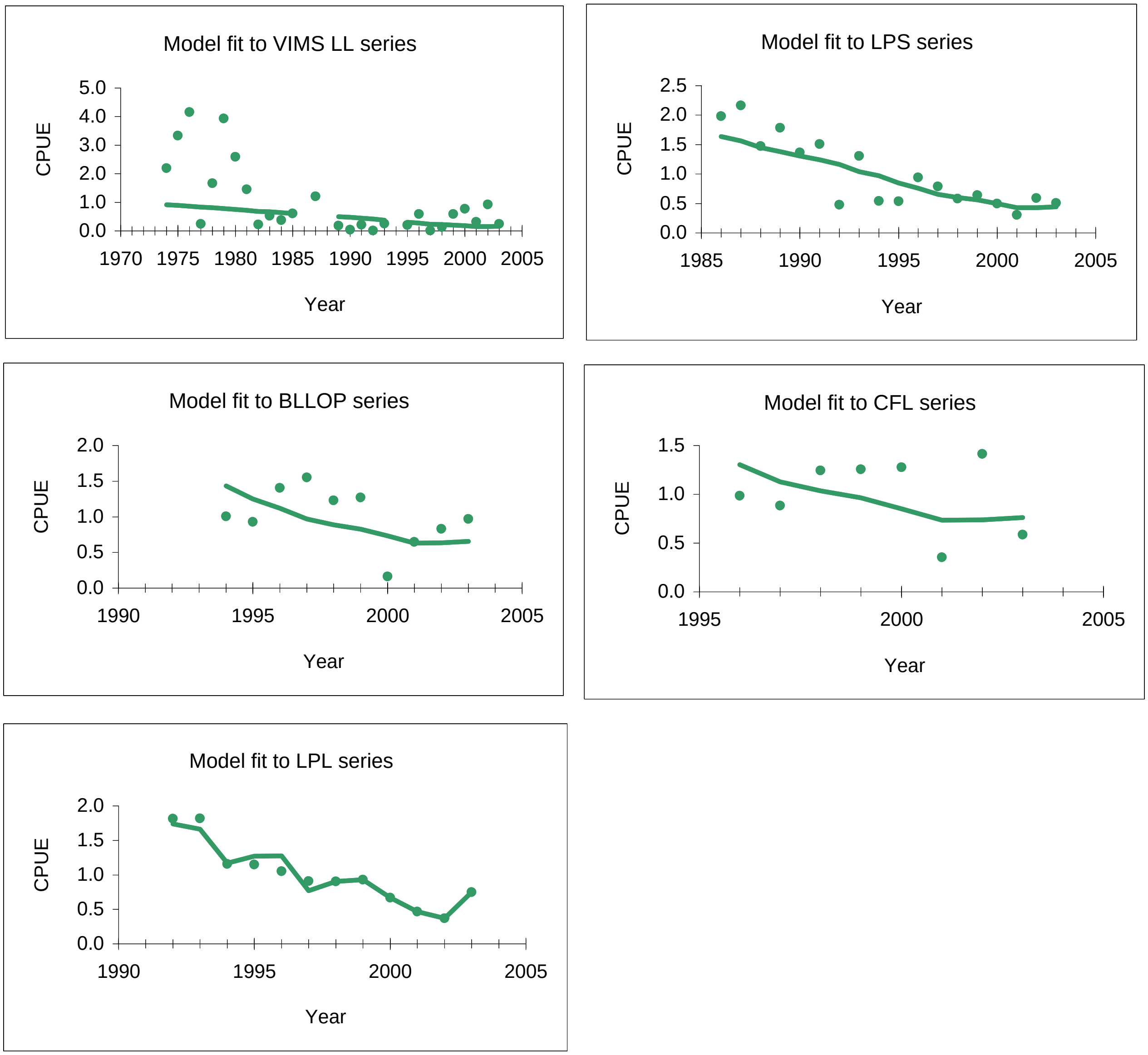


Figure 4.11. Winbugs BSP model fits to the individual CPUE series of the baseline scenario for dusky shark.

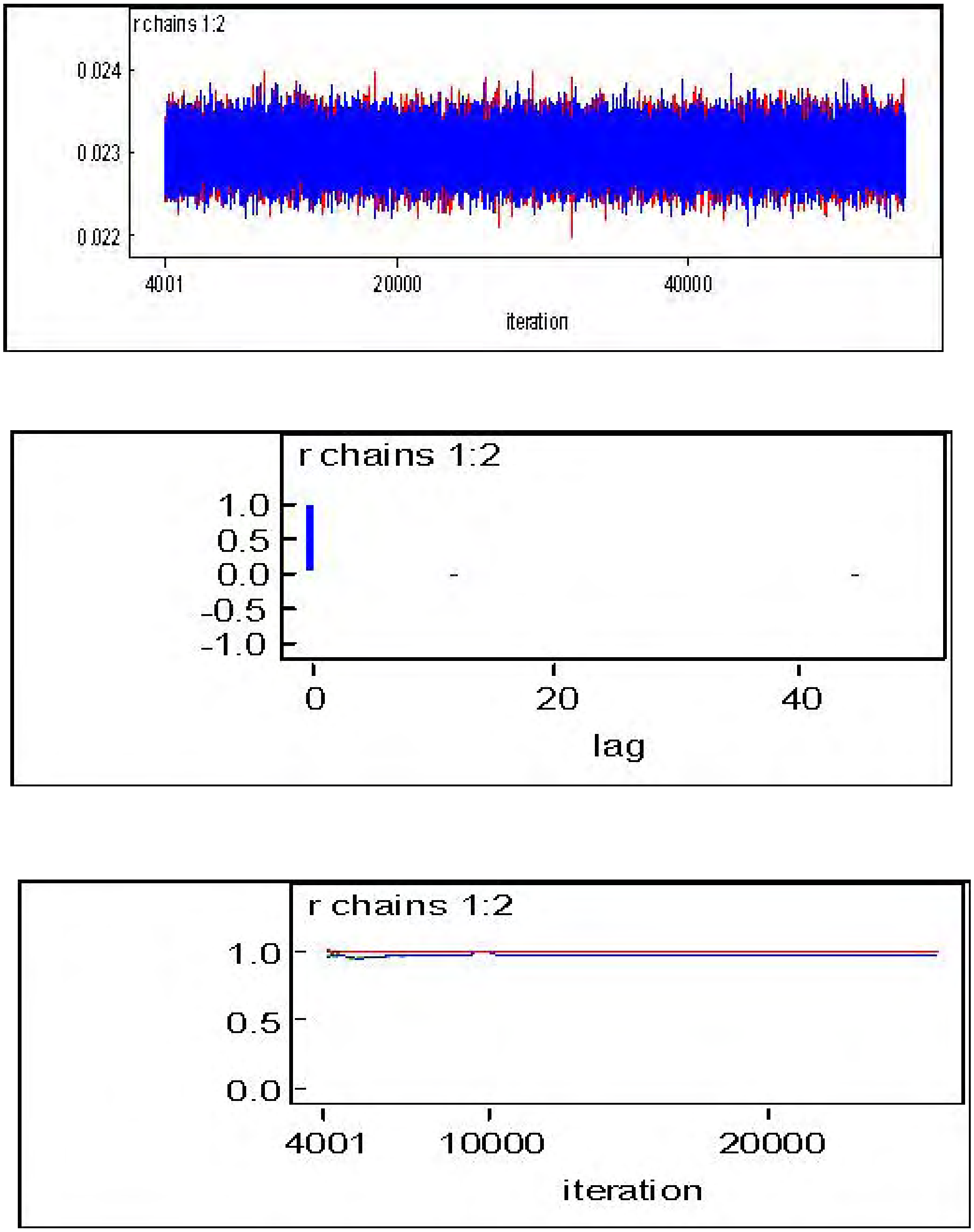


Figure 4.12. Example of good convergence diagnostics (for r) in WinBUGS BSP model fits. The first panel (A) shows good mixing of the two initial chains, the second panel (B) shows low parameter autocorrelation, and the third panel (C) shows the Gelman-Rubin modified convergence statistic (red line at 1, blue and green lines stabilized; see text for full details).

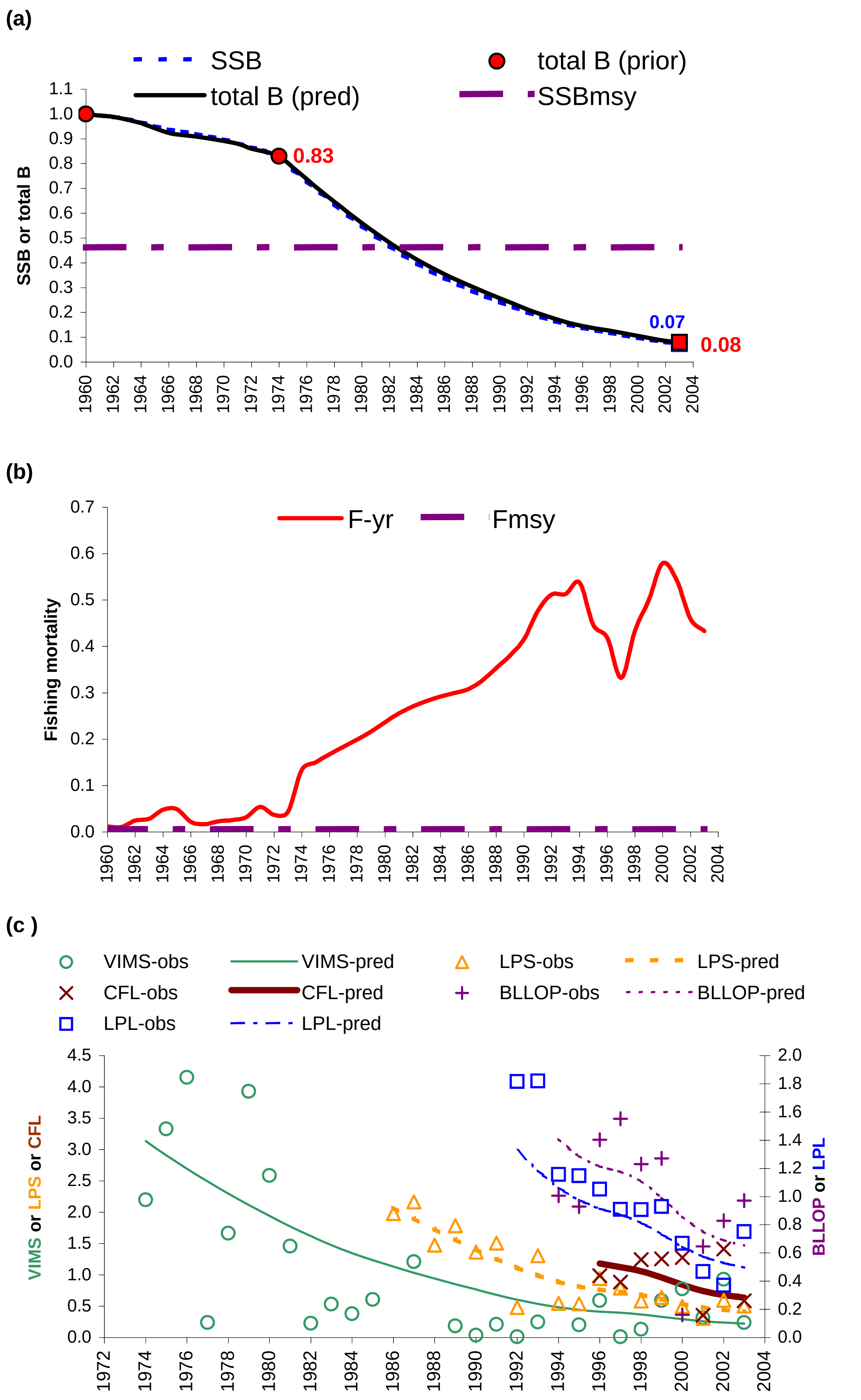


Figure 4.13. Baseline Catch-free model estimates of depletion in terms of spawning stock biomass (SSB) and total biomass (total B) (a), total fishing mortality (b), and fits to indices (c). Horizontal dot-dashed lines are SSBmsy (a) or Fmsy (b).

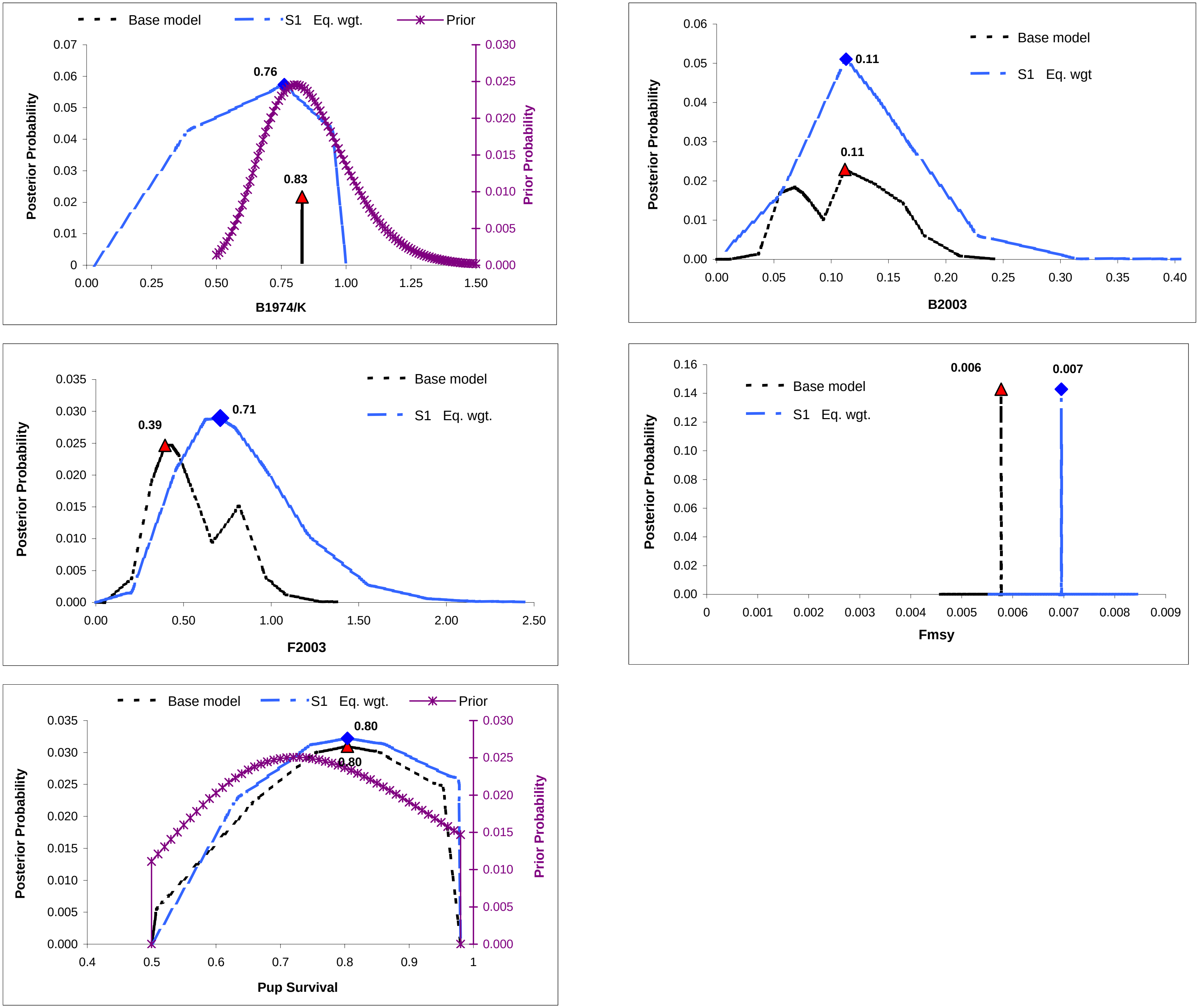


Figure 4.14. Likelihood profile posterior probabilities for the base model and the sensitivity case with equal weighting of indices (S1). Red triangles indicate the modes of BASE case posteriors; blue diamonds are the modes of S1 posteriors.

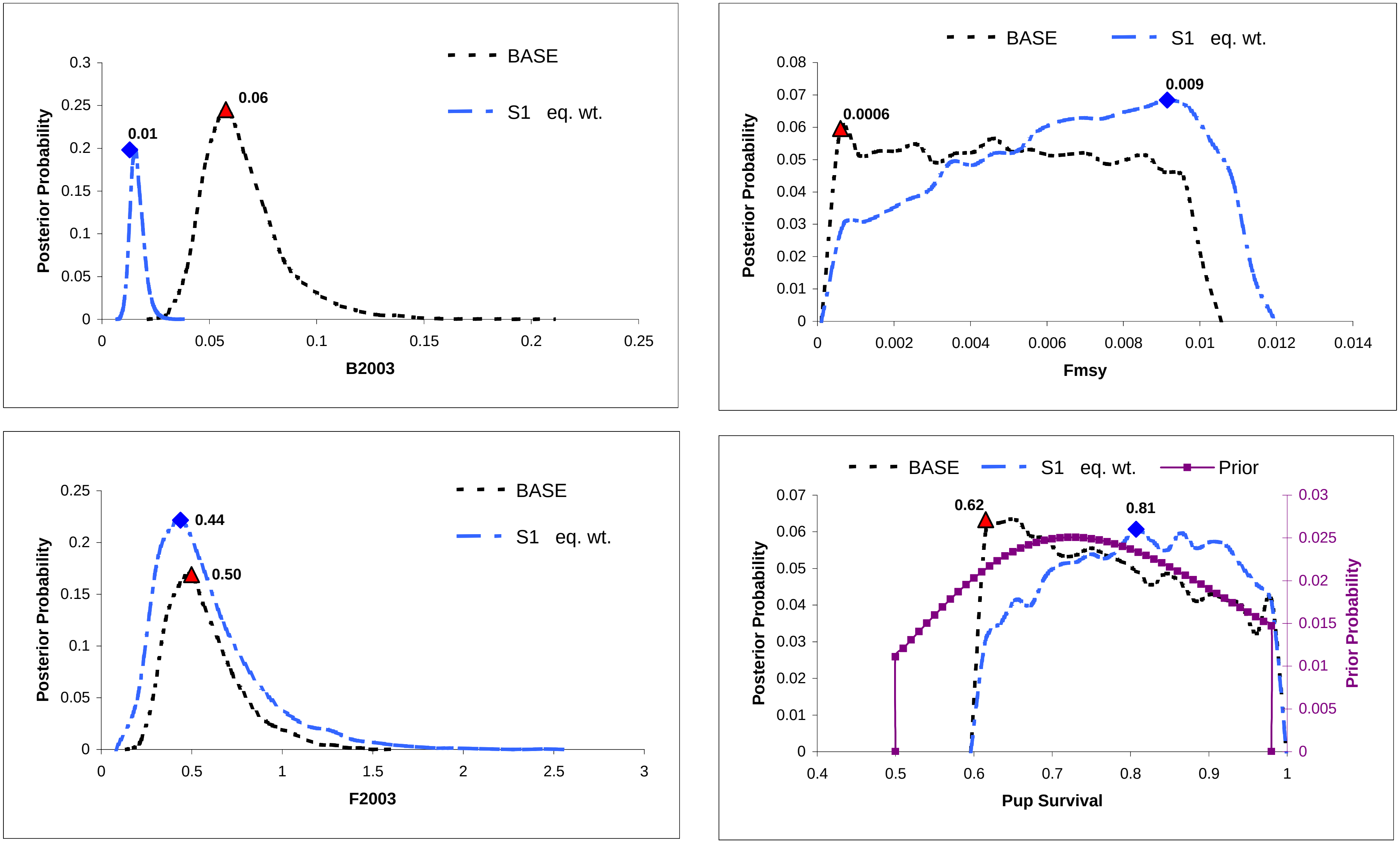


Figure 4.15. MCMC posterior probabilities for the base model and the sensitivity case with equal weighting of indices (S1). B_{1974}/K is not plotted because diagnostics indicated that the chain had not converged to the stationary distribution. Red triangles indicate the modes of BASE case posteriors; blue diamonds are the modes of S1 posteriors. Note that MCMC plots for pup survival seem truncated at 0.6, even though the lower bound was 0.5. In reality, values <0.6 were sampled, but they were associated with F_{MSY} estimates of 3.0 (model-imposed upper bound). This indicated a clear lack of convergence, so those runs were dropped.

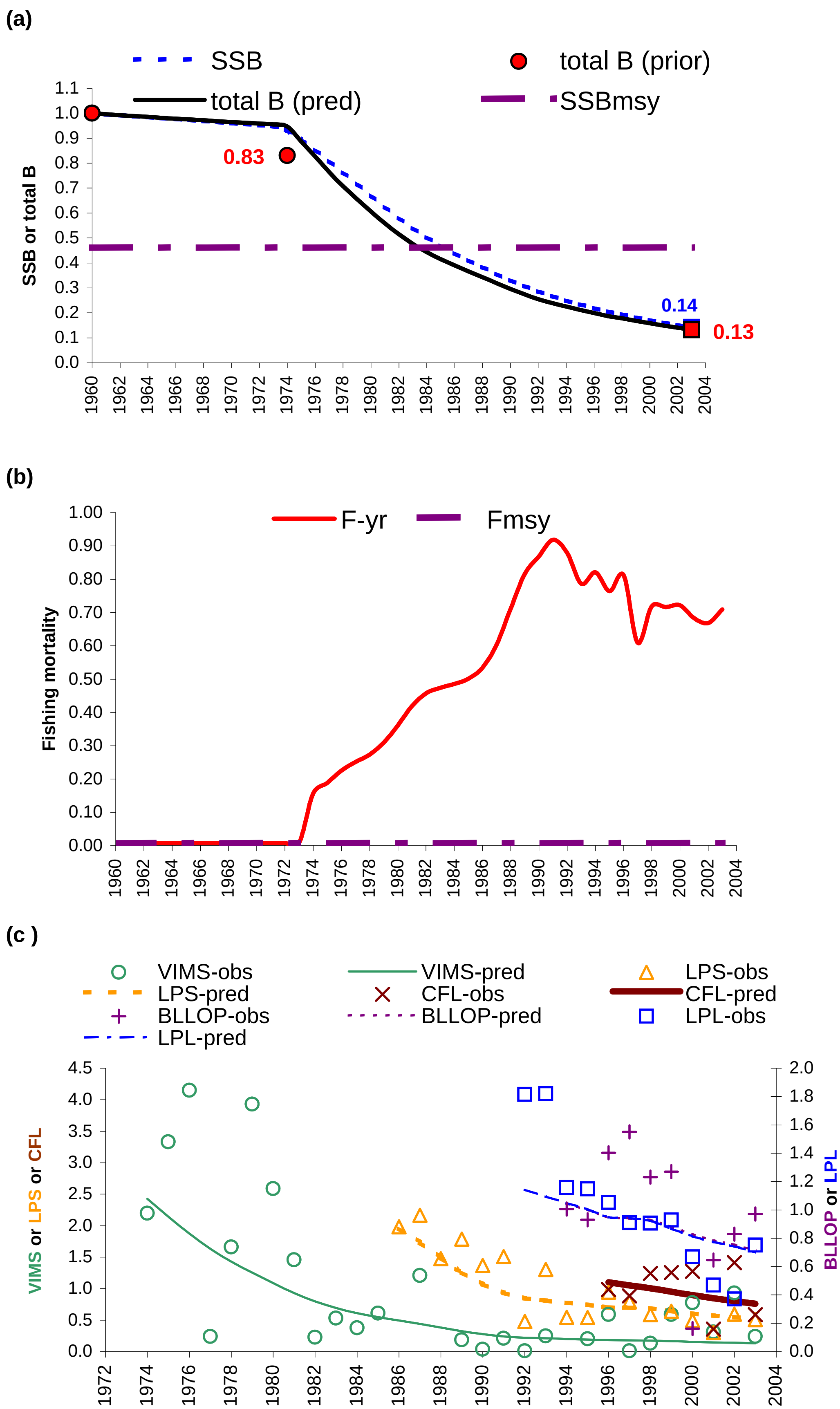


Figure 4.16. Catch-free model estimates of depletion in terms of spawning stock biomass (SSB) and total biomass (total B) (a), total fishing mortality (b), and fits to indices (c) for sensitivity run **S1** with equal weighting. Horizontal dot-dashed lines are SSBmsy (a) or Fmsy (b).

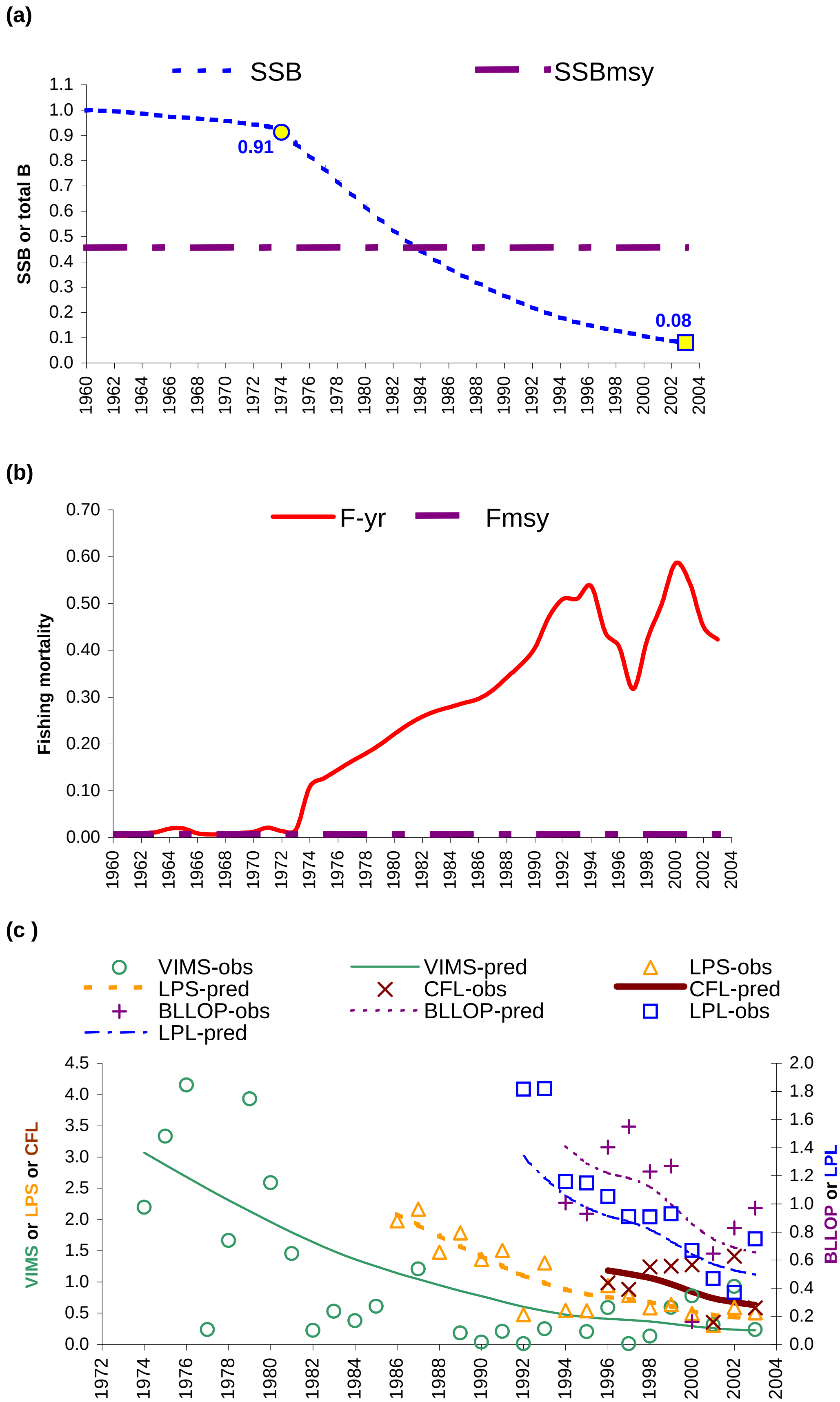


Figure 4.17. Catch-free model estimates of depletion in terms of spawning stock biomass (SSB) (a), total fishing mortality (b), and fits to indices (c) for sensitivity run **S2** with CV weighting and no relative biomass index. Horizontal dot-dashed lines are SSBmsy (a) or Fmsy (b).

(a)

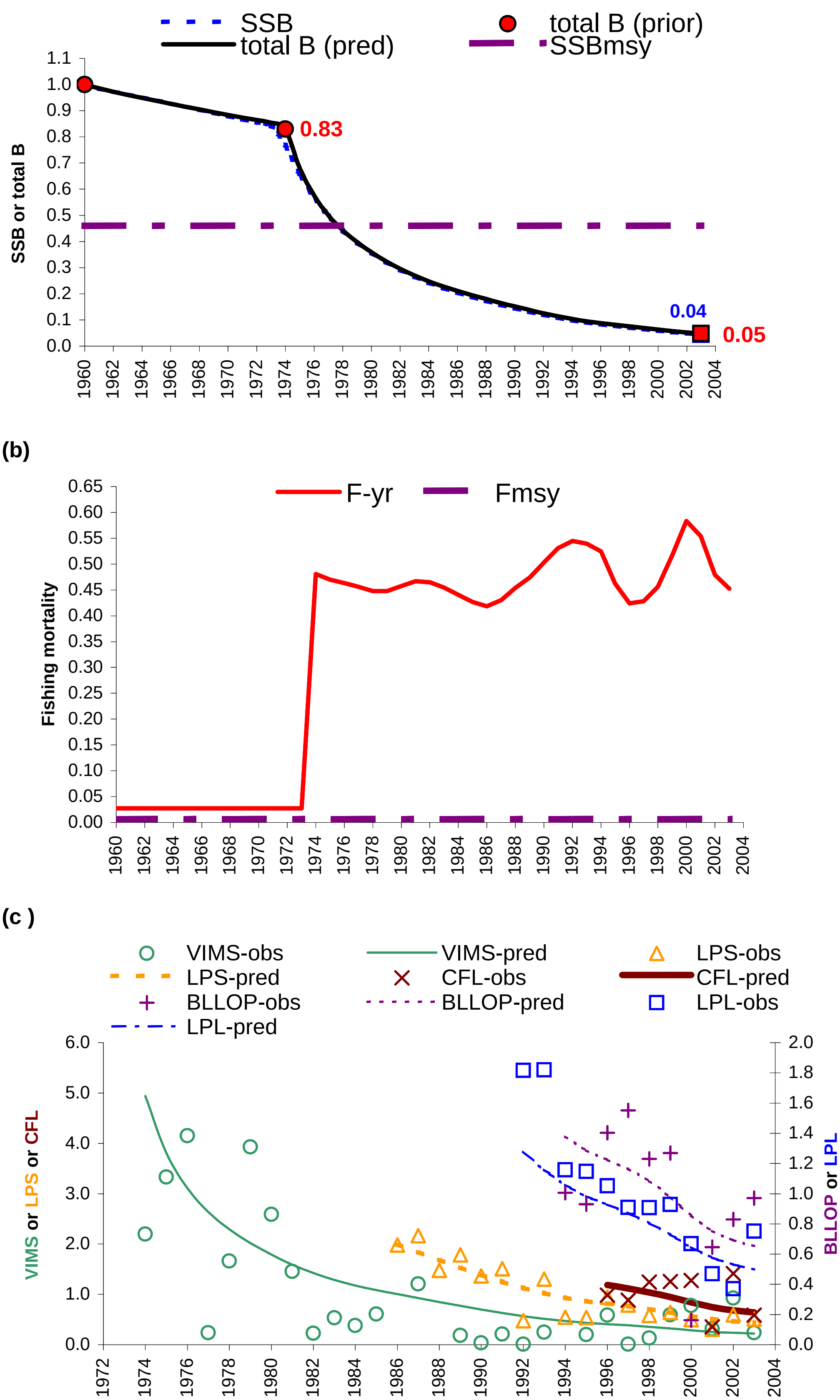
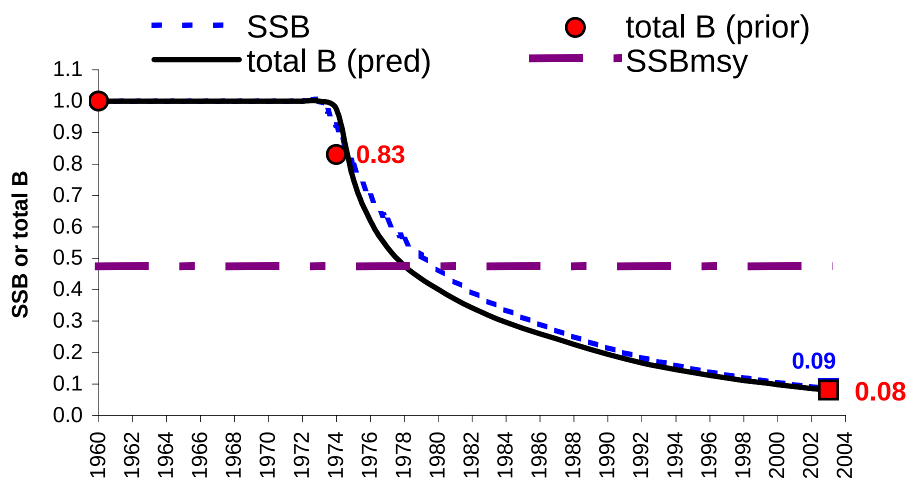
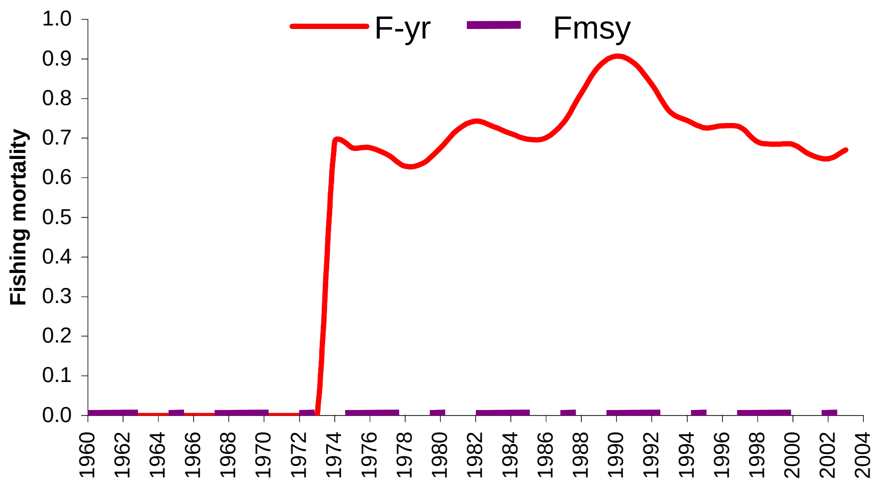


Figure 4.18. Catch-free model estimates of depletion in terms of spawning stock biomass (SSB) and total biomass (total B) (a), total fishing mortality (b), and fits to indices (c) for sensitivity run **S3** with CV weighting and no effort series. Horizontal dot-dashed lines are SSBmsy (a) or Fmsy (b).





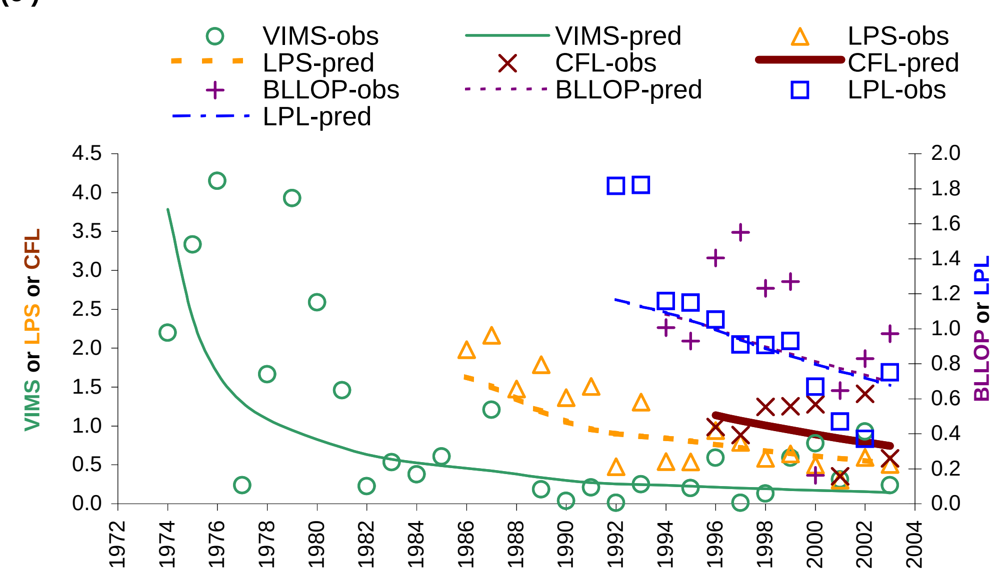
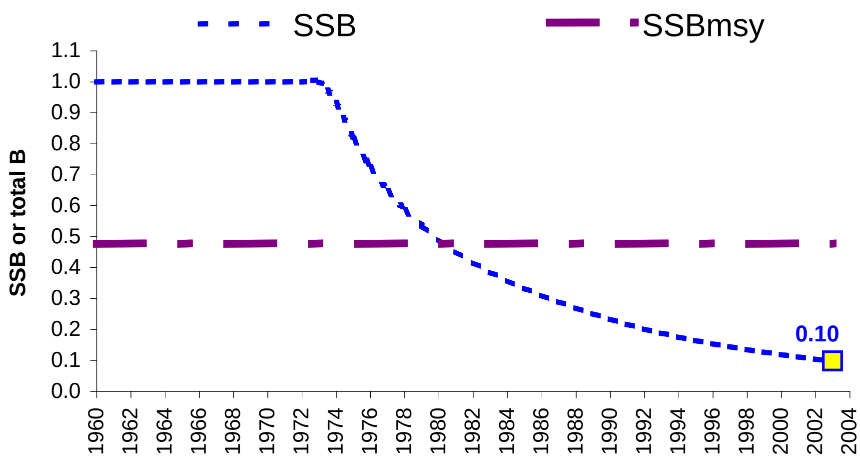
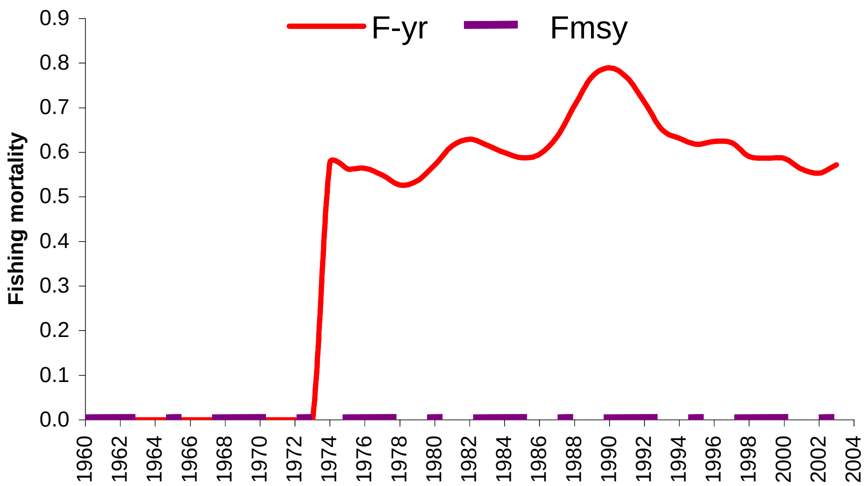


Figure 4.19. Catch-free model estimates of depletion in terms of spawning stock biomass (SSB) and total biomass (total B) (a), total fishing mortality (b), and fits to indices (c) for sensitivity run **S4** with equal weighting and no effort series. Horizontal dot-dashed lines are SSBmsy (a) or Fmsy (b).

(a)



(b)



(c)

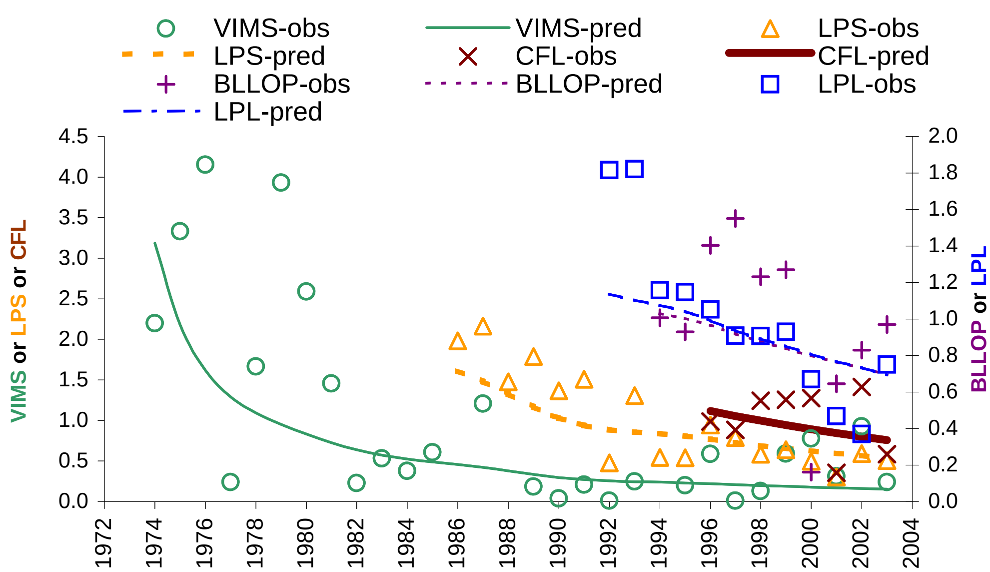


Figure 4.20. Catch-free model estimates of depletion in terms of spawning stock biomass (SSB) and total biomass (total B) (a), total fishing mortality (b), and fits to indices (c) for sensitivity run **S5** with equal weighting, no effort series, and no relative biomass index. Horizontal dot-dashed lines are SSBmsy (a) or Fmsy (b).

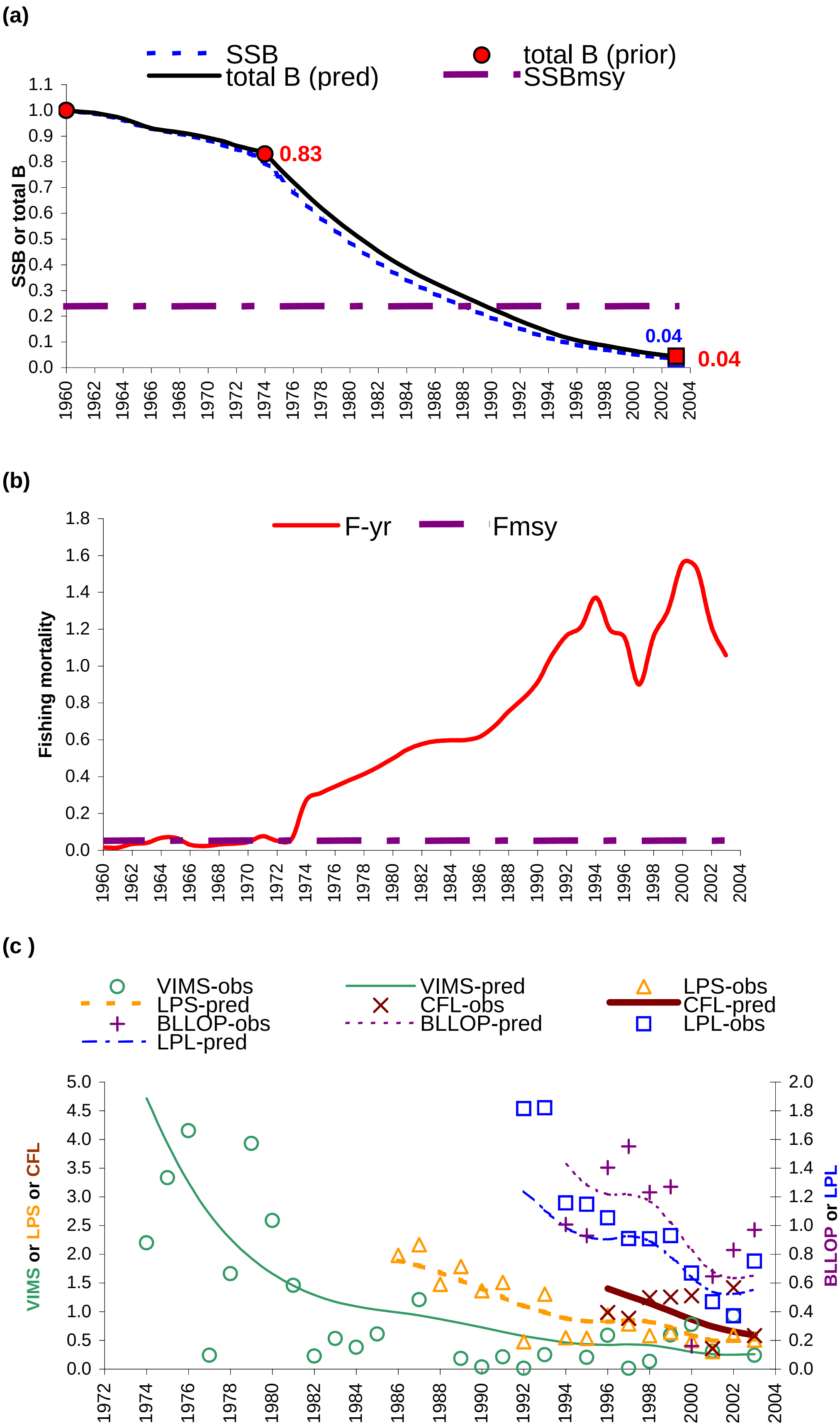


Figure 4.21. Catch-free model estimates of depletion in terms of spawning stock biomass (SSB) and total biomass (total B) (a), total fishing mortality (b), and fits to indices (c) for sensitivity run **S6** with constant M=0.03 for ages 1+. Horizontal dot-dashed lines are SSBmsy (a) or Fmsy (b).

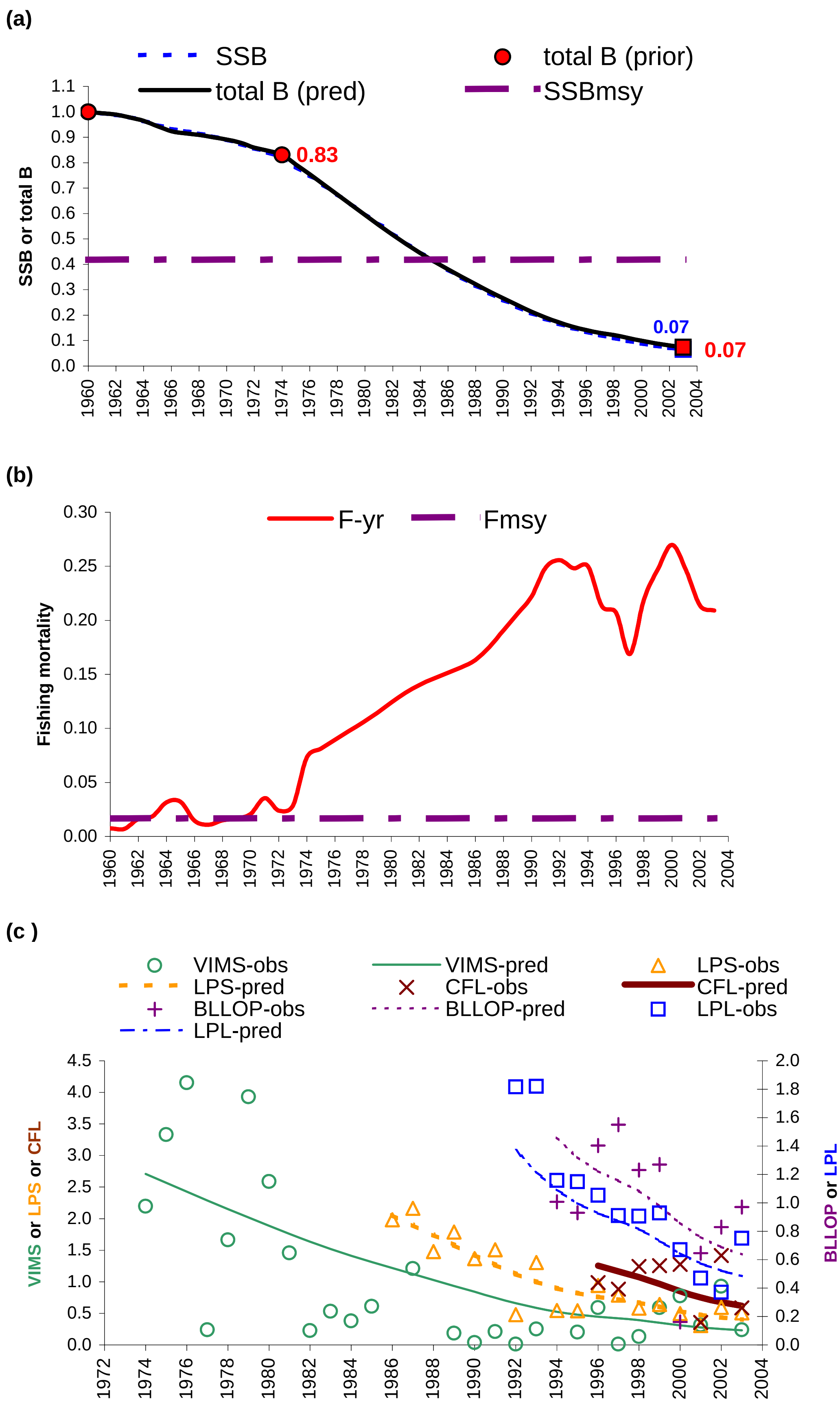
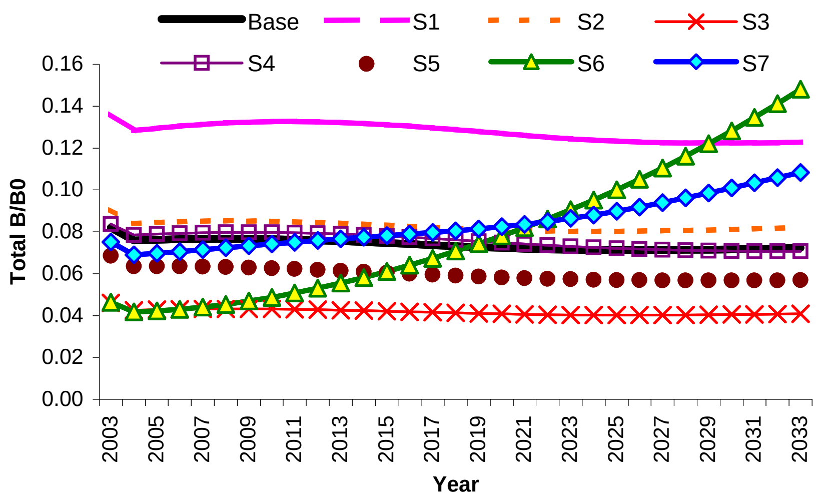
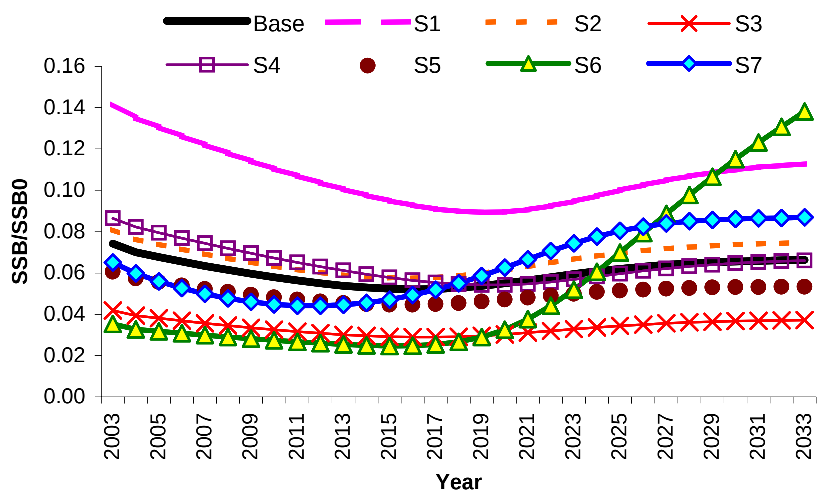


Figure 4.22. Catch-free model estimates of depletion in terms of spawning stock biomass (SSB) and total biomass (total B) (a), total fishing mortality (b), and fits to indices (c) for sensitivity run **S7** with constant M=0.10 for ages 1+. Horizontal dot-dashed lines are SSBmsy (a) or Fmsy (b).

(a)



(b)



(c)

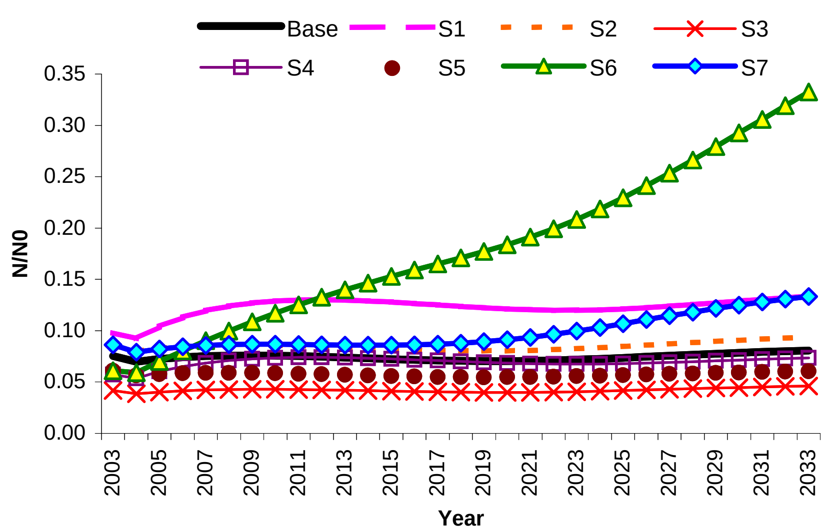


Figure 4.23. Projections to 2033 with F=0. Results are reported for total biomass (a), spawning stock biomass (b) and population size in number (c).

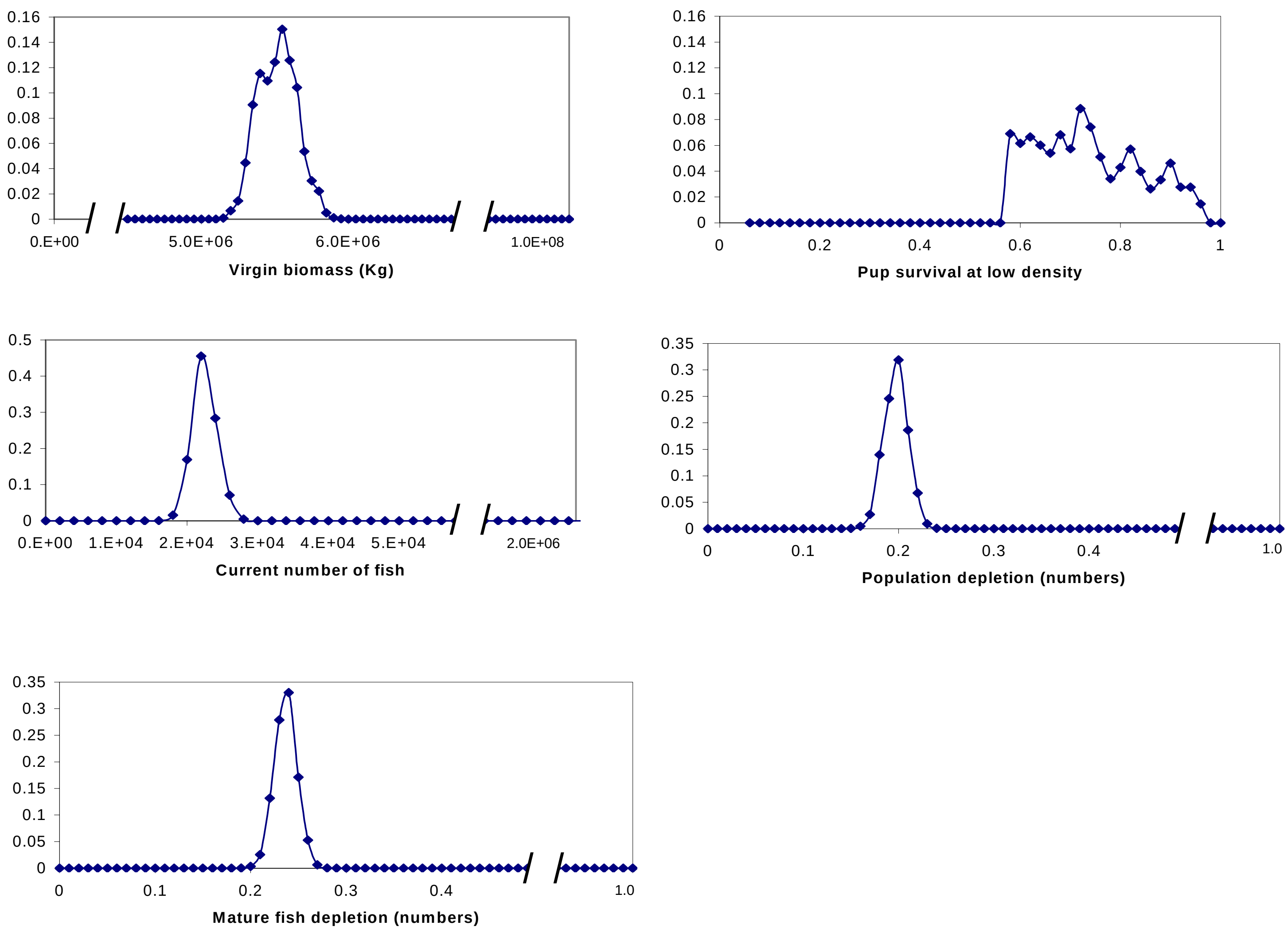


Figure 4.24. Marginal posterior pdfs of the estimated parameters for the baseline run in the ASM.

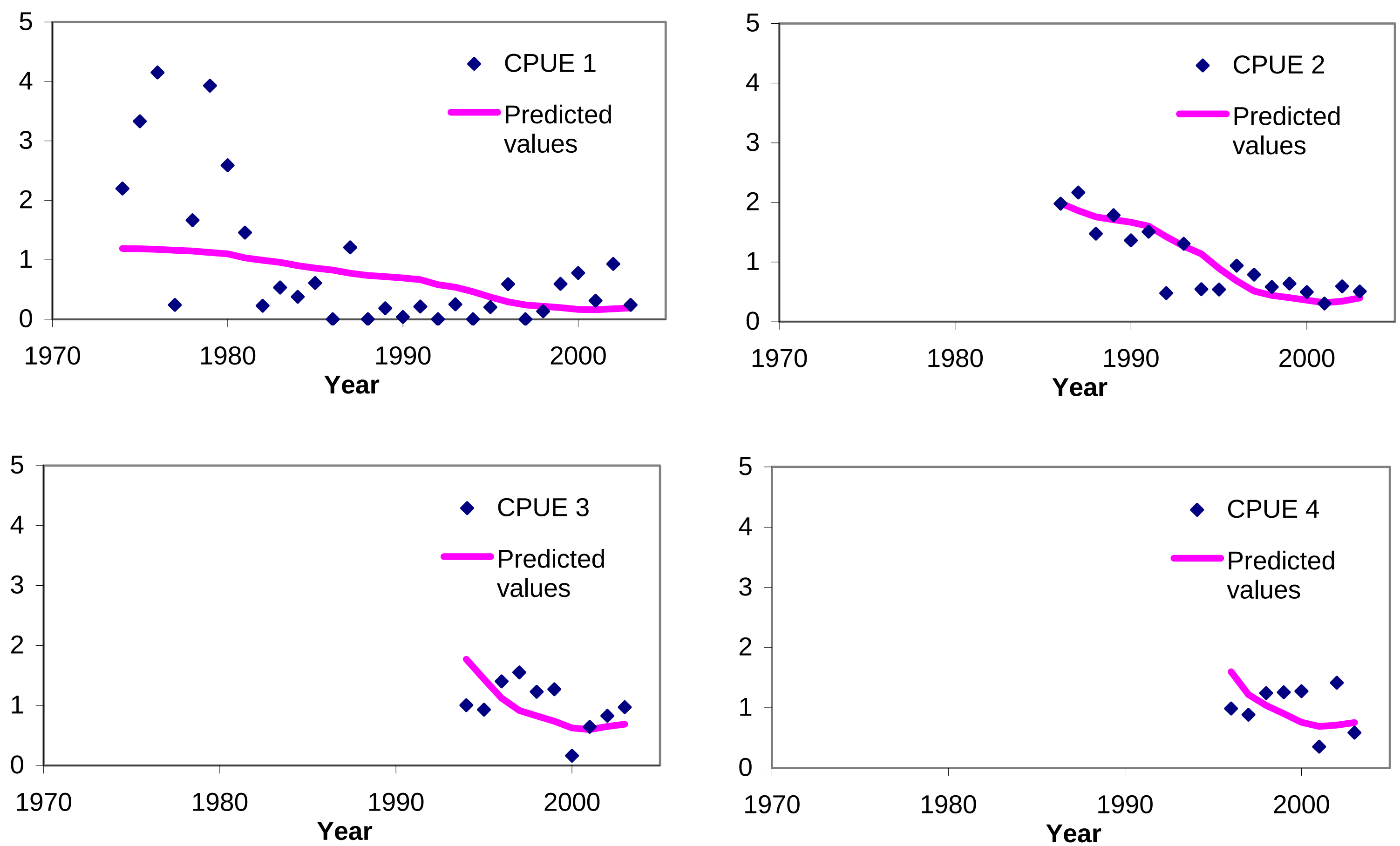


Figure 4.25. Model fit of the ASM to each of the CPUE series used in the baseline run. CPUE 1: VIMS LL series, CPUE 2: LPS series, CPUE 3: BLLOP series, CPUE 4: CFL time series.

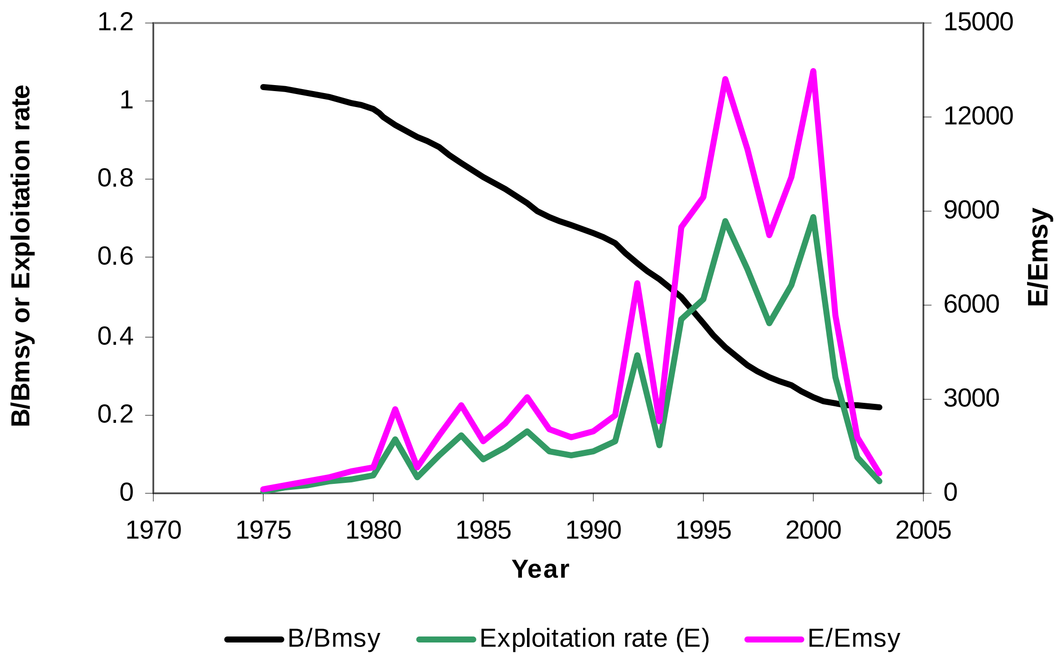


Figure 4.26. Relative biomass and exploitation trends for the base case scenario.

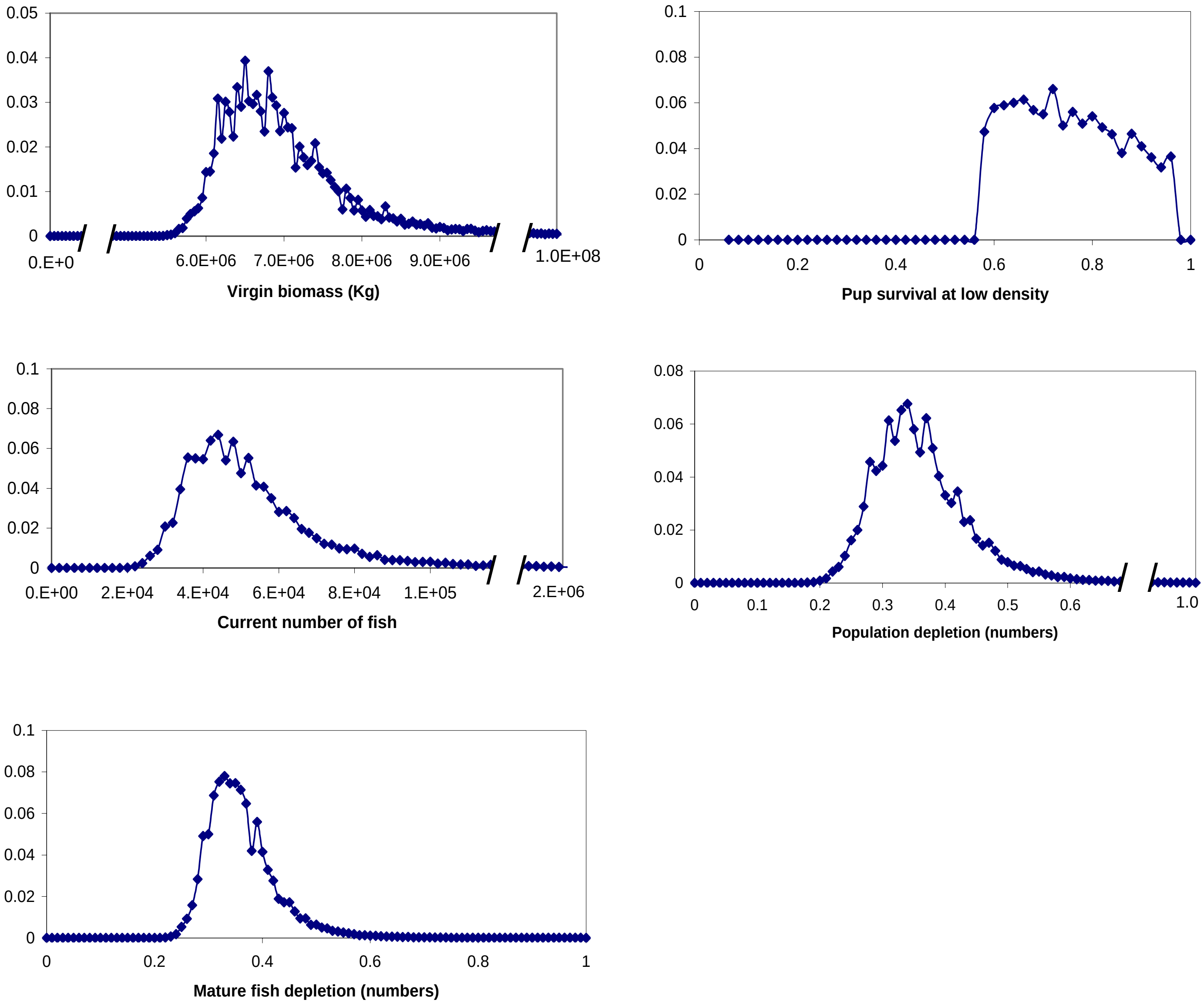


Figure 4.27. Marginal posterior pdfs of the estimated parameters for the baseline run with equal weighting in the ASM.

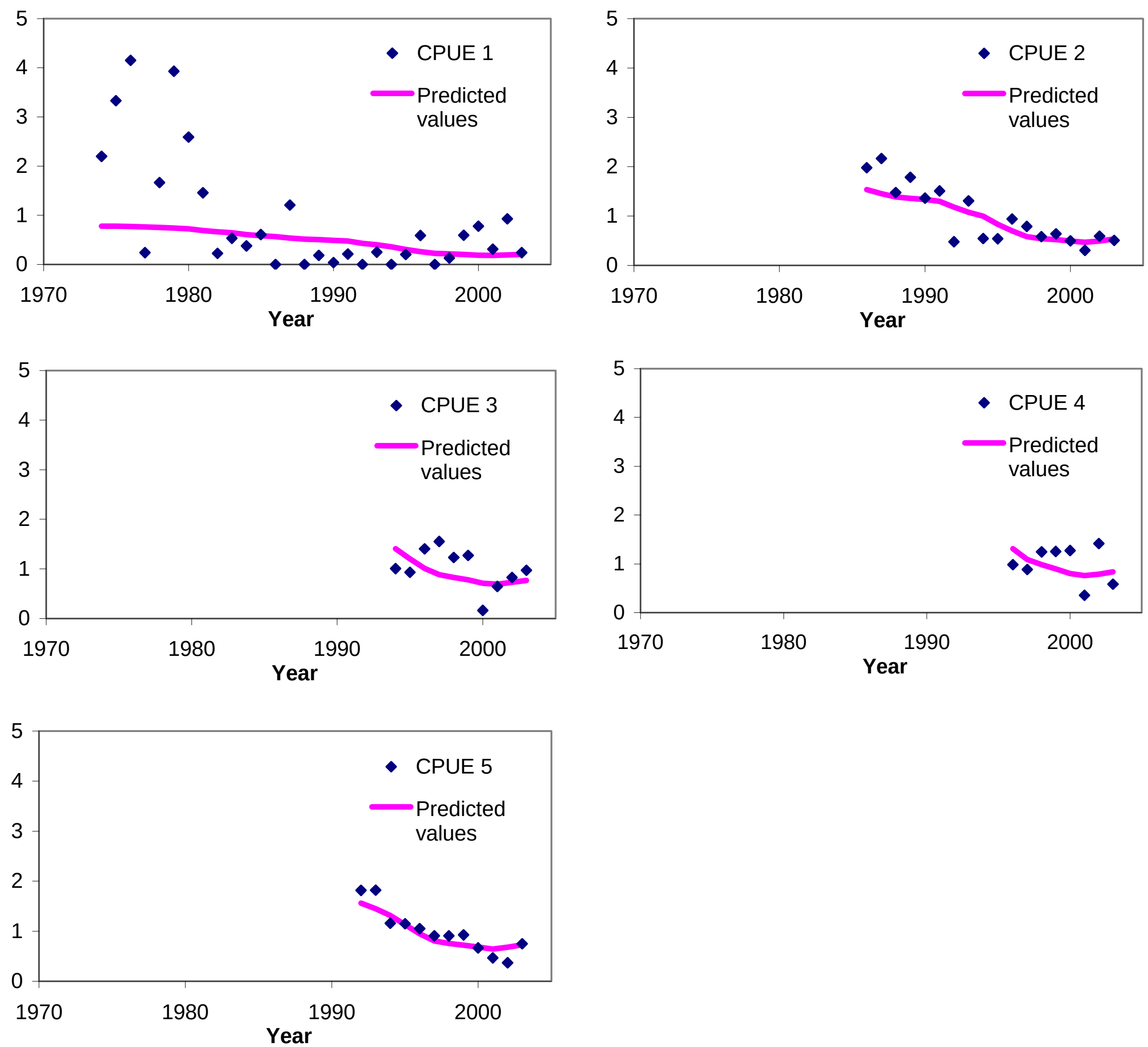


Figure 4.28. Model fit of the ASM to each of the CPUE series used in the baseline run with equal weighting. CPUE 1: VIMS LL series, CPUE 2: LPS series, CPUE 3: BLLOP series, CPUE 4: CFL series, CPUE 5: LPL series.

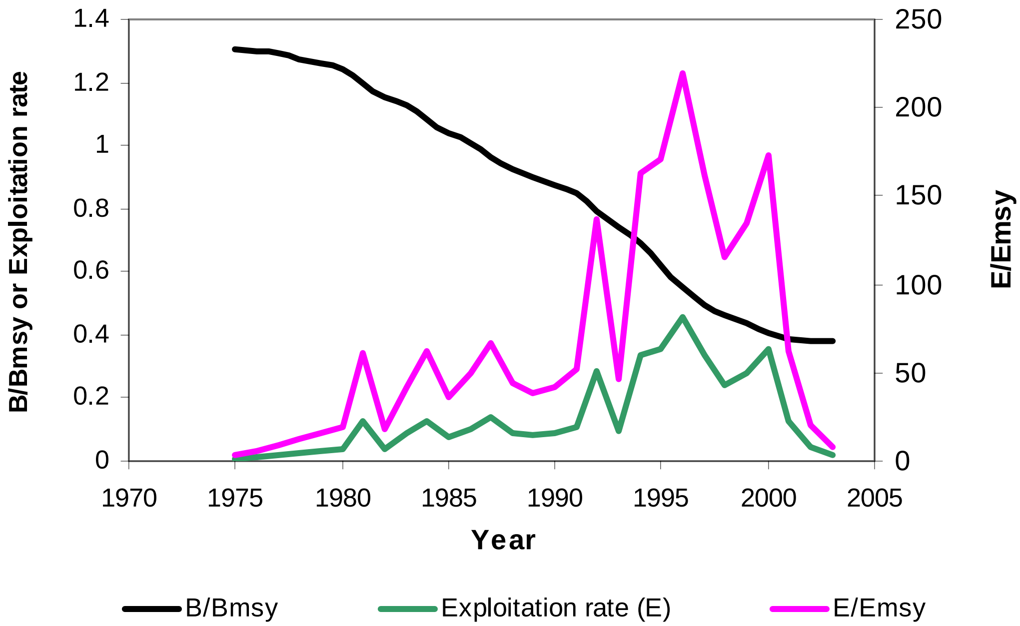


Figure 4.29. Relative biomass and exploitation trends for the base case with equal weighting run.

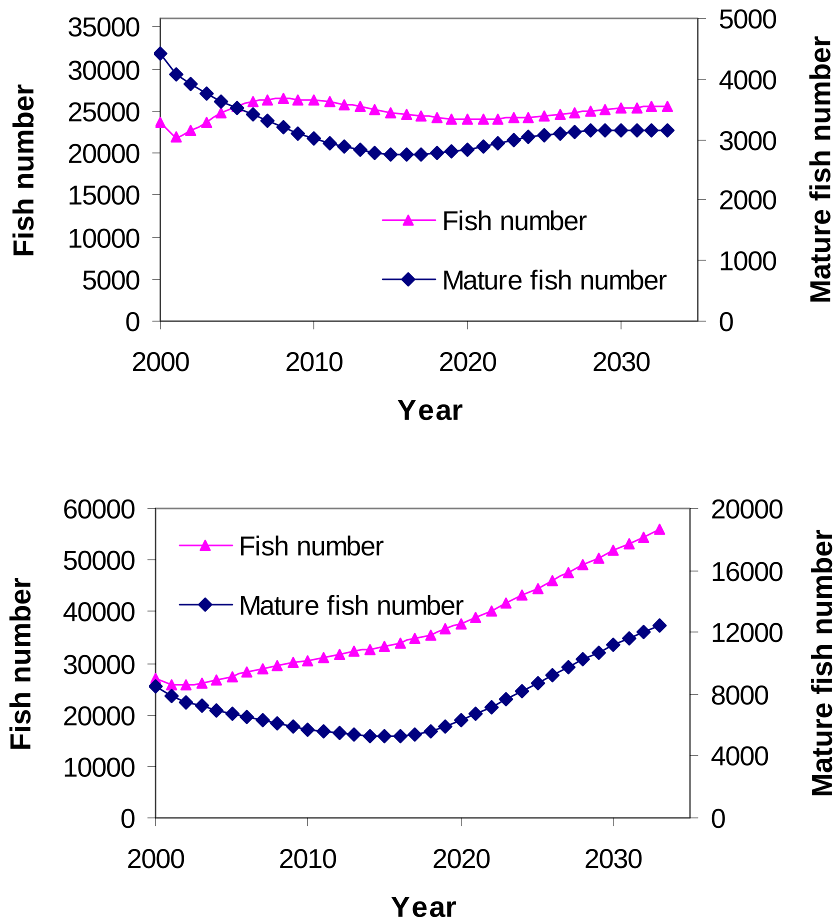


Figure 4.30. ASM results of the projections under two of the scenarios considered: a) base case scenario, b) low natural mortality scenario. These two scenarios yielded the most pessimistic and more optimistic results, respectively. The results are shown for the values of the estimated parameters at the mode of the joint posterior pdf.