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Providing Advice for the Sustainable Exploitation of the Sandbar Shark (*Carcharhinus plumbeus*) off the U.S. East Coast. Application of a Fleet-disaggregated, Age-structured Model

(Elasmobranch Fisheries – Oral)

by

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Abstract

This paper presents a framework for the evaluation of the potential effects of different management measures on populations of large coastal sharks. A sex- and age-structured, fleet disaggregated population dynamics model is used to simulate the dynamics of the shark population and fisheries. Bayesian statistical methods are applied to fit the model to the data and deal with the uncertainty in the model parameters and assumptions.

Starting from the predictions of the model for the current status of the stock, the population is projected into the future under different assumptions for fisheries management. The management options considered are catch quota reduction for the whole fishery or for specific gears, minimum size restrictions and temporal closure of the fishery. The potential consequences of the different management measures with respect to the replacement yield are presented and the effectiveness and limitations of each measure are discussed. For illustration purposes the model is applied to data for sandbar shark (*Carcharhinus plumbeus*) from the U.S. east coast fishery.

Introduction

Advice for the management of shark species has mainly been based on results of demographic or surplus production models (Sminkey and Musick, 1996; Cortés, 1998; McAllister *et al*., 2001)(but see Punt and Walker, 1998 and Simpfendorfer *et al*., 2000 for examples of advice based on age-structured models). Such models require less biological and fisheries data than more sophisticated population dynamics models but cannot account for age-dependent factors that affect the dynamics of the species.

Modelling advice for the management of the large coastal sharks (LCS) in the U.S. east coast has also been based mainly on the predictions of simple population dynamics models. However, in November 2001, the independent review of the 1998 LCS stock assessment called for more refined data and analyses to be used for the stock assessment of large coastal shark populations (NOAA, 2001). In their reports, independent reviewers recommended the development of an age-structured model for the stock assessment of large coastal shark species and encouraged the consideration of conventional and some alternative management measures such as temporal and spatial closures.

This paper presents an age- and sex-structured, fleet disaggregated population dynamics model that accounts for specific characteristics of shark biology and fisheries. Bayesian methods are being used to tackle the uncertainty in the choice of appropriate population dynamics model structure and model parameters. The methodology is applied to the fishery for sandbar shark, *Carcharhinus plumbeus*, off the U.S. east coast and estimates of key biological parameters and the current status of the population are provided. Based on the outcome of the analysis for the current status of the stock, the model evaluates the potential commercial effects of conventional and alternative management measures.

Materials and Methods

Population dynamics model

A fleet disaggregated, age-structured model is used for the simulation of fish population dynamics. Annual steps are used for the calculations and the values of the variables of interest are calculated at the beginning of each year except for the variables characterising fish exploitation. These latter values are calculated twice each year since it has been assumed that the fishery takes place in two discrete fishing periods.

If the number of fish from each group that are caught or die from natural reasons in a year, *t*, is known, then the number of fish of age, *a*, and sex, *g* at the end of this year, $N^{e}_{g,t,a}$ would be:

$$(1) \qquad N^{e}_{g,t,a} = \begin{cases} (f_g \cdot N_{0,t} \cdot S_a^{1/4} - C^{(2)}_{g,t,a}) S_a^{1/4} & a = 0, \\ [(N^{b}_{g,t,a-1} \cdot S_{a-1}^{1/4} - C^{(1)}_{g,t,a-1}) S_{a-1}^{1/4} \cdot S_a^{1/4} - C^{(2)}_{g,t,a}] \cdot S_a^{1/4} & a \geq 1 \\ \{[(N^{b}_{g,t,a_{\max}-1,} \cdot S^{1/4}_{a_{\max}-1} - C^{(1)}_{g,t,a_{\max}-1}) \cdot S^{1/4}_{a_{\max}-1} + & a = a_{\max} \\ (N^{b}_{g,t,a_{\max},} \cdot S^{1/4}_{a_{\max}} - C^{(1)}_{g,t,a_{\max}}) \cdot S^{1/4}_{a_{\max}}] \cdot S^{1/4}_{a_{\max}} - C^{(2)}_{g,t,a_{\max}} \} \cdot S^{1/4}_{a_{\max}} & \end{cases}$$

where S_a is the survival at age a from natural causes of death, $N_{0,t}$ is the number of pups at time t and f_g is the fraction of pups of sex g. It is assumed that pups are vulnerable to fishing and that the survival per year of fish in age class, a, S_a, is constant. Catches of fish of age a and sex, g, during the first and second half of the year, $C^{(1)}_{g,t,a,}, C^{(2)}_{g,t,a}$, respectively, are taken in a pulse in the middle of each fishing period after the population has experienced natural mortality for half of the fishing period. The number of fish caught during the first fishing season of each year with gear, *j*, $C^{(1)}_{g,t,a,j}$, is calculated as follows (Punt and Walker, 1998):

$$(2) \qquad C^{(1)}_{g,t,a,j} = (N^{b}_{g,t,a} \cdot S_a^{1/4} - \sum_{j'}^{j-1} C^{(1)}_{g,t,a,j'}) \cdot v_{g,a+0.5,j} \cdot u^{(1)}_{t,j},$$

where $v_{g,a,j}$ denotes fish vulnerability to gear *j* at age *a*, and $u_{t,j}$ is the exploitation rate per gear, *j*, at time, *t*. The assumption underlying this equation is that fishing using different gears is a successive process such that, at any given time fish are caught with only one gear. If the catch per fishing period and gear, are known then the exploitation rate for the first fishing period, $u^{(1)}_{t,j}$ is (Punt and Walker, 1998):

(3) $$u^{(1)}_{t,j} = \frac{C^{(1)}_{t,j}}{\sum_{g} \sum_{a=0}^{a_{\max}} w_{g,a+0.75} \cdot v_{g,a+0.75,j} \cdot \left[N^{b}_{g,t,a} \cdot S_a^{1/4} - \sum_{j'=1}^{j-1} C^{(1)}_{g,t,a,j} \right]}$$

In the above equation, catch per fishing period is assumed to be in biomass units and therefore, the weight of fish, $w_{g,a}$, is needed to calculate the exploitation rate. If the catch data are given in numbers of fish, then we do not need to multiply by fish weight. The weight of fish in age class, a, used for the calculations is equal to the weight of fish at age $a + 0.75$ for the first period and of age $a + 0.25$ for the second period of each year since it has been assumed that pups are born in the middle of the year. Fish weight at age a, is expressed as a function of fish length, $L_{g,a}$:

(4) $$w_{g,a} = d_g (L_{g,a})^{b_g} ,$$

where d_g and b_g are constants and fish length at age is described by the von Bertalanffy growth equation (VBGE):

(5) $$L_{g,a} = L_{\infty,g} \cdot (1 - e^{-k_g (a - t_{o,g})}) ,$$

where $L_{\infty,g}$ is the theoretical maximum asymptotic length of fish of sex g, and k_g , $t_{o,g}$ are constants.

The exploitation rate per gear for the second fishing period of a year is calculated in a similar way. However, the number of fish at the beginning of the second season is equal to $N^{b}_{g,t,a,r}$ minus the fish that die due to natural and fishing mortality during the first fishing period of the same year.

If the number of fish at age, a, that are caught in each fishery at time period, t, is known then the exploitable fish biomass/number per gear can be calculated. The exploitable number of fish for the first period of a year is:

(6) $$N^{\mathrm{expl}}_{t,j} = \sum_{g=1}^{2} \sum_{a=0}^{a_{\max}} (N^{b}_{g,t,a} \cdot S_a^{1/4} - \sum_{j'}^{j-1} C^{(1)}_{g,t,a,j'} - \frac{C^{(1)}_{g,t,a,j}}{2}) \cdot v_{g,a+0.75,j}$$

The exploitable fish biomass is found by incorporating the weight at age into the above equation. The exploitable fish biomass or number for the second period of the year is calculated in a similar way. The exploitable biomass or number of fish per gear for each year is taken as the mean of the corresponding value for the first and second period of a year.

The total number of female fish is equal to the sum of the females that give birth in year, t, (group p) and the females that are either immature or are mature but are not pregnant at the beginning of time, t, (group r):

(7) $$N^{e}_{g=fem,t,a} = N^{e,p}_{g=fem,t,a} + N^{e,r}_{g=fem,t}$$

The mature females in the latter group are supposed to give birth in the following year. The number of females that are pregnant at the beginning of each year is assumed to be equal to 50% of the total number of mature females.

The number of pups born each year is calculated as the product of pregnant females of age, a, $N^{b,p.}_{g=fem,t,a}$, times the fecundity per age. We assume that pupping is a biannual process. The number of pups that are born in year *t* depends on the fraction of pregnant females at the beginning of year *t* that survive to give birth in the middle of the year:

$$(8) \qquad N_{0,t} = \sum_{a=1}^{a_{\max}} \left(N^{b,p.}_{g=fem,t,a} S_a^{1/4} - \frac{N^{b,p.}_{g=fem,t,a}}{N^{b}_{g=fem,t,a}} C^{(1)}_{g=fem,t,a}\right) \cdot S_a^{1/4} \cdot \overline{\Phi}_a$$

where $\overline{\Phi}_a$ is the number of pups per pregnant female of age a. Pups survival, S_0, is calculated using the Beverton-Holt (Beverton and Holt, 1957) stock-recruitment function.

If y_1 is the year when exploitation of the stock started, then we can calculate the number of fish at the beginning of this year assuming that the population is equal to the virgin population. If catch series that extend back to y_1 are not available we can treat the mean catch during the years for which no data are available as an uncertain random parameter (McAllister *et al.*, 2001). If the number of pups under virgin conditions is N_{0,y_1}, then the total number of fish in each age-class at the beginning of year y_1 is:

$$(9) \qquad N_{g,y_1,a} = \begin{cases} f_g \cdot N_{0,y_1} \cdot S_a^{1/2} & a = 0 \\ f_g \cdot N_{0,y_1} \cdot \prod_{a'=0}^{a-1} S_{a'} \cdot S_a^{1/2} & 0 < a \le a_{\max} - 1 \\ f_g \cdot N_{0,y_1} \cdot \dfrac{\prod_{a'=1}^{a_{\max}-1} S_{a'}}{1 - S_{a_{\max}}} \cdot S_{a_{\max}}^{1/2} & a = a_{\max} \end{cases}$$

where the number of pups under virgin conditions can be calculated if the biomass of fish under virgin conditions, B_o, is known:

$$(10) \quad N_{0,t} = \frac{B_o}{\sum_g f_g \left[w_{g,0.5} + \sum_{a=1}^{a_{\max}-1} w_{g,a} \prod_{a'=1}^{a-1} S_{a'} + w_{g,a_{\max}} \dfrac{\prod_{a'=1}^{a_{\max}-1} S_{a'}}{1 - S_{a_{\max}}} \right]}$$

If the biomass of mature fish under virgin conditions is used instead of the total virgin biomass the summation over age in the above equations must start from the age at maturity.

Statistical framework

The assumptions used for the catch in the period from y_1 until the earliest year for which catch data were available was that the catches during this period (historical catches) remained constant. The parameters virgin biomass, B_o, pup survival at low densities, A, and historical catches for commercial and recreational fisheries C_{his}^{rec}, C_{his}^{com} were estimated parameters. Furthermore, the constants of proportionality, $q_{j,k}$, and the variance, $s_{j,k}$, for each relative abundance series k that corresponds to gear j, were also estimated.

Bayesian statistical methods were used to fit the model to the data and estimate the above parameters. Prior distributions were constructed for each of the uncertain parameters; uninformative priors were used for the parameters for which no information was available.

If $p(q_n)$ is the joint prior probability density function for a set of values of the estimated parameters, q_n, then the value for the posterior probability density function for this set of values, given the data, I, is:

$$p(q_n \mid \mathrm{I}) \propto p(q_n)L(I \mid q_n), \tag{11}$$

where $L(I \mid q_n)$ is the likelihood function of the datafor this set of values of the uncertain parameters of the model. It is assumed that all the observations are independent and that the observed values from each abundance series, $I_{j,k,t}$, are log-normally distributed about the corresponding value predicted by the model, $q_{j,k}B_{j,k,t}$:

$$I_{j,k,t} \sim \log normal(q_{j,k} N_{j,t}^{\mathrm{exp}l}, s_{j,k}{}^2) \tag{12}$$

$N_{j,t}^{\mathrm{exp}l}$ denotes the annual exploitable number of fish that corresponds to observation $I_{j,k,t}$, $q_{j,k}$ is the constant of proportionality for the series, k, that comes from fishery j and $s_{j,k}$ is the lognormal standard deviation for residual errors between the observed and predicted values for each series of relative fish abundance. The equal weight method is used to weight the points of each of the relative abundance series. The loglikelihood function of the data for one potential set of values for the uncertain parameters of the model, q_k, is (McAllister and Kirkwood, 1998, McAllister *et al*., 2001):

$$\ln L(I \mid q_n) = \sum_j \sum_t -\frac{1}{2s_{j,k}{}^2}\left(\ln \frac{I_{j,k,t}}{q_{j,k} B_{j,t,k}^{\mathrm{exp}l}}\right)^2 - \ln(s_{j,k}) - \ln(I_{j,k,t}) - \frac{1}{2}\ln(2p) \tag{13}$$

An alternative weighting method such as the inverse variance weighting method could also be used which would allow for the annual estimate of the CV's for sampling error for each of the relative abundance series to be taken into account.

Parameter values and assumptions

The values of the fixed parameters of the model for sandbar shark are shown in Table 1 and Figure 1. It has been assumed that pupping is a biannual process (50% of the mature fish give birth in a given year and the rest of the mature fish give birth in the following year) and takes place in the middle of each year (Merson and Pratt, 2001). The gestation period was assumed to last approximately a year (Smith *et al*., 1998; Sminkey and Musick, 1996). Catch data from 1981 to 2001 and various fishery dependent and independent relative abundance indices (NMFS 1998 and 2002) were used while 1965 was assumed to be the first year of exploitation. Since there were no catch data for the recreational and commercial fisheries that operated in U.S. waters during the period 1965-1981, catches for the recreational and commercial fleets over this period were assumed to be constant and treated as estimated parameters.

Due to lack of information, non-informative priors were used for $s_{j,k,t}$ and $q_{j,k}$. Informative prior were used for pups survival (~lognormal [0.6, 0.3]), virgin biomass ($\log(B_o) \sim U[\log(10^6\mathrm{Kg}), \log(4\times10^8\mathrm{K})]$) and historical catches ($C_{his}^{com} \sim$ Lognormal[50000, 0.5^2], $C_{his}^{rec} \sim$ Lognormal[40000, 0.5^2].

Estimation of the posterior distribution

We approximated the posterior joint probability distribution of the estimated parameters using the SIR (sampling/importance resampling) algorithm (McAllister and Ianelli, 1997; McAllister and Kirkwood, 1998). After the importance draws had reached convergence according to the maximum weight and CV(weight)/CV(likelihood*priors) criteria, we used importance resampling to subsample 5000 draws. These draws were used to calculate the marginal posterior probability distributions, mode and mean values and CV's for parameters of interest such as current size of stock relative to the virgin one, pup survival at low density and historical catches.

Harvest strategies

Using the results of the model for the current status of the stock and the predicted values of the estimated parameters we projected the population into the future under different management options.

The management options considered were the following.

1. *No fishing mortality*

The population was projected in the future assuming that no fishing was taking place. The number of fish in each age class in 2001 for the set of values of the estimated parameters chosen had been calculated and the model was run using these values as starting values while catch was assumed to be equal to zero. The run for all the scenarios presented below also projects the population in the future starting from 2001.

2. 1999 FMP for catches in number.

Commercial TAC = 78% of 1997 commercial harvest in numbers = 32,304 sharks

Recreational TAC = 18% of 1997 recreational harvest in numbers = 7,491

According to the decision analysis in the 1999 HMS FMP (NMFS 1999, chapter 3, page 67), sandbar mortality should be cut by 82% in numbers for the recreational fishery, and by 22 % (numbers) or 8% (weight) for the commercial fishery from the 1997 harvest levels.

3. Recreational fishery vs commercial fishery

a. Only the recreational fishery is allowed to operate. Total catch in numbers is equal to the maximum number of fish that can be caught without causing reduction in the current size of the population.

b. Only the commercial fishery is allowed to operate. Total catch in numbers is equal to the maximum number of fish that can be caught without causing reduction in the current size of the population

4. Minimum and/or maximum size restrictions.

a. Fish smaller than 90 cm fork length could not be caught. b. Immature fish could not be caught (<105 cm fork length). c. Fish bigger than 200 cm fork length could not be caught.

The number of fish that could be caught without causing further decrease in the size of the stock is calculated. To find the maximum catch that fulfilled these requirements when both the commercial and recreational fishery are allowed to operate we assume that the catch from the commercial fishery are much greater than the catch from the recreational fishery. The ratio of the commercial catches to recreational catches is assumed to be equal to 1:5 which is similar to the ratio of the recreational catch to the commercial catch under the 1999 FMP for catches.

5. Temporal closure of the fishery

Commercial and/or recreational fishery is allowed to operate only in certain periods of the year. Combinations of temporal closure with other measures such as size restrictions are also considered. The same ratio of the commercial to the recreational catches as the one given above was used.

Results

The results of the model for the current status of the stock were characterised by high uncertainty which was, partly, due to the limited information in the catch and relative abundance data that were used. The predictions of the model that corresponded to the mode of the likelihood function showed that the population in numbers has decreased to 40% of the population under virgin conditions while the decrease in number of mature fish is even greater (Fig. 2, Table 2). According to the mean values of the estimated parameters though, the current size of the population was approximately equal to 60% of the size of the population under virgin conditions. Utilisation of more detailed abundance indices, (i.e. different indices for different age groups (NMFS, 2002)) and a more accurate estimation of the catch data could improve the accuracy of the model predictions.

The modal values of the estimated parameters were used as input for the deterministic projection part of the calculations. The model was run for 50 years starting fom 2001 under different assumptions for fisheries management. Although decision analysis could be done in this modelling framework, it was decided that, as a first step, the results of the deterministic projections could be used for comparing management strategies.

The model was originally run without any future exploitation to evaluate the rate of recovery of the population (Table 3). Under the no fishing assumption the population became equal to 48% of the virgin population in numbers by 2050 (50% in mature fish number), showing an increase of approximately 20%. However, the predictions showed that the population would go commercially extinct in less than 25 years under the current catches scenario. Similar results were obtained under the 1999 FMP scenario for catches.

To evaluate the effects of the selectivity of each gear used by the different fisheries (commercial, recreational) (Fig. 1) we ran the model for each of the fisheries, separately. The population was projected in the future assuming that only recreational fishery would operate and the reduction in the total catch in numbers relative to the current catch which was required to sustain the population at its current size was calculated (Table 3). The model was run again assuming that only the commercial fishery was allowed to operate and the replacement yield in numbers, C_{com}^{ref}, for the current size of the population, which is the yield that can be taken without affecting the current size of the population, was calculated (Table 3). The results showed that the catch in numbers that was sustainable when only the recreational fishery operated could not be sustained by the population when only the commercial fishery was allowed to operate.

Since the recreational fishery exploits young fish while the commercial fishery targets mainly larger fish these results imply that the population is more sensitive to removals of large immature and mature fish than to the removal of smaller immature fish.

The replacement yield at the current population size when the commercial only fishery was assumed to operate was much smaller than the current catches (11%) (Table 3). Using this value for the replacement yield in numbers, C_{com}^{ref}, and in biomass, Y_{com}^{ref}, as a reference point we investigated whether an increase in the replacement yield in numbers and/or biomass, would be possible under different management measures. The management measures considered were minimum and maximum size restrictions, change in selectivity and temporal closure of the fishery (Table 4).

As mentioned above, the replacement yield in numbers at the current size of the population was greater for the recreational than the commercial fishery (Table 3). However, the replacement yield in biomass for the recreational only fishery was less than the replacement biomass yield for the commercial only fishery.

In order to ensure that enough fish would reach the age at maturity, one of the management measures applied did not allow any fishing for immature fish (length < 105 cm FL). Under this assumption the replacement yield, when the commercial only fishery operated, was 38% smaller than the C_{com}^{ref}. The replacement yield in biomass presented an increase of 21% relative to the reference yield, Y_{com}^{ref}, since the weight of fish caught in this case was greater than the weight of fish caught when the whole population could be exploited. When both commercial and recreational fishery were allowed to operate but there were minimum and maximum size restrictions the replacement yield in numbers increased relative to the reference one but the replacement biomass yield declined to 87% of the reference replacement biomass yield, Y_{com}^{ref}. The replacement yield in both numbers and biomass were greater than the reference ones when temporal closures of the fisheries were introduced. The replacement biomass yield (commercial + recreational) became equal to Y_{com}^{ref} when the commercial fishery was allowed to operate only in the second half of the year and the recreational could operate the whole year round but with minimum size restriction. The value of the replacement biomass yield increased by 3% relative to the reference value when a temporal closure for the recreational fishery was also introduced (no size restrictions for any of the fisheries). The increase in the replacement catch in numbers relative to the reference value was 7% and 16 %, respectively.

Since, the values that each of the estimated parameters could take varied considerably, the projections were repeated using the mean instead of the modal values of the estimated parameters. The number of fish that could be caught by the commercial fishery without causing any decrease in the current size of the population (replacement yield in numbers) was approximately 16000 fish (replacement yield in biomass:Y_{com}^{ref}~$5\text{x}10^5$Kg). This is less than one third of the number of fish caught by the commercial fishery in 2001. The predictions of the model regarding the current status of the stock that corresponded to the mean values of the estimated parameters showed that the current status of the stock is less depleted than in the previous case (Table 2). Nevertheless, the projections showed that the population could not sustain the current level of exploitation. The results of the projections using the mean values of the estimated parameters are shown in Table 5.

The results of the projections for each set of input parameters (mean and modal values of the estimated parameters) were compared to each other to evaluate the sensitivity of the model predictions to the choice of the values of the estimated parameters. Although the quantitative results of the projections for the two different set of values presented some differences, the qualitative predictions of the model were not affected by the change in the values of the estimated parameters.

Discussion

Although it is difficult to derive conclusion about the status of the stock due to the considerable uncertainty in the model predictions, it is unlikely that the current levels of exploitation are sustainable. The uncertainty in the model predictions could be reduced if more informative exploitation and abundance data are used. The choice of the weighting method applied is also a source of uncertainty. Equal weighting was used for the calculations described here, however, other methods could also be applied to evaluate the sensitivity of the model predictions to the weighting method used.

The replacement yield in numbers and biomass depended on the measures applied for the management of the shark fishery. Some management measures resulted in an increase in the number of fish caught and some in an increase in the yield biomass. Thus, it is important to provide catch in both biomass and number of fish to describe the exploitation of the stock. Furthermore, in such cases, the evaluation of the potential financial benefits of each management option would be necessary for the adoption of the most effective measure. Nevertheless, measures that allowed for part of the population to be protected from fishing during some periods of the year such as temporal fishery closures resulted in an increase in the replacement yield in both numbers and biomass. Such measures could be more appropriate for the management of species of low productivity like sandbar shark than conventional measures such as catch reduction. The enforcement of temporal fishery closures may also be easier than the enforcement of measures such as size restrictions.

The population seems to be more sensitive to removals of mature individuals than to removals of young fish. A reason for this is because the survival of older fish is greater than the survival of young fish and therefore, the removal of young fish has a smaller impact on the size of the population since a proportion of the fish caught would die from natural causes. The replacement yield in numbers predicted when selectivity for mature fish was used was smaller than the replacement yield when immature fish were mainly targeted but the replacement biomass yield was greater in the former case. Thus, the assumptions for the selectivity used could influence, considerably the predictions of the model about key parameters such as MSY which are often used to set the catch quota for a fishery and evaluate the rebuilding potential of a population.

The modelling framework presented here requires more information than the frameworks currently used to provide advice for the management of many shark species. However, it allows for the simulation of age-dependent processes and can be used to test a great variety of management options such as size limits, gear restrictions and partial protection of certain age-classes. Furthermore, many shark species have biological characteristics similar to those of the sandbar shark. Thus, this framework could also be extended to evaluate the potential effects of different management options on the population of other shark species.

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References

BARROWMAN, N.J. and R.A. Myers. 2000. Still more spawner-recruitment curves: the hockey stick and its generalizations. Can. J. Fish. Aquat. Sci. 57; pp. 665-676

BEVERTON, R. J. and S. J. Holt. 1957. On the Dynamics of Exploited Fish Population. Her Majesty's Stationary Office,

BREWSTER-GEISZ K. J. and Miller T. J. 2000. "Management of the sandbar shark, Carcharhinus plumpeus: implications of a stage-based model." Fishery Bulletin 98: 236-249.

CASEY, J. G. and L. J. Natanson. 1992. Revised estimates of age and growth of the sandbar shark (*Carcharhinus plumbeus*) from the western North Atlantic. Can. J. Fish. Aquat. Sci. 49: 1474- 1477.

CORTÉS, E. 1998. Demographic analysis as an aid in shark stock assessment and management. Fisheries research 39; pp. 199-208

MCALLISTER, M. K., E. K. Pikitch and E. A. Babcock. 2001. Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. Can. J. Fish. Aquat. Sci 58; pp. 1871–1890

MCALLISTER, M. K. and G. P. Kirkwood. 1998. Bayesian stock assessment: a review and example application using the logistic model. ICES J. Mar. Sci. 55; pp. 1031-1060

MCALLISTER. M. K. and J. N. Ianelli. 1997. Bayesian stock assessment using catch-age data and the Sampling/Importance Resampling Algorithm. Can. J. Fish. Aquat. Sci. 54; pp. 284–300.

NMFS. 1999. Final Fishery Management Plan For Atlantic Tuna, Swordfish, and Sharks. April 1999. Highly Migratory Species Management Division, Office of Sustainable Fisheries, National Marine Fisheries Service Silver Spring, Maryland

NMFS (National Marine Fisheries Service). 1998. Report of the Shark Evaluation Workshop. National Oceanic and Atmospheric Association. National Marine Fisheries Service. Southeast Fisheries Science Center. 3500 Delwood Beach Road. Panama City, FL 32408.

NMFS (National Marine Fisheries Service). 2002. Report of the Shark Evaluation Workshop. National Oceanic and Atmospheric Association. National Marine Fisheries Service. Southeast Fisheries Science Center. 3500 Delwood Beach Road. Panama City, FL 32408.

NOAA 2001, http://www.publicaffairs.noaa.gov/releases2001/nov01/noaa01110.html. *last accessed*: 15/8/02

PUNT, A., E., and T. I. Walker. 1998. Stock assessment and risk analysis for the school shark (*Galeorhinus galeus*) off southern Australia. Mar. Freshwater Res. 49; pp. 719-31

RICKER, W. E. 1954. Stock and recruitment. J. Fish. Res. Board Can. 11; pp. 559-623

RUND MERSON, R. and H. L. Pratt, Jr. 2001. Distribution, movemnets and growth of young sandbar sharks, *Carcharhinus plumbeus*, in the nursery grounds of Delaware Bay.

SIMPFENDORFER, C. A., Donohue, K. and Hall, N. G. 2000. Stock assessment and risk analysis for the wiskery shark (furgaleus macki (Whiley)) in south-western Australia. Fisheries research 47: 1-17

SMINKEY, T. R., and J. A. Musick. 1996. Demographic analysis of the sandbar shark, *Carcharhinus plumbeus*, in the western North Atlantic. Fish. Bul. 94; pp. 341-347

SMINKEY, T. R., and J. A. Musick. 1995. Age and growth of the sandbar shark, *Carcharhinus plumbeus*, before and after population depletion. Copeia 4: 871-885

SMITH, S., E., D. W. Au. and C. Show. 1998. Intrinsic rebound potentials of 26 species of Pacific sharks. Mar. Freshwater Res. 49; pp. 663-78

SPRINGER, S. 1960. Natural History of the Sandbar Shark *Eulamia milberti*. Fishery Bulletin 61: 1-36.

Table 1. Values of input parameters for sandbar shark (*Carcharhinus plumbeus*).

Parameter	**Value**	**Source**
a_{mat}	14,years, females 13 years, males	Sminkey and Musick, 1995 Smith *et al.*, 1998
a_{max}	35 years	
b_g	3.0124 g=1, 2	
d_g	1.0885×10^{-5} Kg	
f_1, f_2	0.5	Sminkey and Musick (1996)
k	0.059, fem. & males	Sminkey and Musick, 1995
L_∞	197 cm, females 184 cm, males	Sminkey and Musick, 1995
S_a	0.72, a=1 0.77, a=2 0.80, a=3 0.82, a=4 0.85, 4< a <10 0.9, a >= 10	Cortés, 1998
t_o	-4.8, females -5.4, males	Sminkey and Musick, 1995
$\overline{\Phi}_a$	9 pups	Springer 1960, Sminkey and Musick, 1996
Φ_a	0.5 for a = a_{mat}, 1 for a > a_{mat}	Brewster-Geisz *et al.*, 2000

Relationships between fork length (FL) and total length (TL), and between precaudal length (PCL) and total length (TL) used:
TL=1.34PCL-0.64 (Sminkey and Musick, 1995)
FL=0.8265TL+1.3774 (Casey and Natanson, 1992)

Table 2. Summary statistics for the ratio of SSB in 2001 to SSB under virgin conditions, ratio of total number of fish in 2001 to the number of fish under virgin conditions, ratio of historic catches in the U.S. commercial and recreational fishery to the corresponding catches in 2001, and pup survival at low population sizes.

	rSSB	**rN_{tot}**	**$rC_{0(com)}$**	**$rC_{0(rec)}$**	**S_{pups}**
Mode	0.36	0.40	0.26	0.32	0.56
Mean	0.60	0.63	0.86	0.89	0.58
Median	0.66	0.69	0.59	0.69	0.58
Standard Deviation	0.17	0.17	0.68	0.84	0.07
CV	0.29	0.27	0.86	0.90	0.12

Table 3. Future status of the stock expressed as the ratios of the mature fish and total fish in the future to the mature fish under virgin conditions and total fish under virgin condition, respectively. Catch is given as the ratio of the predicted catch in 2050 to the total catch in 2001 (biomass and numbers) under different harvest strategies. The modal values of the estimated parameters have been used for the calculations.

Harvest	rN_{mat}	rN_{tot}	$rC_{0(com)}$		$rC_{0(rec)}$	
			Number	***Biomass***	***Number***	***Biomass***
No fishing	0.48	0.5	-		-	
Status quo	Depletion (2024)		-		-	
1999 FMP for catches (in numbers)	Depletion (2042)		-		-	
Rec. fishery only. Replacement yield in numbers (at current population size): 20000 fish	0.42	0.40	-		0.21	0.08
Commercial fishery only. Replacement yield (at current population size): 6500 fish	0.39	0.41	0.07	0.10	-	-

Table 4. Future status of the stock, expressed as the ratios of the mature fish and total fish in the future to the mature fish under virgin conditions and total fish under virgin condition, respectively. Catch under different harvest options is given as percentage of the replacement yield in numbers and biomass at the current size of the population when only the commercial fishery operates (see Table 3). The modal values of the estimated parameters have been used for the calculations.

Harvest	rN_{mat}	rN_{tot}	$rC_{0(com)}$		$rC_{0(rec)}$	
			Number	***Biomass***	***Number***	***Biomass***
Fishery for mature fish only	0.39	0.41	62%	121%	-	-
Com + rec. fishery. Size limit for very small + big fish	0.39	0.41	100%	75%	23%	12%
Temporal closure for com. fishery. Minimum size limit for rec.	0.39	0.41	92%	90%	15%	8%
Temporal closure for com and rec. fishery. No size limits	0.39	0.41	100%	98%	16%	5%

Table 5. Future status of the stock, expressed as the ratios of the mature fish and total fish in the future to the mature fish under virgin conditions and total fish under virgin condition, respectively. Catch under different harvest options is given as percentage of the replacement yield in numbers (16419 fish) and biomass (500645 kg) at the current size of the population when only the commercial fishery operates. The mean values of the estimated parameters have been used for the calculations.

Harvest	**rN_{mat}**	**rN_{tot}**	**$rC_{0(com)}$**		**$rC_{0(rec)}$**	
			Number	***Biomass***	***Number***	***Biomass***
Fishery for mature fish only	0.66	0.69	67%	110%	-	-
Com + rec. fishery. Size limit for very small + big fish	0.66	0.69	91%	68%	20%	23%
Temporal closure for com. fishery. Minimum size limit for rec.	0.66	0.69	87%	85%	18%	20%
Temporal closure for com and rec. fishery. No size limits	0.66	0.69	98%	96%	18%	5%

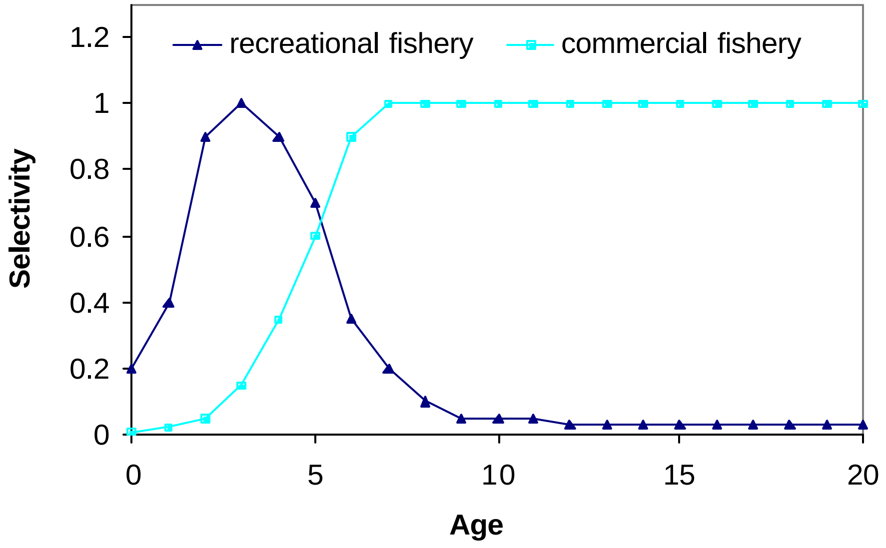

Fig. 1. The selectivity of the gears used by the commercial and recreational fishery.

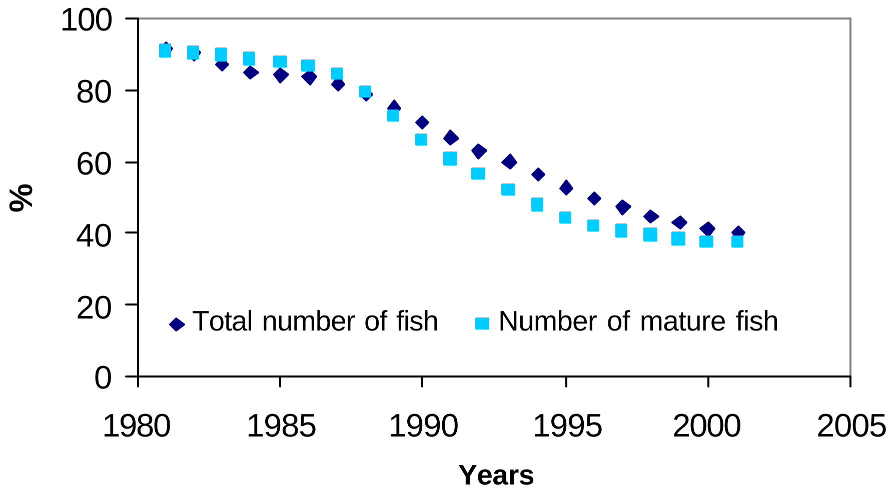

Fig. 2. Change in the total number of fish and number of mature fish over the years. Values are given as a percentage of the corresponding values under virgin conditions

Appendix 1

Parameters and variables of the model

A	pups survival at low densities
a	age
$\tilde{a}$	constant
B_o	virgin biomass
$C_{g,t,a}^{(1)}$	catch of fish during the first half of the year (2: second half of the year)
d_g, b_g	constants used in the weight function
d	constant of hockey stick stock-recruitment function
f_g	fraction of the total pups which are: females (g=1), males (g=2)
g	gender
j	gear
k_g , $t_{o,g}$	constants of the length at age function
$L_{\infty,g}$	the theoretical maximum asymptotic length of fish
$N_{g,t,a}^{e}$	number of fish of age, a, and sex, g, at the end of year t
$N_{g,t,a}^{b}$	number of fish of age, a, and sex, g, at the beginning of year t
$N_{t,j}^{\text{exp}l}$	exploitable number of fish for gear, j
$\overline{N}_0$	constant of the hockey stick model
$p(q_n)$	joint prior probability density function for a set of values of the estimated parameters, q_n
$q_{j,k}$	constant of proportionality for the CPUE series, k, that comes from fishery j
S_a	survival at age from natural causes of death
$s_{j,k}$	lognormal standard deviation for residual errors between the observed and predicted values for each series of relative fish abundance
t	time
$u_{t,j}$	exploitation rate per gear, j, at time, t
$v_{g,a,j}$	fish vulnerability to gear j at age a
y_1	year when the exploitation started
$w_{g,a}$	weight of fish
$\overline{\Phi}_a$	number of pups per pregnant female of age a