FIRST ESTIMATES OF THE STATUS OF SANDBAR SHARK STOCK OFF THE EASTERN COAST OF THE US

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Summary

Predictions about the current status of sandbar shark stock off the eastern coast of the US are presented in this document. An age-structured population dynamics model has been used as part of a Bayesian statistical framework to analyse CPUE series and catch data. The model was run under a base case scenario but sensitivity runs were also conducted to evaluate model sensitivity to assumptions about the value of parameters such as pup survival. The results show that the size of the stock has been reduced to less than 35% of its virgin size. This prediction remained the same under both the base case and sensitivity runs.

Methods and Data

An age-structured population dynamics model is used for the calculations and the uncertainty in model parameters and input data is taken into account using Bayesian statistical methods. The age-structured population dynamics model used in the analysis is described in Appendix 1. The catch and CPUE series used are shown in Tables 1 and 2, respectively. The values of the input parameters of the model are presented in Table 3. Four uncertain parameters were estimated in the analysis which are: Virgin population Biomass, Pup survival at low population densities, and commercial and recreational historical catches. The model assumes virgin conditions prior to 1975. The priors for the historical commercial and recreational catches are used to describe catches between 1975 and 1981. The priors used for the estimated input parameters are:

- Virgin Biomass: Uniform on log(B) in the range [10^5 Kg, 10^9 kg]
- Pup survival (base case): Lognormal (0.6, 0.29^2) in the range [0.3, 0.9]
- *Alternative pup survival*: Lognormal (1.47, 0.7^2) in the range [0.3, 0.99]

- Historical commercial catches: Normal (6000, 6000^2)
- Historical recreational catches: Normal (65960, 132000^2)

The constant of proportionality, $q_{j,k}$, and the lognormal standard deviation for residual errors between the observed and predicted values for each CPUE series, $\sigma_{j,k}$, are also uncertain parameters. Non-informative priors were used for those parameters.

The selectivities that characterise each of the catch and CPUE series are shown in Figure 1. It has been assumed that the selectivity that corresponds to commercial catches is the same as the one for unreported catches. Similarly, the selectivity that was used for recreational catch series was also used to describe the selectivity of the gears used in the Mexican fishery.

Runs

Case 1. *Base case*: The first 10 CPUE series shown in Table 2 were used for the base case run together with the catch data shown in Table 1. The base case prior for pup survival at low population density was used for this run. Also, equal weight was given to all CPUE series used.

Case 2. *Alternative pup survival*: As above, but with the alternative prior for the pup survival at low population densities instead of the base case one.

Case 3. *CPUE sensitivity run*: Same assumptions as in the base case run except that all the CPUE series shown in Table 2 are used.

Case 4. *Inverse CV weighting*. All the assumptions are the same as under the base case except the assumption about the weight assigned to each CPUE series. Inverse CV weighting is used to weight the CPUEs in this case.

Results

Base case run

The fit of the model to the CPUE series for the values of the estimated parameters at the mode of the joint posterior distribution is shown in Figure 2. The model follows well the changes in the longest CPUE series (CPUE series 3) but fails to replicate the rapid changes in stock abundance supported by some of the other CPUE series. The predictions of the model about the status of the stock and its original stock are given in Table 4. The model predicts that the population is below 35% (modal or mean value) of its original size regardless of whether the size is measured in biomass or number of fish. The mode of the posterior probability distribution function for historical catches is very similar to that of the priors used. However, the posterior for historical recreational catches is shifted more to the right that the corresponding prior. The marginal posterior probability distributions for some of the estimated parameters of the model are shown in Figure 3. The posterior distribution for pup survival at low population densities assigns probability to a very small range of values (0.8 – 0.9). The reason for that is that the steepness of the Beverton-Holt stock recruitment functions becomes smaller than 0.2 for values of pup survival smaller than 0.8.

Sensitivity runs

The model was also run under the alternative scenarios described above. The predictions of the model for each of the sensitivity runs (modal values) are shown in Table 5. The model predictions about pup survival were sensitive to the choice of prior for that parameter (Case 2). However, the predictions of the model about the status of the stock were not affected by the choice of prior pdf for pup survival. Under this scenario, the model converged to the smallest value of virgin stock size and the highest value of pup survival of those found under any of the cases examined.

The use of the alternative set of CPUEs gave the most pessimistic predictions about the status of the stock and also supported a higher value for historical commercial catches. Similarly to the first case considered (base case), the modal value of pup survival was the smallest one allowed. The use of inverse CV weighting to weight the CPUE series also resulted in similar results to those found under the base case scenario. However, under this scenario, the model did not converge to the minimum allowed value for pup survival as happen in the base case run.

Table 1. Catches of sandbar shark in number of fish.

Year	Commercial +Unreported	Recreational + Mexican	Menhaden
1981	6640	139160	696
1982	6640	45402	713
1983	7173	428112	705
1984	9797	69503	705
1985	9100	88083	635
1986	25826	134938	626
1987	73983	39625	653
1988	124680	76875	635
1989	160712	36950	670
1990	122440	69559	653
1991	96680	45857	505
1992	100592	46081	444
1993	71977	35870	452
1994	126454	23738	486
1995	84371	36188	445
1996	65515	47403	444
1997	41415	50264	452
1998	62776	42200	435
1999	53248	28060	479
2000	37330	17909	409
2001	50138	43145	383
2002	56342	15278	374
2003	45190	12202	365
2004	39068	10669	374

Table 2. Indices used in the analysis. The indices labelled “base case” were used for the base case run. A sensitivity run included all the indices used in the base case run plus the indices labelled “sensitivity”.

YEAR	**LPS**	**BLLOP**	**VA-LL**	**NMFS LLSE**	**DEL Bay LL**	**DEL Bay age 0**	**DEL Bay Juvs**	**BLL Logs**	**NMFS-NE**	**Pelagic Logs**	**PC gillnet**	**SC LL recent**	**MRFSS**
	Base case										**Sensitivity**		
	CPUE 1	CPUE 2	CPUE 3	CPUE 4	CPUE 5	CPUE 6	CPUE 7	CPUE 8	CPUE 9	CPUE 10	CPUE 11	CPUE 12	CPUE 13
1975			1.900										
1976													
1977			2.077										
1978			1.085										
1979													
1980			1.995										
1981			1.925										2.011
1982													2.195
1983													2.766
1984			0.647										2.408
1985													2.094
1986	3.557		0.665										2.119
1987	0.859												1.167
1988	2.326												0.789
1989	3.204		0.911										0.714
1990	1.008		0.746										0.634
1991	2.327		0.788										0.431
1992	1.382		1.331										0.874
1993	0.739		0.915										0.402
1994	0.378	0.799								0.083			0.243
1995	0.302	0.882	0.860	1.293						0.854		0.458	0.492
1996	0.369	1.000	0.770	0.831				0.789	0.321	2.050	1.00	0.964	0.612
1997	0.530	0.956	0.721	1.301				1.002		0.770	2.25	0.643	0.504
1998	0.124	1.292	0.826					0.919	2.045	0.883	1.22	0.750	0.917
1999	0.202	0.849	0.528	0.390				1.150		1.024	0.53	2.547	0.524
2000	0.213	0.744	0.865	0.971				1.171		1.167	0.69	0.666	0.525
2001	0.986	1.650	0.754	1.041	0.950	0.645	1.162	1.115	1.004	1.032	1.25	0.972	0.503

2002	0.236	0.865	0.626	1.072	0.386	0.518	0.325	0.887		0.707	0.61		0.49
2003	0.181	1.007	0.547	0.880	1.409	1.776	1.163	1.170	-1	0.872	0.97	-1	0.386
2004	0.076	0.955	0.519	1.221	1.070	0.877	1.164	0.798	0.629	1.557	0.47	-1	0.201
Ages Vulnerable													
	all	all	all	all	"juveniles"	0 and 1	"juveniles"	all	all	all	all	"juveniles"	"2-7"
Selectivity function													
	Commercial	Commercial	Commercial	Commercial	"juveniles"	“pups”	"juveniles"	Commercial	Commercial	Commercial	Commercial	"juveniles"	"2-7"

Table 3. Model input parameters

Parameter	**Value**	
Time step	3 months	
	females	*males*
Age at 50% maturity a_{50}	19 years	15 years
Age at 95% maturity a_{95}	25 years	18 years
a_{max}	40 years	
Survival from natural causes of death	Survival	Age
	0.77	1
	0.80	2
	0.82	3
	0.83	4
	0.84	5
	0.85	6
	0.86	7
	0.86	8
	0.87	9
	0.87	10
	0.88	11-13
	0.89	14-18
	0.90	19-31
	0.91	32-40
K	0.089	0.089
L_∞	164 cm PCL	164 cm PCL
t_o	-3.8 y	-3.8 y
Length transformations	FL=1.1 PCL +1	
b_g	3.0124	
d_g	1.09×10^{-5} length in cm (FL), weight in Kg	
Fecundity	8.4 pups	
Reproduction frequency	2 years	
Gestation period	1 year	
Sex ratio	1:1	
Pupping season	June	

Table 4. Model predictions under the base case scenario

PARAMETER	MODAL VALUE	MEAN VALUE	CV
Virgin biomass (kg)	80,024,488	92,139,767	0.2346
Virgin number of fish	5,389,818	6,091,482	0.2346
Pup survival	0.81*	0.85	0.03
N_{2004}/N_v	0.29	0.33	0.27
B_{2004}/B_v	0.29	0.33	0.27
SSB_{2004}/SSB_v	0.28	0.32	0.28
Historical recreational catches (# of fish)	65,783	132,575	0.67
Historical commercial catches (# of fish)	6,009	7,376	0.59

* The value of steepness *h* for this value of pup survival is ~ 0.20 which is the minimum allowable value fot that parameter.

Table 5. Model predictions (modal values) under the different scenarios considered

PARAMETER	BASE CASE	CASE 2	CASE 3	CASE 4
Virgin biomass (kg)	80,024,488	74,770,716	76,716,073	79,495,732
Virgin number of fish	5,389,818	5,035,966	5,166,990	5,354,206
Pup survival	0.81*	0.97	0.81*	0.847
N_{2004}/N_v	0.29	0.29	0.24	0.29
B_{2004}/B_v	0.29	0.28	0.23	0.29
SSB_{2004}/SSB_v	0.28	0.26	0.23	0.28
MSY (kg)	-	120,252	37,587	-
H_{2004}/H_{MSY}	-	15	41	-
Historical recreational catches (# of fish)	65,783	63,184	109,365	75,748
Historical commercial catches (# of fish)	6,009	5,991	6,630	6,261

* The value of steepness *h* for this value of pup survival is ~ 0.20 which is the minimum allowable value fot that parameter.

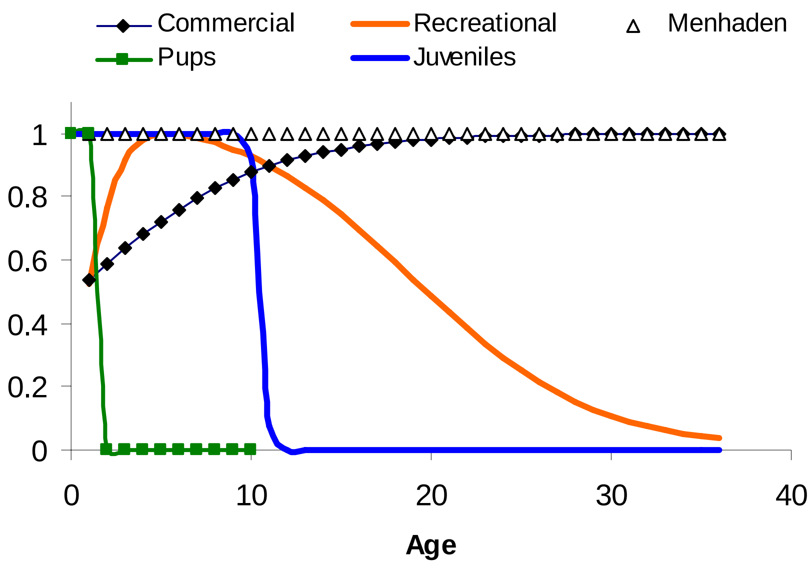


Figure 1. Selectivity of gears for the diffeent gears assumed in the analysis (see Table 2)

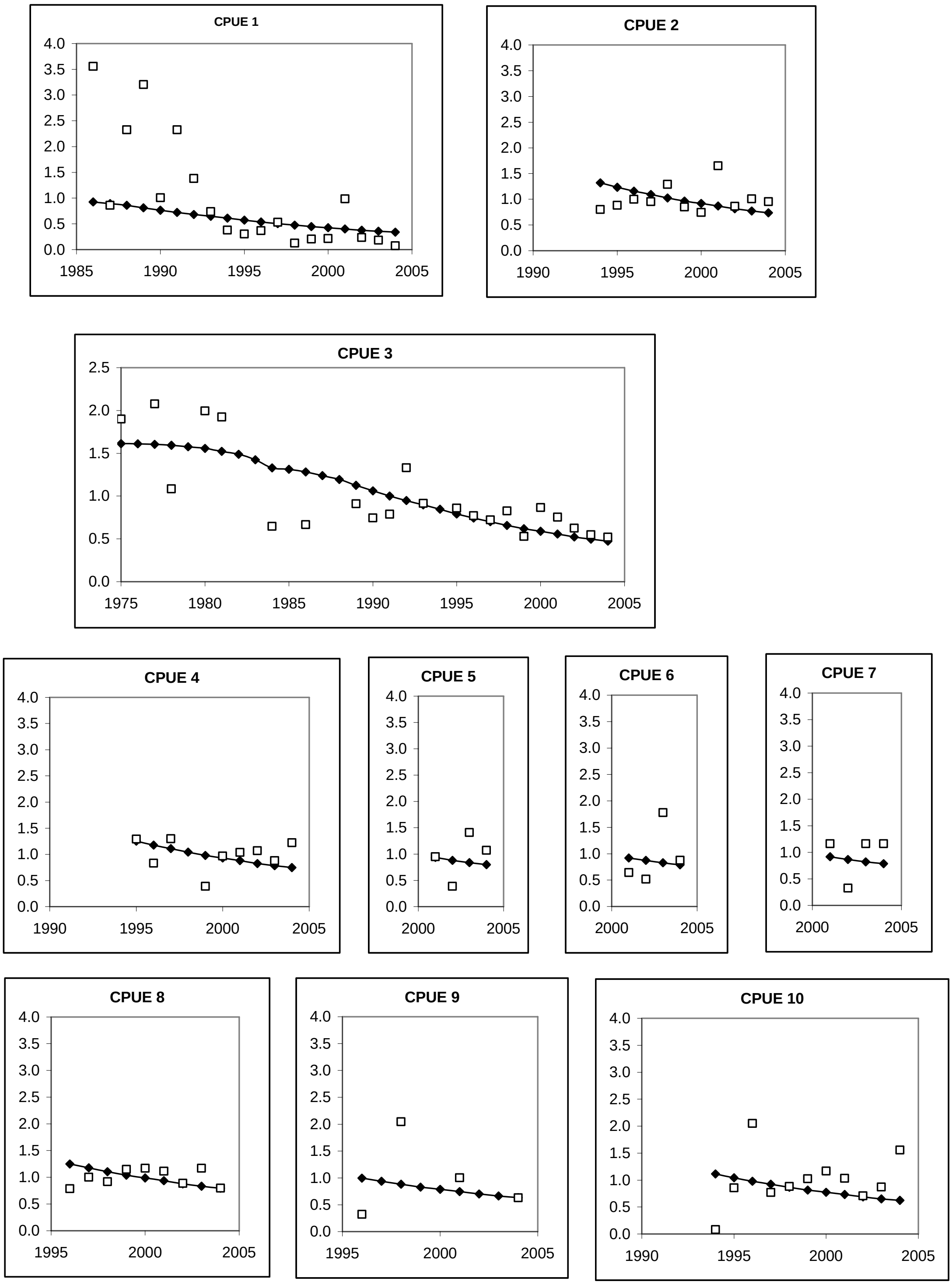


Figure 2. Fit of the model to the CPUE series used under the base case scenario for the values of the estimated input parameters at the mode of the joint posterior distribution..

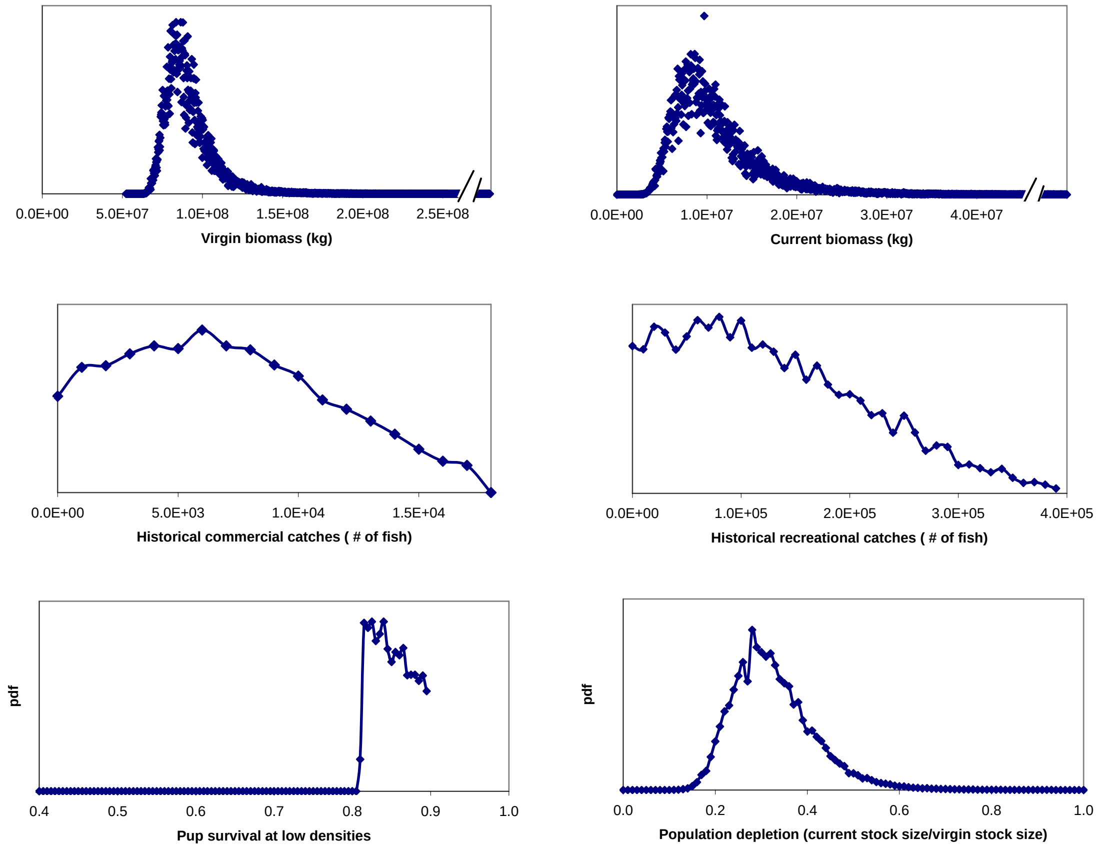


Figure 3. Marginal postrerior probability density functions for some of the estimated parameters (base case scenario).

Appendix 1

The population dynamics model calculates 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:

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

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 gender, *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 at the end of the pupping season and pups could be vulnerable to fishing.

Since the time step used is equal to three months, 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 unless non-uniform temporal distribution of fishing is simulated. 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):

$$(2) \qquad C_{g,y,t,a,j} = (N^{b}_{g,y,t,a} \cdot S_a^{1/8} - \sum_{j'=1}^{j-1} C_{g,y,t,a,j'}) \cdot v_{g,a,j} \cdot u_{y,t,j},$$

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*. If the catch (number of fish) per fishing period and gear, are known then the exploitation rate for each fishing period, $u_{y,t,j}$ is:

(3)
$$u_{y,t,j} = \frac{C_{y,t,j}}{\sum_g \sum_a v_{g,a,j} \cdot \left[N^b_{g,y,t,a} \cdot S_a^{1/8} - \sum_{j'=1}^{j-1} C_{g,y,t,a,j'} \right]}$$

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

The model uses a stock-recruitment function to calculate the survival of pups from natural causes of death during the first period of their life. Density-dependent population regulation at the first stages of fish life can be included through the stock-recruitment function while it is assumed that no density dependent processes are taking place at older ages. Two different stock-recruitment functions have been considered; the Beverton-Holt and the Ricker stock recruitment functions (Beverton and Holt 1957, Ricker 1954). According to the former, the survival of fish of age 0 is equal to:

(4)
$$S_{0,y} = \frac{R_y}{N_{0,y}} = \frac{1}{\alpha + \beta \cdot N_{0,y}},$$

where α and β are constants. Similarly the survival predicted when a Ricker stock recruitment function is used is:

(5)
$$S_{0,y} = \frac{R_y}{N_{0,y}} = \gamma \cdot e^{-\delta \cdot N_{0,y}},$$

where γ and δ are also constants. The susvival of pups at low population density is equal to $1/\alpha$ and γ for the Beverton-Holt and Ricker stock recruitment function, respectively.

The model allows for multi-annual reproductive cycles thus, the number of females which give birth in a given year could be a fraction of the number of mature females in that year. The number of pups born in year, *y*, is:

(6)
$$N_{0,y} = \frac{1}{2} \sum_a N^{\cdot}_{g=fem,\, y,\, t=t_p, a} \cdot \phi_{g=fem,\, a-1} \cdot \overline{\Phi}_a$$

where, $\phi_{g,a}$, is the proportion of fish of age *a* and sex, *g*, that are mature and $\overline{\Phi}_a$, is the number of pups per pregnant female at age *a*. A logistic curve is used to describe the proportion of fish at age *a* which are mature:

(7) $$\phi_{g,a} = \frac{1}{1+e^{(-k_g \cdot (a - a_{50_g}))}},$$

where a_{50_g} is the age at 50% maturity and k_g is a constant which can be calculated if the ages at 50% and 95% maturity are known.

Virgin conditions

If the survival at age and the total number, $N_{y_v,t}$, or biomass of fish, $B_{y_v,t}$, before any exploitation takes place is known the number of fish of age, *a*, at the beginning of year, y_v, under no exploitation conditions, can be calculated as follows:

(8) $$N^b_{g,y_v,t=1,a} = \begin{cases} f_g \cdot R_{y_v,t=t_p} \cdot S_a^{1/2} & a = 1 \\ f_g \cdot R_{y_v,t=t_p} \cdot \prod_{a'=1}^{a-1} S_{a'} \cdot S_a^{1/2} & 0 < a \le a_{\max} - 1 \\ f_g \cdot R_{y_v,t=t_p} \cdot \dfrac{\prod_{a'=1}^{a_{\max}-1} S_{a'}}{1 - S_{a_{\max}}} \cdot S_{a_{\max}}^{1/2} & a = a_{\max} \end{cases}$$

$R_{y_v,t}$ denotes number of recruits under virgin conditions and is calculated from the total number or biomass of fish of age 1 or older under virgin conditions:

(9)
$$R_{y_v,t=t_p} = \frac{B_{y_v,t=t_p}}{\sum_g f_g \left[w_{g,a=1} + \sum_{a=1}^{a_{\max}-1} w_{g,a} \prod_{a'=1}^{a-1} S_{a'} + w_{g,a_{\max}} \frac{\prod_{a'=1}^{a_{\max}-1} S_{a'}}{1-S_{a_{\max}}} \right]}$$

The number of pups born under virgin conditions are calculated using equation (6) once the number of fish in each age class has been found.

Appendix 1 for SEDAR 11-AW-01 (Apostolaki)

The group decided to change the values of the input parameters used in the population dynamics model for sandbar shark. The changes were the result of discussions about the productivity of the population when the original input values were used (see original document). The changes that were decided were:

- New prior pdf for the survival of pups at low densities: Lognormal (0.75, 0.3^2) in the range [0.3, 0.98]
- New survival at age values which were higher than those suggested originally (Table A.1)

Table A.1. New values for survival at age

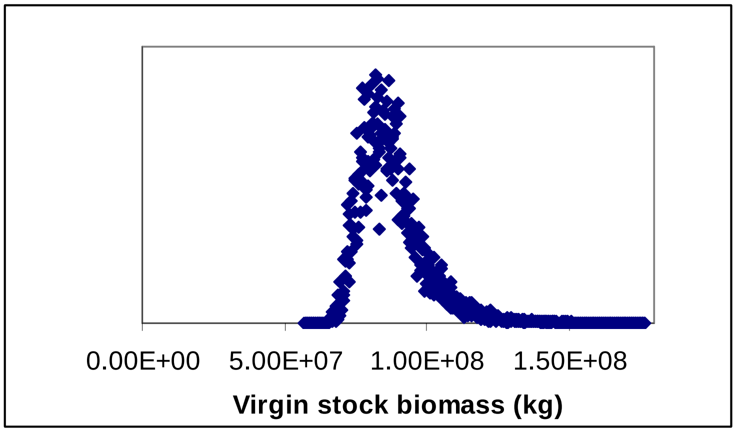
Survival	Age
0.79	1
0.82	2
0.84	3
0.86	4
0.87	5
0.88	6
0.88	7
0.89	8
0.90	9
0.90	10
0.90	11
0.91	12-14
0.92	15-20
0.93	21-40

The results of the model with the updated input data are shown below:

Virgin biomass (kg)	74,798,916
Virgin number of fish	4,431,319
Pup survival	0.79
N_{2004}/N_v	0.25
B_{2004}/B_v	0.22
SSN_{2004}/SSN_v	0.17
MSY (kg)	497,689
H_{2004}/H_{MSY}	4.54
Historical recreational catches (# of fish)	4.27E+04
Historical commercial catches (# of fish)	5952.79
B2004/Bmsy	0.224037
Bmsy/Bv	0.458207
Recovery time*	50 years

* It has been assumed that catches equal to the catches in 2003 are taken in years 2005-2007. No fishing is taking place from 2008 onwards

The predictions of the model shown in Table 1 were found using the values of the estimated input parameters at the mode of the joint posterior pdf. The recovery time was calculated by projecting the population forward with no exploitation and estimating the number of years that it will take for the size of the population to become equal to B_{MSY}. The projection runs assume that the catches are equal to 0 for years 2008 onwards. The catch for the period from 2005 to 2007 were assumed to be equal to the catches in 2003 (Table 2 in original document)). The results show that the population is overexploited and overexploitation is taking place. The model predicted that, under no exploitation conditions, it would take approximately 50 years for the size of the population to increase from its current size to B_{MSY}. The marginal posterior pdf for some of the estimated parameters are also shown below:



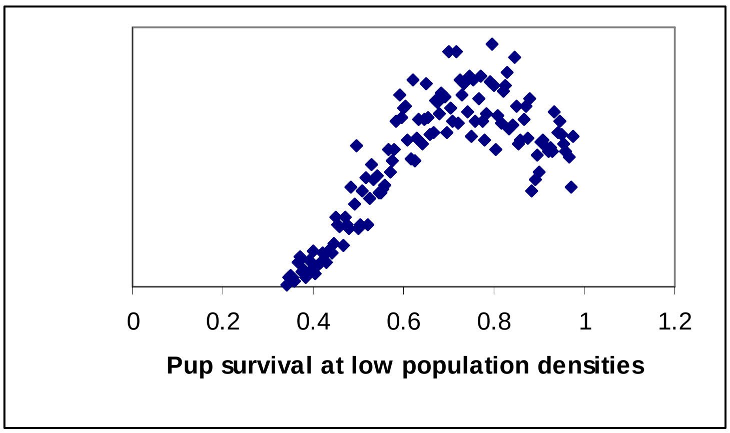
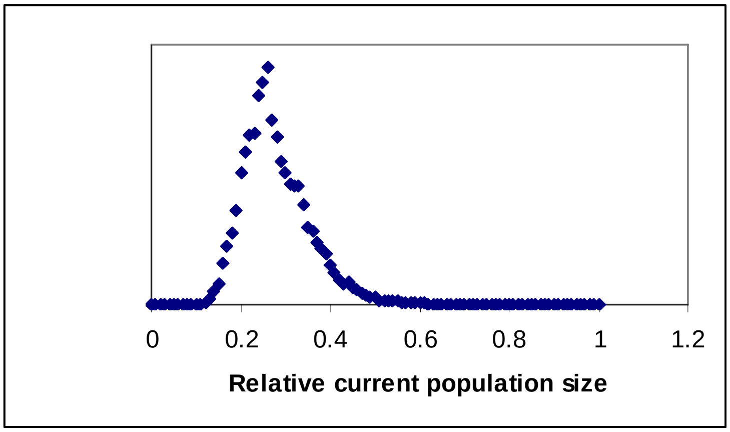


Figure A1. Marginal posterior probability density functions for the virgin biomass and survival of pups at low population densities (base case runs).



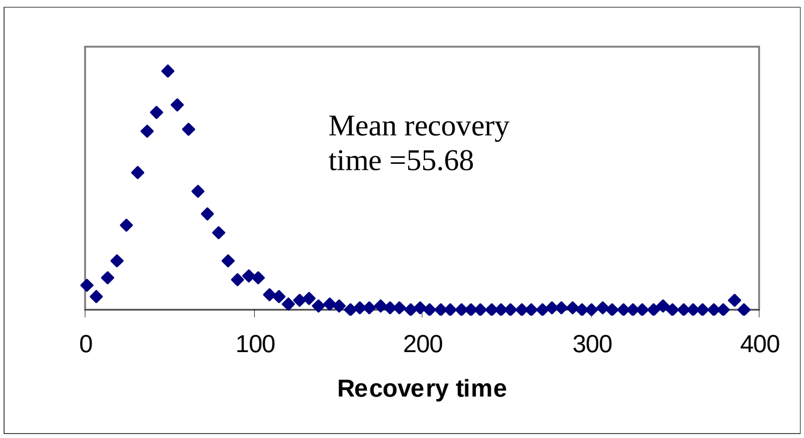


Figure A2. Marginal posterior probability density functions for the current size of the population relative to its virgin size and the time that is needed for the population to recover to its B_{MSY}.