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USING AN AGE-STRUCTURED AND PARTIALLY SPATIALLY-STRUCTURED POPULATION DYNAMICS MODEL TO EVALUATE THE POTENTIAL EFFECTS OF AREA CLOSURES ON STOCK REBUILDING OF NORTH ATLANTIC SWORDFISH[*],[**]

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SUMMARY

The effectiveness of the established closed area in the western Atlantic and of closed areas in general, as a management tool for the regulation of the North Atlantic swordfish fishery and stock rebuilding is evaluated in this paper using an age-structured, fleet disaggregated population dynamics model. The model uses population dynamics model parameter inputs from recent stock assessments and the catch data to predict the current status of the stock with and without the established closed fishing areas. The future effects of the closed area on the status of the stock under the current stock-rebuilding plan and different assumptions for the size of the closed area, the age classes that it protects and the response of the fishery (i.e., the amount and spatial distribution of fishing effort) to the introduction of a closed area are also evaluated.

RÉSUMÉ

Le présent document évalue l'efficacité du cantonnement établi dans l'Atlantique ouest et des cantonnements en général, en tant qu'outil de gestion destiné à réglementer la pêcherie d'espadon et le rétablissement du stock dans l'Atlantique nord à l'aide d'un modèle de dynamique des populations par flottille individualisée et structuré par âge. Le modèle a recours à des valeurs d'entrée du paramètre du modèle dynamique de population à partir des récentes évaluations de stock et des donnés de captures pour prédire l'état actuel du stock avec et sans cantonnement. Sont également évalués les effets que le cantonnement aura à l'avenir sur l'état du stock dans le cadre du programme actuel de rétablissement du stock, ainsi que les différents postulats sur la taille du cantonnement, les classes d'âges qu'il protège et la réaction de la pêcherie (c'est-à-dire le volume et la distribution spatiale de l'effort de pêche) face à l'introduction d'une fermeture de zone.

RESUMEN.

En este documento se evalúa la eficacia de la zona de veda establecida en el Atlántico occidental y de las zonas de veda en general como instrumentos de ordenación para la pesquería de pez espada del Atlántico norte y para la recuperación del stock, utilizando un modelo dinámico de población estructurado por edad con flota disgregada. El modelo utiliza las entradas del parámetro del modelo dinámico de población de las recientes evaluaciones de stock y los datos de captura para predecir el actual estado del stock con o sin zonas de veda a la pesca establecidas. También se evalúan efectos futuros de las vedas en el estado del stock en el marco del actual plan de recuperación y los diferentes supuestos para el tamaño de la zona de veda, las clases de edad que protege y la respuesta de la pesquería (es decir, la cantidad y distribución espacial del esfuerzo de pesca) a la introducción de una zona de veda.

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[*] This document presents preliminary results. Please contact the authors for information on updated versions of the model and further results.

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KEYWORDS

Marine closed areas, fishery management, gear selectivity, size composition, migrations, nursery grounds.

1 INTRODUCTION

Around 1990, the North Atlantic swordfish (*Xiphias gladius*) population dropped below the biomass level that would allow maximum sustainable yield (ICCAT, 2001). In 1991 the Commission introduced a minimum size of 125 cm LJFL to reduce mortality on juvenile fish (Recommendation 90-2), a measure intended (along with quotas) to prevent further declines of the population. The population continued to decline, and is currently under a rebuilding program. In 1999, the Commission, recognizing that mortality on undersized swordfish remained problematic, requested that SCRS consider the effectiveness of closed areas and other measures to reduce undersize swordfish mortality (ICCAT Resolution 99-4). To that end, this paper reports on a preliminary model to evaluate the potential impacts of closed areas on the recovery of North Atlantic swordfish. Since, the United States has recently implemented several closed areas within the U.S. EEZ, the model was used to predict the potential impact of these closed areas on stock recovery. As a demonstration of the methodology, the method was also applied to one of the potential sets of closed areas identified in document SCRS/02/118 (Cramer, 2002).

For swordfish, there is no information available on the migration rates for either juvenile or adult fish into and out of any potential closed areas. Therefore, it was not possible to develop a multi-area model to describe the migratory behaviour of swordfish. However, there is information on the catch at age and sex by fleet, and the size, sex and age composition by fleet of the catch by 5x5 areas throughout the North Atlantic (finer spatial resolution is available for some areas) (ICCAT, 2000; Ortiz et al., 2000). Thus, it was possible to estimate the selectivity of each national fleet. This information was utilised to estimate the effect of closed areas on the overall selectivity at age of each fleet. This partially spatially-structured approach allows the modelling of closed areas with limited information on migration.

2 POPULATION DYNAMICS MODEL

A fleet disaggregated, age- and sex-structured population dynamics model is used for the simulation of the dynamics of swordfish. A six-month step is used for the calculations and the values of the parameters of interest are calculated at the beginning of each time step except for the number and biomass of mature fish which are calculated at the end of the first time step in each year. It has been assumed that, in a given year, half of the yearly catches are taken in the first half of the year and the rest are taken in the second half of the year.

If the number of fish of age, *a*, and sex, *g* at the beginning of a time step, *t*, in a given year, *y*, $N^b_{g,y,t,a}$, is known then the number of fish of age, *a*, and sex, *g* at the end of this time step, $N^e_{g,y,t,a}$, will be:

$$(1) \qquad N^e_{g,y,t,a} = \begin{cases} (f_g \cdot N_{0,y,t} \cdot S_a^{1/4} - C_{g,y,t,a})S_a^{1/4} & a = 0, \\ \\ [(N^b_{g,y,t,a} \cdot S_a^{1/4} - C_{g,y,t,a})S_a^{1/4} & a \geq 1 \end{cases} ,$$

where S_a is the survival of fish at age *a* from natural causes of death, $N_{0,y,t}$ is the number of new fish in year, *y,* and time step, *t*, f_g is the fraction of new fish of sex *g* and $C_{g,t,a}$ is the number of fish of age, *a*, and sex, *g*, caught in year, *y,* at time step, *t* (**Table 1**). Young fish appear in the middle of each year and are vulnerable to fishing. The survival per year of fish in age class, *a*, S_a, is constant and is the same for males and females.

Although fishing takes place the whole year round, we assumed that catches were taken in a pulse in the middle of each time step. The number of fish caught during the first fishing season of each year with gear, *j*, $C_{g,y,t=1,a,j}$, is calculated as follows (Punt and Walker, 1998):

$$(2) \qquad C_{g,y,t=1,a,j} = (N^b_{g,y,t=1,a} \cdot S_a^{1/4} - \sum_{j'}^{j-1} C_{g,y,t=1,a,j'}) \cdot v_{g,a+0.75,j} \cdot u_{y,t=1,j},$$

where $v_{g,a,j}$ denotes fish vulnerability to gear *j* at age *a*, and $u_{y,t,j}$ is the exploitation rate per gear, *j*, at time step, *t*, and in year, *y*. The assumption underlying this equation is that fishing using different gears is a successive process such that, at any given time fish are caught only with one gear.

If the catch per time step and gear, are known then the exploitation rate for each time step can be found. The exploitation rate for the first time step, in year , *y*, $u_{y,t=1,j}$ is (Punt and Walker, 1998):

$$(3) \qquad u_{y,t=1,j} = \frac{C_{y,t=1,j}}{\sum_g \sum_{a=0}^{a_{\max}} w_{g,a+0.75} \cdot v_{g,a+0.75,j} \cdot \left[N^b_{g,y,t=1,a} \cdot S_a^{1/4} - \sum_{j'=1}^{j-1} C_{g,y,t=1,a,j} \right]}$$

In the above equation, catch in each time step are assumed to be in biomass units and therefore, the weight of fish, $w_{g,a}$, is needed to calculate the exploitation rate. Since it was assumed that young fish appear in the middle of each year, the weight of fish in age class, *a*, used for the calculations was 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. The weight of fish at age, *a*, was expressed as a function of fish length, $L_{g,a}$:

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

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

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

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 half of a year is calculated in a similar way. However, the number of fish at the beginning of the second half of the year is equal to $N^b_{g,y,t,a}$ minus the fish that died due to the natural and fishing mortality at the first half of the same year.

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

$$N^{\exp l}_{y,t=1,j} = \sum_{g=1}^{2} \sum_{a=0}^{a_{\max}} (N^{b}_{g,y,t=1,a} \cdot S_a^{1/4} - \sum_{j'}^{j-1} C_{gy,,t=1,a,j'} - \frac{C_{g,y,t=1,a,j}}{2}) \cdot v_{g,a+0.75,j} \tag{6}$$

The exploitable fish biomass is found by incorporating the weight at age into the above equation. The exploitable fish biomass or exploitable number of fish for the second half 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 exploitable biomass / number of fish for the first and second half of the year.

Mature fish were assumed to spawn at the end of the first half of each year. The number of mature females at the beginning of the first half of a year was found using the equation:

$$N^{b,sp}_{g=fem,y,t=1,a} = \sum_{a=1}^{a_{\max}} N^{b}_{g,y,t=1,a} \cdot \Phi_a \text{ ‘} \tag{7}$$

where Φ_a is the proportion of mature female fish at age, *a*. The number of eggs produced each year is calculated as the product of pregnant females of age, *a*, times the fecundity per age, φ_a. However, only a fraction of the mature female fish at the beginning of a year (eq. 7) actually spawn since some of the fish die due to natural and fishing mortality before they spawn. The eggs produced each year, *y*, will be:

$$E_y = \sum_{a=1}^{a_{\max}} (N^{b,sp.}_{g=fem,y,t=1,a} S_a^{1/4} - C_{g=fem,y,t=1=1,a}) \cdot S_a^{1/4} \cdot \overline{\Phi}_a \tag{8}$$

For the implementation presented here, the number of age 0 recruits was assumed to be independent of the number of mature fish and eggs produced each year, but lower than the number of age zero fish under virgin conditions. A parameter, C_{No}, was used for the calculations which determined the reduction in age zero recruitment relative to virgin age zero recruitment:

$$N_{0,y} = (1 - C_{N_0}) \cdot N_{0,y_1} \tag{9}$$

Alternatively, the Hockey stick (Barrowman and Myers, 2000) or Beverton-Holt (Beverton and Holt, 1957) or Ricker (Ricker, 1954) stock-recruitment functions can be used to relate the number of fish of age 0 to the spawning stock.

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 before that year was equal to the virgin population. If we assume that N_o is the virgin number of fish of age 0 then the total number of fish in each age-class at the beginning of year y_1 will be:

(10)
$$N^{b}{}_{g,y_1,a} = \begin{cases} f_g \cdot N_{0,y_1} \cdot S_a^{1/2} & a = 0 \\ f_g \cdot N_{0,y_1} \cdot \prod\limits_{a'=0}^{a-1} S_{a'} \cdot S_a^{1/2} & 0 < a \le a_{\max} - 1 \\ f_g \cdot N_{0,y_1} \cdot \dfrac{\prod\limits_{a'=1}^{a_{\max}-1} S_{a'}}{1 - S_{a_{\max}}} \cdot S_{a_{\max}}^{1/2} & a = a_{\max} \end{cases} ‘$$

where the number of age zero recruits under virgin conditions can be calculated if the virgin biomass of the stock, B_o, is known:

(11)
$$N_{0,y_1} = \frac{B_o}{\sum\limits_g f_g \left[w_{g,0.5} + \sum\limits_{a=1}^{a_{\max}-1} w_{g,a} \prod\limits_{a'=1}^{a-1} S_{a'} + w_{g,a_{\max}} \dfrac{\prod\limits_{a'=1}^{a_{\max}-1} S_{a'}}{1 - S_{a_{\max}}} \right]}$$

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. Note that the number of age zero recruits under virgin conditions is determined by the virgin biomass, growth curve and natural mortality. To have a constant recruitment that is lower than this level, it was necessary to assume that the recruitment was at the unfished level in the last year before the fishery, but would drop to the level determined by equation 9 after the first year of the fishery and throughout the projections.

3 STATISTICAL FRAMEWORK

The virgin biomass, B_o, and the parameter that determines the number of fish of age 0 in each year, C_{No}, were estimated parameters. The constants of proportionality and the variance for each relative abundance series k that corresponds to gear j, $q_{j,k}$ and $\sigma_{j,k}$, respectively were also estimated parameters. Bayesian statistical methods 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 $p(\theta_n)$ is the joint prior probability density function for a set of values of the estimated parameters, θ_n, then the value for the posterior probability density function for this set of values, given the data, I, is:

(12)
$$p(\theta_n|\mathrm{I}) \propto p(\theta_n|)L(I\,|\theta_n|),$$

where $L(I\,|\theta_n|)$ is the likelihood function for this set of values of the uncertain parameters of the model. In order to construct the likelihood function we assumed that all observations were independent and that the observed values from each abundance series, $I_{j,k,t}$, were log-normally distributed about the corresponding value predicted by the model, $q_{j,k}B_{j,k,t}$:

(13) $$I_{j,k,y} \sim \log normal(q_{j,k} N_{j,y}^{\exp l}, \sigma_{j,k}{}^2).$$

N_{jyt} is the annual exploited number of fish that corresponds to observation $I_{j,k,y}$, $q_{j,k}$ is the constant of proportionality for the series, *k,* that comes from fishery *j* and $\sigma_{\mathrm{j,k}}$ is the lognormal standard deviation for residual errors between the observed and predicted values for each series of relative fish abundance. The loglikelihood function for one potential set of values for the uncertain parameters of the model, θ_k , is (McAllister and Kirkwood, 1998; McAllister et al., 2001):

(14) $$\ln L(I \mid \theta_n) = \sum_j \sum_k \sum_y -\ln\left(I_{j,k,y}\right) - \frac{1}{2\sigma_{j,k}^2}\left(\ln \frac{I_{j,k,y}}{q_{j,k} B_{j,y,k}}\right)^2 - \ln\sqrt{\sigma_{j,k}^2 2\pi}.$$

$\sigma_{j,k}^2$ is the same for all points in this implementation (equal weighting).

Non-informative priors were used for $\sigma_{\mathrm{j,k}}$ and $q_{j,k}$ while an informative prior was used for virgin biomass (log(B_o)~U[log(10^7Kg), log($6x10^8$Kg)]). Information regarding the recruitment over the years from the previous stock assessment report was used for the construction of an informative prior for C_{No} (C_{No} ~ Lognormal[0.35, 0.5^2]). The median was chosen to reflect the fact that the average number of age zero recruits (male + female) in the sex specific VPA from the 1999 assessment (ICCAT, 2000) was equal to about 78% of the maximum recruitment.

4 PARAMETER VALUES AND ASSUMPTIONS

The values of the fixed parameters of the model are shown in **Table 2**. They are taken from the 1999 stock assessment and associated documents. Total catches and CPUE data (**Table 3**) were taken from the 1999 swordfish detailed report and the 2001 executive summary. The North Atlantic combined biomass index (Swo-det-99) was used as a CPUE index. The total exploitable biomass calculated using the selectivities of the U.S. fleet was fit to the index.

Selectivities

The sex specific selectivities for each fleet were calculated with a catch curve analysis similar to that used for the South Atlantic swordfish ASPM model inputs at the 1999 assessment (ICCAT, 2000). Catch in numbers at sex and age were available (Ortiz et al., 2000), for the fleets of Canada, Chinese Taipei, Spain, Japan, "Other", Portugal and the USA. Examining the log proportions by fleet (**Fig. 1**) it seemed reasonable to assume that the selectivities were constant between age 5 and 10 for each fleet and sex, although selectivities varied for younger fish, and older fish. For each fleet and sex, the selectivity (*v*) for each age (*a*), sex (*s*) and fleet (*j*) was calculated as:

(15) $$v_{g,a,j} = {P_{g,a,j}} \big/ {\hat{P}_{g,a,j}},$$

where $P_{g,a,j}$ is the proportion in each age and sex of the total catch from fleet *j*, averaged over the years 1996 through 1998. The estimated proportions $\hat{P}_{g,a,j}$ were calculated from the exponent of the predicted value, for ages from 5 to 10, from the following linear regression:

(16) $$\ln\left(P_{g,a,j}\right) = -za + intercept,$$

where z is the instantaneous mortality rate. The log proportions and predicted log proportions are shown in **Fig. 1**.

Because the ageing of swordfish over the age of nine is not reliable, the selectivities calculated for nine year olds were applied to ages 10 through 15. The estimated selectivities were then standardized by dividing the selectivities for each age, sex and fleet by the maximum selectivity for the fleet. The results are shown in **Fig. 2**. These fleet wide selectivities were used in the estimation part of the model, for the years 1950 to 1998, during which there were no closed areas.

Estimation of 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 et al., 2001; McAllister and Kirkwood, 1998). After the importance draws had reached convergence according to the maximum weight and CV(weight)/CV(likelihood*priors) criteria (McAllister et al., 2002), we used importance resampling to subsample 5000 draws. We used these draws to calculate the marginal posterior probability distributions, mean values and CVs for virgin mature fish biomass, virgin number of fish, number of fish in 1998, mature fish biomass in 1998 and the recruitment parameter.

5 PROJECTION AND DECISION ANALYSIS FOR CLOSED AREAS

The model was fitted to the data through 1998 using the fleet-wide selectivities. To evaluate the effect of closed areas, the model was projected twenty years into the future, with modified selectivities and catches to mimic the effect of several possible closures. Deterministic projections were done at the mode of the posterior distribution for both the U.S. closed areas and the potential international closed area.

For the U.S. closed area, an example decision analysis was carried out to evaluate the potential consequences of various closed area management strategies taking into account parameter uncertainty and uncertainty about the migratory behaviour of the fish. The decision analysis was performed by projecting the population forward (final year 2020) for each of the 5000 resamples of parameter values generated by the SIR algorithm in the assessment phase. For each closed area strategy (closure/no closure), the management measures performance indices reported are the probability that the spawning stock biomass will recover to 50% of the virgin SSB, the probability that the total numbers will recover to 50% of virgin total numbers, the expected ratio of small (0, 1 and 2 year old) to large (3 and greater) fish in the U.S. fishery, and the probability that the discard rate would decrease and the probability that the discard rate would decline by more than 25%.

The options considered are:

1. *No closed areas*

2. *The closed areas in the U.S. EEZ*

In 1999, the U.S. began implementing closed areas in the U.S. exclusive economic zone to reduce bycatch of small swordfish, marlins, and protected species such as sea turtles (**Fig. 3**, NMFS 2000a, NMFS 2000b,). We projected the population forward assuming that the DeSoto Canyon, Florida East Coast and Charleston closures were implemented in the beginning of 2001. No other U.S. closed areas were included in this analysis.

3. *Closing the top 20 5x5 squares in each quarter.*

Cramer (2002) shows several possible sets of closed areas throughout the North Atlantic. This modelling approach could be used for any of these potential closures. We demonstrate the method with the closure of the 20 5x5 degree squares with the highest total catch of fish less than 125 cm LJFL in the U.S. and Spanish fleets (the boxes in **Fig. 2**, (Cramer, 2002)).

For each closed area strategy, we evaluated two scenarios for future catches. The first case assumed that there would be no effort redistribution out of the closed area. The catch previously taken in the closed areas would not be taken in the future, so that the future catch in weight would be the 2000 catch in weight less the catch previously taken in the closed areas. The second case assumed full effort re-distribution, so that the future catches were equal to the 2000 catch in weight.

For each closed area strategy there were two different assumptions regarding the exploitation of the population by the other fleets. It was assumed either that the fleets could exploit the whole population or that the fleets cannot exploit the number of fish of age 0 to 2 that would be caught if the selectivity of the fisheries implementing closed areas hadn't changed. The latter assumption was used to simulate a situation in which no fleet can enter the closed areas and the fish of age 0 to 2 remain in the closed area for one six-month time step. The number of young fish saved was calculated by subtracting the young fish that would be caught with the selectivity in the open area only from the number of young fish that would be caught with the selectivity of the entire fleet. The saved fish were then removed from the population used to calculate the number of fish that were caught by any of the other fisheries in the current 6-month time step. The number of fish protected by the closed area would actually be greater than the difference in catches. On the other hand, fish may stay in the closed areas for more or less than six months, which would change the number of fish vulnerable to the fishery.

Modification of selectivity to account for closed areas.

To project the impact of U.S. closed areas, the selectivities for the entire fleets ($v_{g,a,j}$) were modified using estimates of the discards in areas that would later be closed (D_c), landed catch in areas that would later be closed (L_c), and discards (D_r) and landed catch (L_r) in areas that would remain open, in weight of fish (**Table 4a**). Assuming that all discards were age 0, 1 and 2, and that all landings were ages 3 and higher, the total landings (L_c+L_r) were used to calculate the harvest rate (H_1) applied to fish of age 3 and higher, using the overall selectivity curve for the U.S. fleet calculated above. Similarly, the total discards (D_c+D_r) were used to calculate the harvest rate (H_2) applied to fish of age 0,1 and 2 for the time period before the closed areas. The harvest rates outside the closed areas for age 3+ fish (H_1^0) and for age 0-2 fish (H_2^0) were then calculated using just the catches and discards in the open areas (L_r and D_r). The selectivity for the whole fishery without closed areas $v^w_{g,a,j}$ was calculated as:

$$v^w_{g,a,f} = \begin{cases} v_{g,a,f} \cdot \dfrac{H_2}{H_1} & a \le 2 \\ v_{g,a,f} & a > 3 \end{cases} \tag{17}$$

The ratio H_2/H_1 should be close to 1.0, if the assumption that all discards are age 0-2 and all retained catches are age 3+ is justified, and if the selectivity curve is well estimated. The selectivity for the whole fishery with closed areas, $S^c_{g,a,j}$, was calculated in the same way, except using the harvest rates calculated outside the closed areas.

$$v^c_{g,a,f} = \begin{cases} v_{g,a,f} \cdot \dfrac{H_2^0}{H_1^0} & a \le 2 \\ v_{g,a,f} & a > 3 \end{cases} \tag{18}$$

This has the effect of decreasing the selectivity of small fish for the entire fishery when the closed area is in place. This calculation was done for 1999 and 2000, and the average values were used for the projections. Note that these selectivities were calculated with longline fisheries, so non-longline fisheries are assumed to have the same selectivity. Since, the majority of the north Atlantic swordfish catch (92% by weight in 1998, ICCAT, 2001) is taken by longline fisheries such an assumption will not affect our results significantly.

A similar modification of selectivity (**Table 4b**) was used to examine the potential effect of international closed areas. Fewer data were available to calculate these selectivities than for the U.S. case, so this should be considered an exploratory modelling exercise. The projections were done assuming that all catch of fish less than 125 cm LJFL were age 0-2, and all fish greater than 125 cm LJFL were age 3 and older. The potential closed areas were the 20 5x5 degree squares in each quarter with the highest total catch of fish <125 in 1998 from the US and Spanish fleets combined (Cramer, 2002, **Fig. 2**; ICCAT, 2000, **Fig. 3**). Total catch of small and large fish in each quarter was assigned to the Spanish and U.S. fleets based on the total catch in numbers from the U.S. and Spanish fleets (ICCAT, 2000,**Table 29**). The total catch and discards inside and outside the closed areas were then converted from numbers to kg using the average weights of fish above and below 125 cm LJFL from the U.S. fleet (15 kg and 47 kg). The total catch plus discards from this analysis was greater than the total catch plus discards reported to ICCAT by Spain and the U.S. for 1998 and 1999. We assumed that the proportions of catches and discards in each fleet were correct, and reduced the estimated values of the catches and discards in the closed area and the total discards by a factor of 0.85 so that the total catch and discards for each fleet would equal the total reported catches plus discards for each fleet (ICCAT, 2001). The total selectivities for the U.S. and Spanish fleets were then calculated as above. The selectivities of the other fleets were not changed, because they were not used to choose the closed areas. However, if the other fleets fished in the same areas as the U.S. and Spain, their small fish catch would also be reduced due to the establishment of these closed areas.

6 RESULTS

Assessment

The 1998 population was estimated to be at 23% of the unfished spawning stock biomass level and 48% of the unfished number of fish (**Table 5, Fig. 4, Fig. 5**). The greater decline in biomass reflects the fact that older fish have declined much more than younger fish. The median exploitable biomass calculated using the selectivities of the U.S. fishery declined to 21% of the 1950 median level (**Fig. 4**). This decline was greater than the decline shown in the base case ASPIC run from the 1999 assessment, which was fitted to the same biomass index and showed a depletion in 1998 to 37% of the 1950 biomass (32% of the virgin biomass) The current model and the ASPIC run estimated a similar biomass trend in the 1980s and 1990s, but current model estimated a steeper decline in the 1950s. The current model also showed a somewhat steeper decline between 1978 and 1998 in both numbers and biomass than did the 1999 VPA assessments. The VPA estimated that the 1998 total spawning stock biomass was 37% of the value in 1978, while in the current model, the median total SSB in 1998 was 22% of the median SSB in 1978.

Projections

For the U.S. closed area case, the selectivities of small fish (**Table 6a**) in the areas that remained open was about 80% of their selectivity in the entire fishery. The impact of the closed area on the rebuilding trajectory depended strongly on the assumptions that were made about effort redistribution and fish migration (**Fig. 6, Table 7**). If the small fish that were not caught by the U.S. fleet in the closed areas could be caught immediately by the other fleets, then the population rebuilt only slightly faster than without closed areas. This was true even if the total catch was reduced by the amount of fish that had been caught in the closed area. However, if the small fish that would have been caught by the U.S. fishery were assumed to be safe from fishing for half a year before they could be caught outside the closed area, then the population rebuilt much more quickly. The decision table (**Table 7**) shows that the discard ratio in the U.S. fishery would decrease as the population rebuilds, even without a closed area. The closed area reduced the predicted discards in the U.S. fishery whether or not the fish were assumed to migrate out of the closed area immediately. However, the population was not predicted to rebuild much faster with the closed area unless the fish remain in the closed area long enough to be protected from the fisheries in the open areas.

For the international closed area example, the total catch of large fish in the closed area was much larger than the total catch of large fish outside the closed area (**Table 5b**), implying that this was not an optimal choice of closed areas. However, the selectivities for small fish for both the U.S. and Spanish fleets outside the closed area were about half the selectivities for the entire fishery. Small fish were less vulnerable to the U.S. fish in this scenario than in the U.S. closed area scenario. This was partly because the closed area was in a different place, partly because the age 0-2 and age 3+ catches were defined from catches of fish greater and less than 125 cm LJFL, and partly because the selectivities for the U.S. closed area were calculated with data from 1999-2000, instead of 1998. Projections are presented only for the case when future catches are equal to the 2000 total catch (**Fig. 7**). Unlike the U.S. closed area the international closed area was predicted to speed rebuilding even when the fish were assumed to migrate out of the closed area immediately. This is because a high proportion of the total catch is taken by the U.S. and Spain, so that reducing their selectivities for small fish saves many small fish even if other fleets can still catch them.

7 DISCUSSION

Possible improvements to the model

The current model is simple, but more realism could be added if data were available (see Apostolaki et al., 2002). We have assumed that the only fish protected when the closed area is introduced are the fish that are not caught by the fleets that previously fished there. However, the number of fish occupying the closed area is expected to be bigger than that so the protection that the closed area will provide could be greater than we predicted (depending on the movement rate). Also, the model did not evaluate the effects of the closed area on the fish older that 3 years that would occupy the closed areas.

To fully model the effects of migration on the closed areas, it would be necessary to have a multi-area model, instead of this essentially single area model which uses selectivity to mimic the effects of closed areas. However, such a model would require detailed information about migration, preferably directly estimated from tagging data.

A finer temporal scale may be needed for our calculations if the fish change areas very quickly. The use of the continuous version of the equations used for the calculation of the number of fish caught, number of fish that spawn etc. will increase the realism of the simulation and the accuracy of the predictions.

This model did not specifically examine the impact of size limits. Although the fact that the selectivities are based on landings plus dead discards accounts for the size limit at present, this does not account for changes in discarding behaviour of fishermen over time. Also, if the size limit was modelled explicitly, it would be possible to examine the effect of higher or lower survival rates for live-released small swordfish, which could significantly impact the total mortality of small fish, and hence the rebuilding plan.

The assumption of constant recruitment is unlikely to hold at very low stock sizes. Alternative approaches to the calculation of the recruitment need to be investigated in the future.

8 CONCLUSIONS

This modelling exercise demonstrates that protecting undersize swordfish could greatly speed the recovery of the North Atlantic swordfish population. However, whether closed areas do this effectively or not depends on how quickly small fish can migrate out of the closed areas. A large decrease in the vulnerability of small fish in some fleets will not necessary save large numbers of small fish, if the same fish are vulnerable to other fleets that catch small fish. The modelling approach presented here can be used when few movement data are available but discard information exists, to provide insight in the potential effects of a closed area. The approach can be used to predict the effectiveness of closed areas under various plausible scenarios about swordfish migration, so that closed area management strategies can be developed which adequately account for uncertainty about migration. However, a better understanding of the migratory behaviour of swordfish would increase the accuracy of the model predictions and therefore research to develop further information about the migratory behaviour of swordfish should be a priority.

9 ACKNOWLEDGEMENTS

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REFERENCES

AROCHA, F. 1997. The reproductive dynamics of swordfish (Xiphias gladius) and management implications for the Northwest Atlantic. Doctoral Dissertation. University of Miami.

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, London.

CRAMER, J. 2002. Distribution of juvenile swordfish (Xiphias gladius) caught by pelagic longline in the Atlantic Ocean. SCRS/02/118

ICCAT. 2000. Detailed Report On Swordfish: Report of the ICCAT Swordfish Stock Assessment Session (Madrid, Spain, September 27-October 4, 1999). ICCAT Collective Volume of Scientific Papers 51; pp. 1001 – 1209

ICCAT. 2001. Swordfish Executive Summary. ICCAT SCRS Report 2001. http://www.iccat.es

MCALLISTER, M.K., E.A. Babcock, E. K. Pikitch and R. Bonfil 2002. Importance sampling issues in the 1998 Large Coastal Shark assessment. Document presented at the 2002 NMFS Shark Evaluation Workshop, Panama City Florida.

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.

NATIONAL MARINE FISHERIES SERVICE. 2000a. Final Supplemental Environmental Impact Statement Regulatory Amendment 1 To The Atlantic Tunas, Swordfish, And Sharks Fishery Management Plan Reduction Of Bycatch, Bycatch Mortality, And Incidental Catch In The Atlantic Pelagic Longline Fishery June 14, 2000. National Oceanic and Atmospheric Administration National Marine Fisheries Service Office of Sustainable Fisheries Highly Migratory Species Division 1315 East-West Highway Silver Spring, MD 20910

NATIONAL MARINE FISHERIES SERVICE. 2000b. Small Entity Compliance Guide Regulatory Amendment To The Atlantic Tunas, Swordfish, And Sharks Fishery Management Plan. August 9, 2000. (http://www.nmfs.noaa.gov/sfa/hmspg.html)

ORTIZ, M., V. Restrepo, and S. Turner. 2000. North Atlantic swordfish sex-ratios at size keys: analysis and development. ICCAT Collective Volume of Scientific Papers 51; pp. 1480-1509

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

Table 1. Parameters of the model

Symbol	Parameter
a	age
B_o	virgin biomass
$C^1_{g,y,t,a}$	catch of fish during the first half of the year (2: second half of the year)
C_{No}	parameter which shows reduction in age 0 recruits in a given year, compared to the virgin age 0 recruitment.
d_g, b_g	constants used in the weight function
f_g	fraction of the total fish 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
$N^e_{g,y,t,a}$	number of fish of age, a, and sex, g, at the end of time step t, in year, y.
$N^b_{g,y,t,a}$	number of fish of age, a, and sex, g at the beginning of time step t, in year, y.
$N^{\exp l}_{y,t,j}$	exploitable number of fish for gear, j
$p(\theta_n)$	joint prior probability density function for a set of values of the estimated parameters, θ_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
$\sigma_{j,k}$	lognormal standard deviation for residual errors between the observed and predicted values for each series of relative fish abundance
t	time step
$u_{y,t,j}$	exploitation rate per gear, j, at time step, t
$v_{g,a,j}$	fish vulnerability to gear j at age a and sex g
y	year
y_1	year when the exploitation started
$w_{g,a}$	weight of fish
Φ_a	proportion of mature female fish at age a
$\overline{\Phi}_a$	fecundity at age, a

Table 2. Parameter values used in the model implementation.

Parameter	Value	Source
Maturity fraction	Assumed 50% mature at age 5, 100% at age 6+ for both sexes	ICCAT(2000) VPA assumed knife edge maturity at age 5 for both sexes.
Maximum age modelled	40	ICCAT (2000)
Natural mortality	M=0.2	ICCAT (2000) Assumed in the VPA models
Length at age	For females $L_t = 364.69[1-\exp(-0.0262x1.898(t + 0.556))]^{(1/1.898)}$ For males $L_t = 189.58[1-\exp(-0.105x2.009(t + 0.41))]^{(1/2.089)}$	ICCAT(2000) (relationship between lower jaw fork length in cm and age in years).
Weight length relationship	$RWT=4.203x10-6\ LJFL^{3.2133}$	ICCAT (2000), values for Northeast Atlantic
Fecundity[1]	Batch fecundity at size (Lower Jaw Fork Length): $BF=1757430+11.5748 \cdot LJFL^{2.8814}$ at age: $BF=1846990+77.407 \cdot Age^{4.637}$ Total annual fecundity is 88.7 * batch fecundity	Arocha (1997).
Movement assumptions, stock recruit relationship and selectivity	See text	

Table 3. Catches and CPUE data used to fit the model. The 1999 and 2000 data were not used in the estimation part of the calculations

Year	Canada	Ch-Taipei	EC-Espana	Japan	Other	EC-Portugal	USA	CPUE	CPUE-CV
1950	1290	0	1445	0	100	0	911		
1951	1523	0	966	0	200	0	92		
1952	1890	0	966	0	200	0	137		
1953	1990	0	1203	0	200	0	110		
1954	2573	0	305	0	100	0	156		
1955	2722	0	619	0	100	0	161		
1956	2761	0	374	0	0	0	223		
1957	3102	0	1000	10	100	0	366		
1958	3219	0	832	43	100	0	710		
1959	4014	0	1100	28	400	0	690		
1960	2328	0	722	20	300	0	458		
1961	1913	0	1700	54	306	0	408		
1962	2092	0	2300	106	420	0	424		
1963	7482	3	1000	311	144	0	1250	1398.86	0.08
1964	7099	1	1800	700	265	9	1384	501.05	0.05
1965	4674	1	1433	1025	286	6	1227	314.35	0.06
1966	4433	48	2999	658	582	15	614	293.67	0.06

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[1] Note, the current implementation assumed a constant recruitment, so the fecundity information was not used

1967	4794	99	2690	280	759	11	474	351.31	0.06
1968	4393	150	3551	262	530	12	274	284.72	0.05
1969	4257	283	3502	130	850	11	170	258.54	0.05
1970	4800	304	3160	298	638	8	287	296.39	0.06
1971	0	294	3384	914	628	11	35		
1972	0	168	3210	784	337	21	246		
1973	0	316	3833	518	964	37	406		
1974	2	265	2893	1178	807	92	1125		
1975	21	272	3747	2462	579	58	1700	433.51	0.04
1976	15	471	2816	1149	784	32	1429	372.42	0.04
1977	113	246	3309	793	998	38	912	392.43	0.05
1978	2314	164	3622	946	1088	17	3684	627.49	0.05
1979	2970	338	2582	542	857	29	4619	355.6	0.05
1980	1885	134	3810	1167	922	15	5625	478.38	0.04
1981	561	182	4014	1315	565	13	4530	333.95	0.04
1982	554	260	4554	1755	671	11	5410	385.78	0.03
1983	1088	272	7100	537	701	9	4820	280.03	0.03
1984	499	164	6315	665	385	14	4749	276.91	0.03
1985	585	152	7441	921	557	22	4705	266.85	0.03
1986	1059	157	9719	807	1066	468	5210	256.75	0.03
1987	954	52	11135	413	1441	994	5247	235.11	0.02
1988	898	23	9799	621	1384	617	6171	232.53	0.02
1989	1247	17	6648	1572	1055	300	6411	222.13	0.02
1990	911	270	6386	1051	1060	475	5519	209.34	0.02
1991	1026	577	6633	992	408	773	4525	217.24	0.02
1992	1547	441	6672	1064	893	542	4235	201.22	0.02
1993	2234	127	6598	1126	422	1961	4190	183.19	0.02
1994	1676	507	6185	933	318	1599	4074	166.63	0.02
1995	1610	489	6953	1043	460	1617	4552	176.71	0.02
1996	739	521	5547	1494	794	1703	4147	142.68	0.02
1997	1094	509	5140	1218	621	903	3432	147.61	0.02
1998	1167	286	4079	1391	982	773	3491	165.24	0.02
1999	1154	285	3993	1212	862	777	3402		
2000	1018	347	4595	771	395	732	3353		

Table 4. Catches and discards of small and large fish inside and outside of closed areas, used to modify the selectivities of the fleets. (a) U.S. closed areas, landings and discards in tonnes from Cramer (2002), ICCAT (2001). (b) International closed areas. Numbers refer to catch in numbers inside and outside the 20 5x5 squares with the highest small fish catch in numbers in each quarter, for the U.S. and Spanish fleets in 1998, from ICCAT 2000, Fig. 3, Cramer (2002) Fig. 2, ICCAT (2001).

(a)

Year	landings open	discards open	discards total	catch total
1999	2249	264	494	3402
2000	2323	359	490	3353

(b)

		<125 open	>125 open	<125 total	>125 total
	Total numbers	16411	54391	94420	155636
Numbers	Spain	9518	28283	54764	80931
	USA	6893	26108	39657	74705
Tonnes	Spain	143	1329	821457	3803736
	USA	103	1227	595	3511
Tonnes adjusted to give correct total catch	Spain	121	1130	698	3295
	USA	88	1043	506	2896

Table 5. Summary statistics for the marginal posterior distribution of unfished spawning stock biomass, recruitment constant, unfished total numbers, total numbers in 1998, spawning stock biomass in 1998, ratio of SSBcur to SSBo, and ratio of Ncur to No.

	Virgin SSB ($x10^6$ kg)	Recruitment const	Virgin number of fish ($x10^3$)	1998 number of fish ($x10^3$)	1998 SSB ($x10^6$ kg)	SSB-ratio	N-ratio
Mean	281	1.31	6101	2970	68	0.23	0.48
CV	0.17	0.08	0.17	0.31	0.56	0.45	0.21
Sd	50	0.11	1085	955	40	0.11	0.10
Median	279	1.31	6068	2945	65	0.24	0.49
5th percentile	199	1.13	4318	1501	11	0.05	0.31
95th percentile	345	1.47	7512	4547	137	0.40	0.64

Table 6. Selectivity modifications for juvenile fish a) in the U.S. fleet to reflect U.S. closed areas, b) for international closed areas (the U.S. selectivity is different).

(a)

Entire fishery				
Age	Season 1 Females	Season 2 Females	Season 1 Males	Season 2 Males
0	0.04	0.04	0.07	0.07
1	0.13	0.13	0.19	0.19
2	0.35	0.35	0.48	0.48
Fishery in open areas only				
0	0.03	0.03	0.06	0.06
1	0.11	0.11	0.15	0.15
2	0.28	0.28	0.38	0.38

(b)

Fleet	Age	Season 1 Females	Season 2 Females	Season 1 Males	Season 2 Males
Entire fishery					
US	0	0.04	0.04	0.07	0.07
	1	0.14	0.14	0.19	0.19
	2	0.36	0.36	0.48	0.48
Spain	0	0.02	0.02	0.14	0.14
	1	0.11	0.11	0.40	0.40
	2	0.28	0.28	0.59	0.59
Fishery in open areas only					
US	0	0.02	0.02	0.04	0.04
	1	0.07	0.07	0.10	0.10
	2	0.20	0.20	0.26	0.26
Spain	0	0.01	0.01	0.07	0.07
	1	0.06	0.06	0.21	0.21
	2	0.14	0.14	0.31	0.31

Table 7. Decision analysis results for closed areas in the U.S. EEZ. DR refers to the discard ratio discards/discards plus catches in weight. N_0 and SSB_0 refer to virgin total numbers and spawning stock biomass, respectively.

	Full migration					Saved fish stay in closed area 6 months				
	Prob. N_{2020} $>0.5N_0$	Prob SSB_{2020} >0.5 SSB_0	Prob $DR_{2020,US}$ <0.75 $DR_{2000,US}$	Exp val $DR_{2020,US}/DR_{2000,US}$	Exp val $DR_{2020,US}$	Prob. N_{2020} $>0.5N_0$	Prob SSB_{2020} >0.5 SSB_0	Prob $DR_{2020,US}$ <0.75 $DR_{2000,US}$	Exp val $DR_{2020,US}/DR_{2000,US}$	Exp val $DR_{2020,US}$
No closed area, Catch= 2000 Catch	0.72	0.07	0.28	0.77	0.11	0.72	0.07	0.28	0.77	0.11
Closed area, Catch= 2000 Catch	0.72	0.07	0.99	0.63	0.09	0.91	0.14	0.99	0.58	0.09
No closed area, Catch= 2000 catch less catch in closed area	0.77	0.11	0.39	0.74	0.11	0.77	0.11	0.39	0.74	0.11
Closed area, Catch= 2000 catch less catch in closed area	0.77	0.11	0.99	0.60	0.09	0.95	0.19	0.99	0.56	0.08

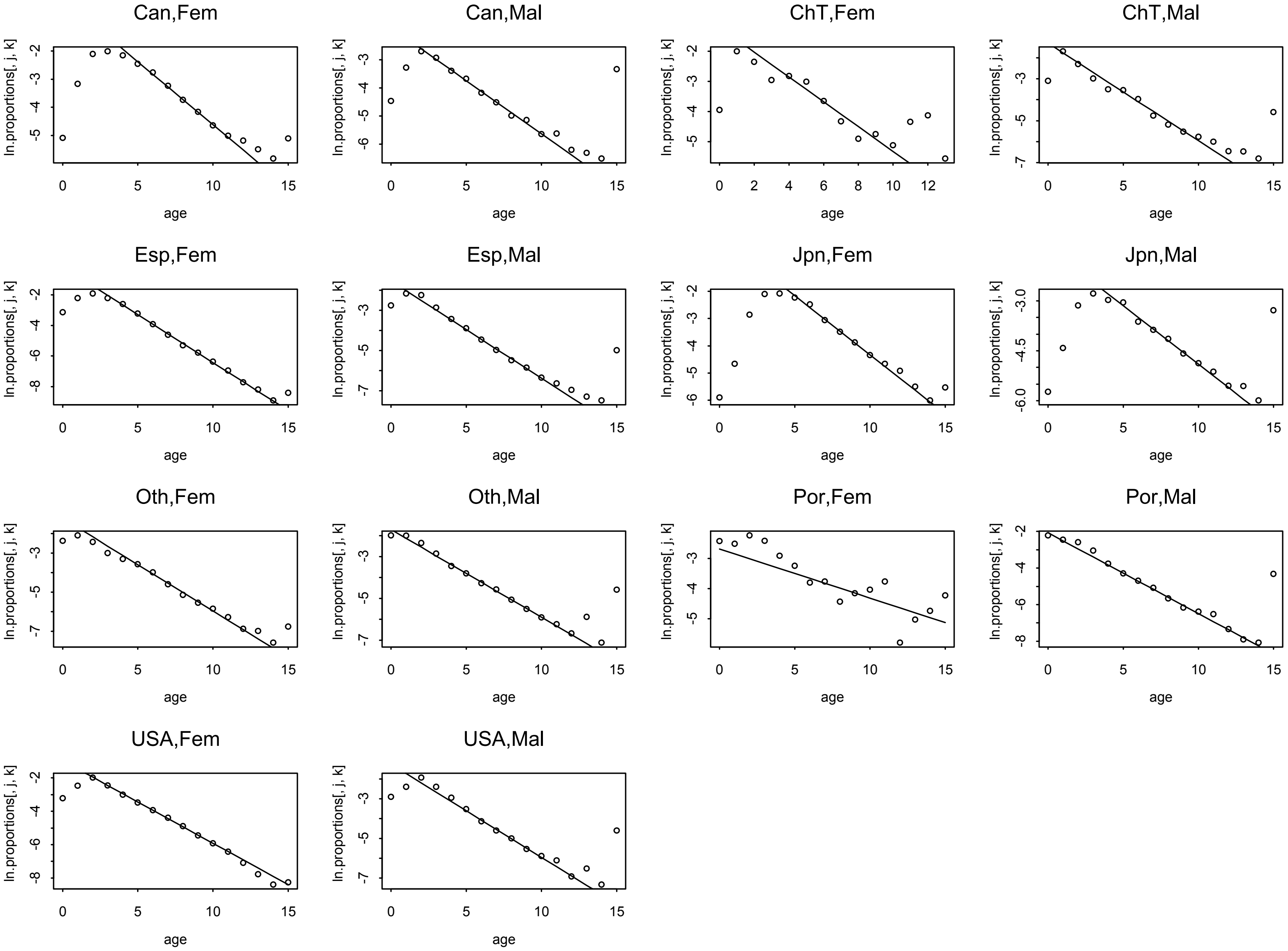


Figure 1. Log of proportions by age and sex in the catch in numbers of each fleet, with predicted values from a linear regression on age 5 - 10.

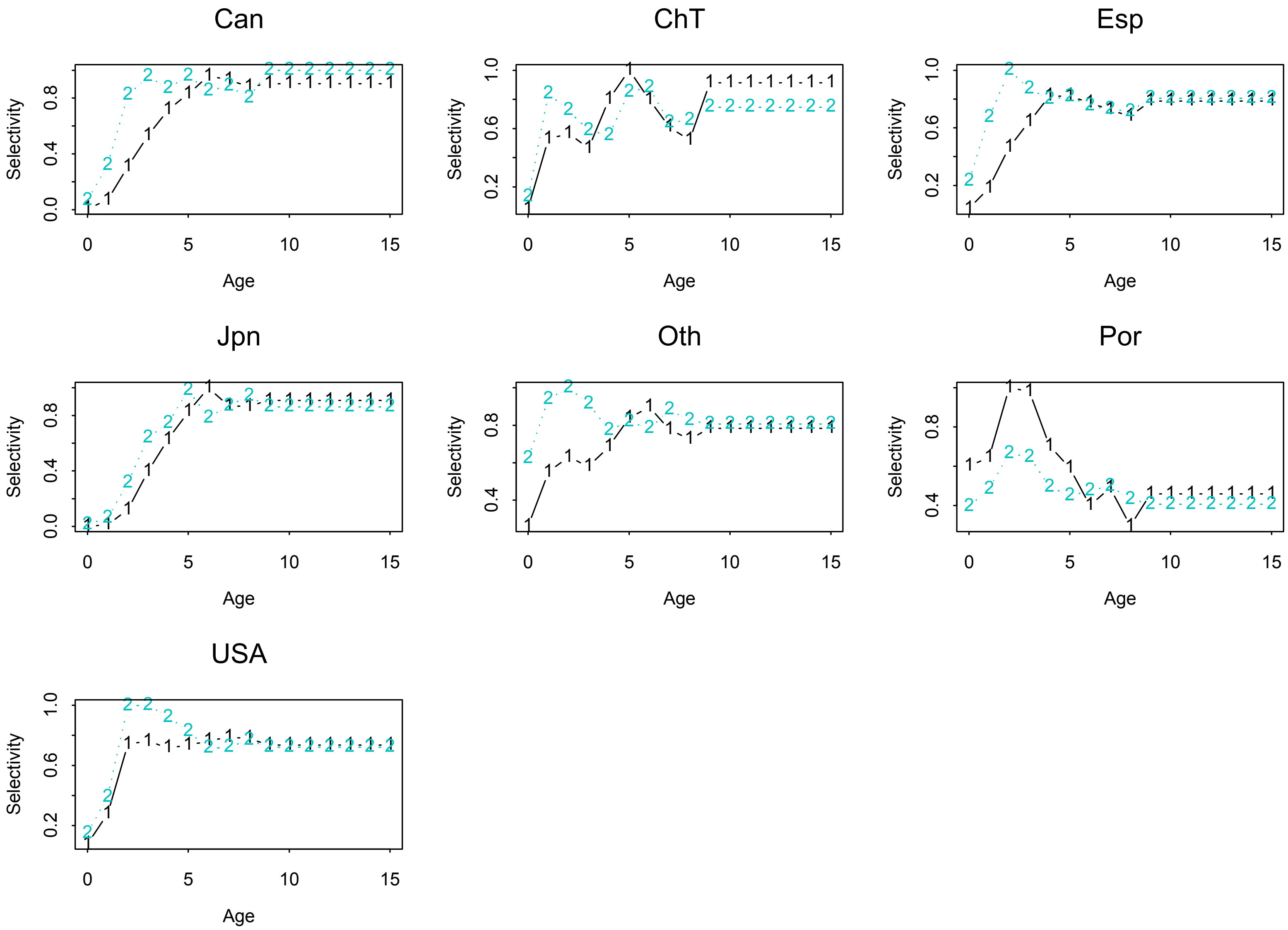


Figure 2. Longline selectivity by sex (1, female; 2, male) and fleet (Can,Canada; ChT, Chinese Taiepei; Esp, Spain; Jpn, Japan; Oth, all other fleets; Por, Portugual), calculated from catch proportions averaged over 1996-1998.

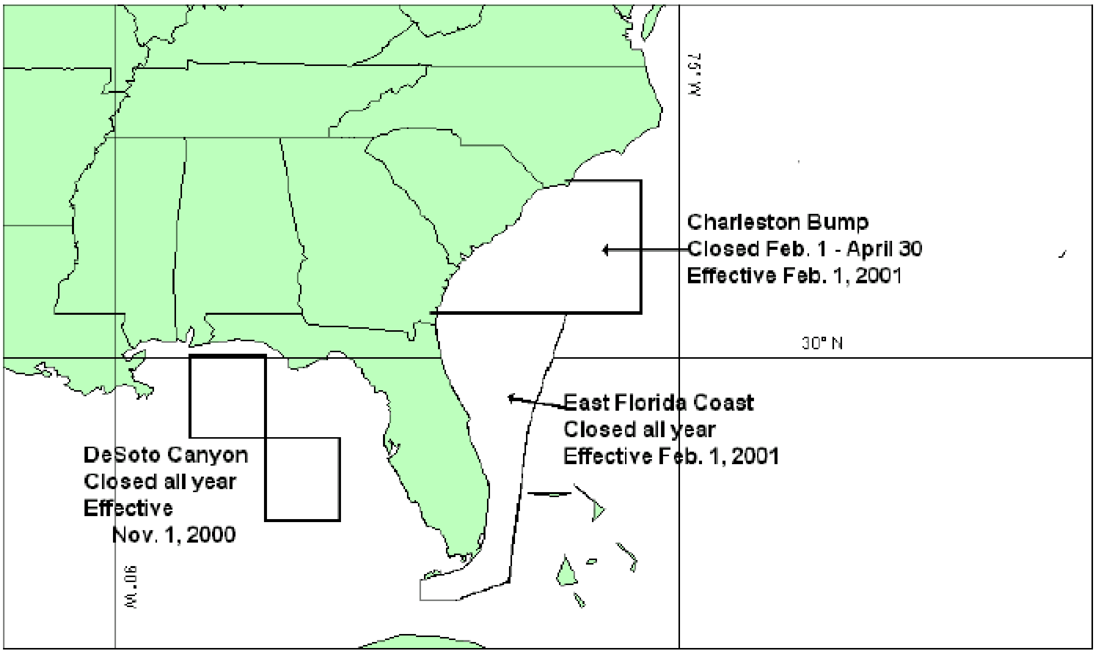


Figure 3. U.S. closed areas, from NMFS 2000b.

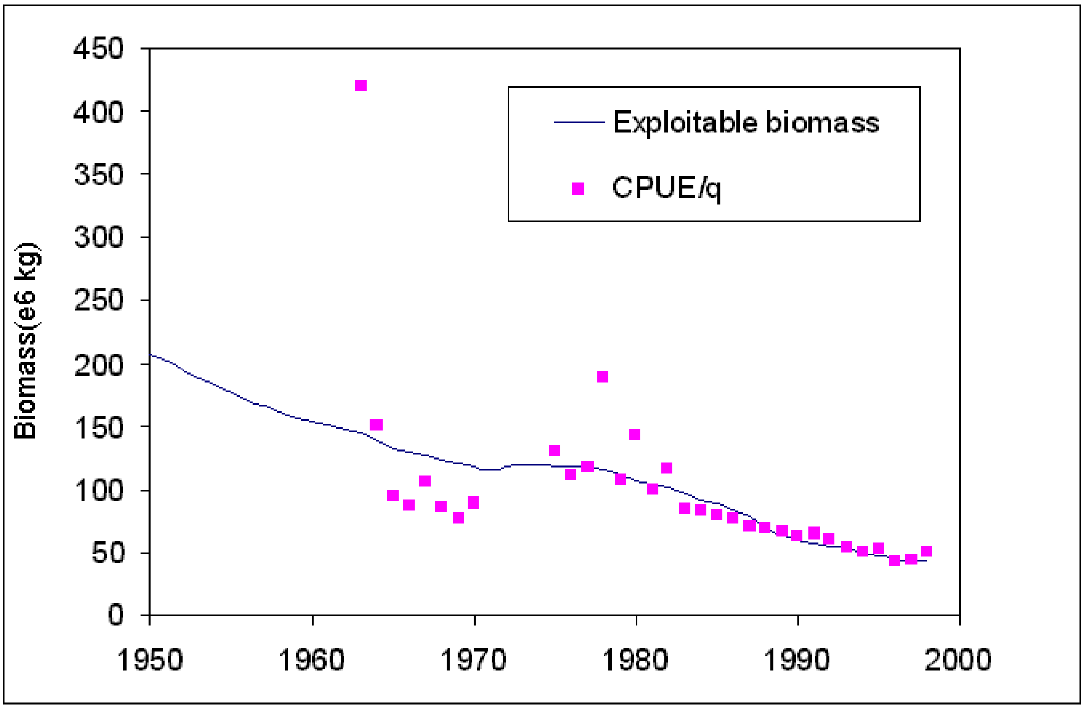
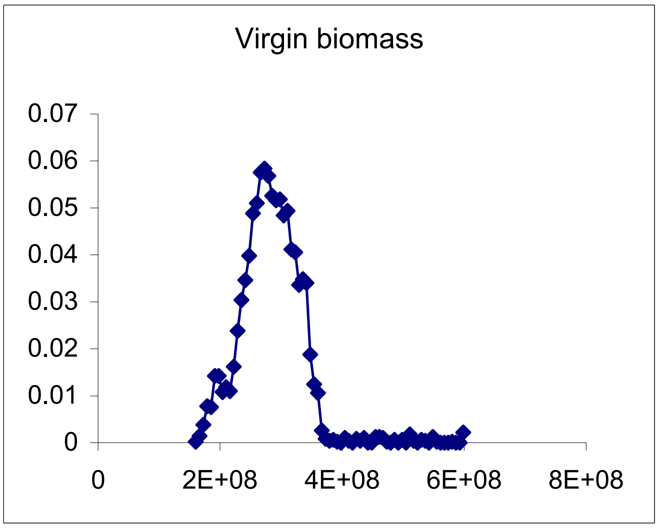


Figure 4. Exploitable biomass trajectory at the mode of the posterior distribution compared to the North Atlantic biomass CPUE index divided by the MLE estimate of q.



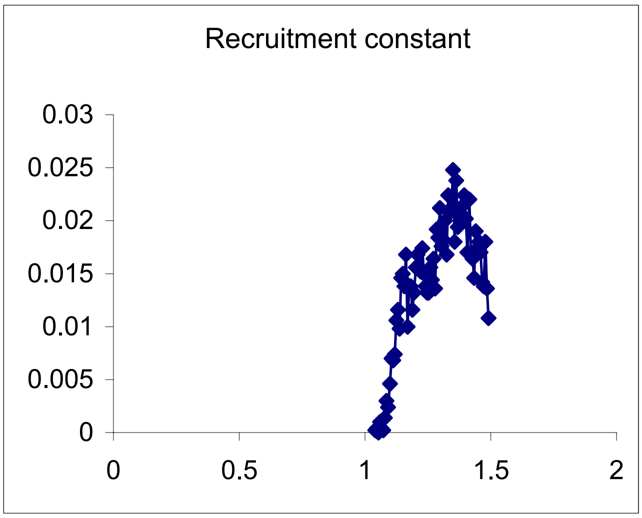
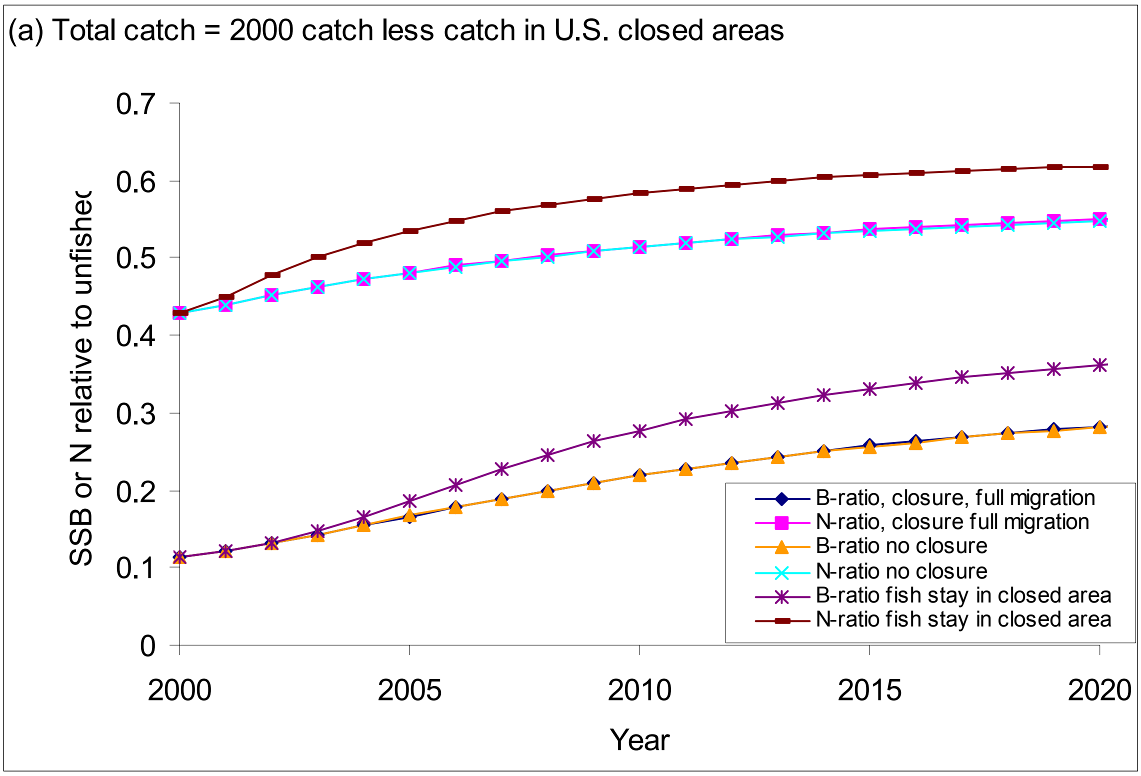


Figure 5. Marginal posterior distributions of unfished spawning stock biomass and the recruitment constant.

(a) Total catch = 2000 catch less catch in U.S. closed areas



(b) Future catches = 2000 catch

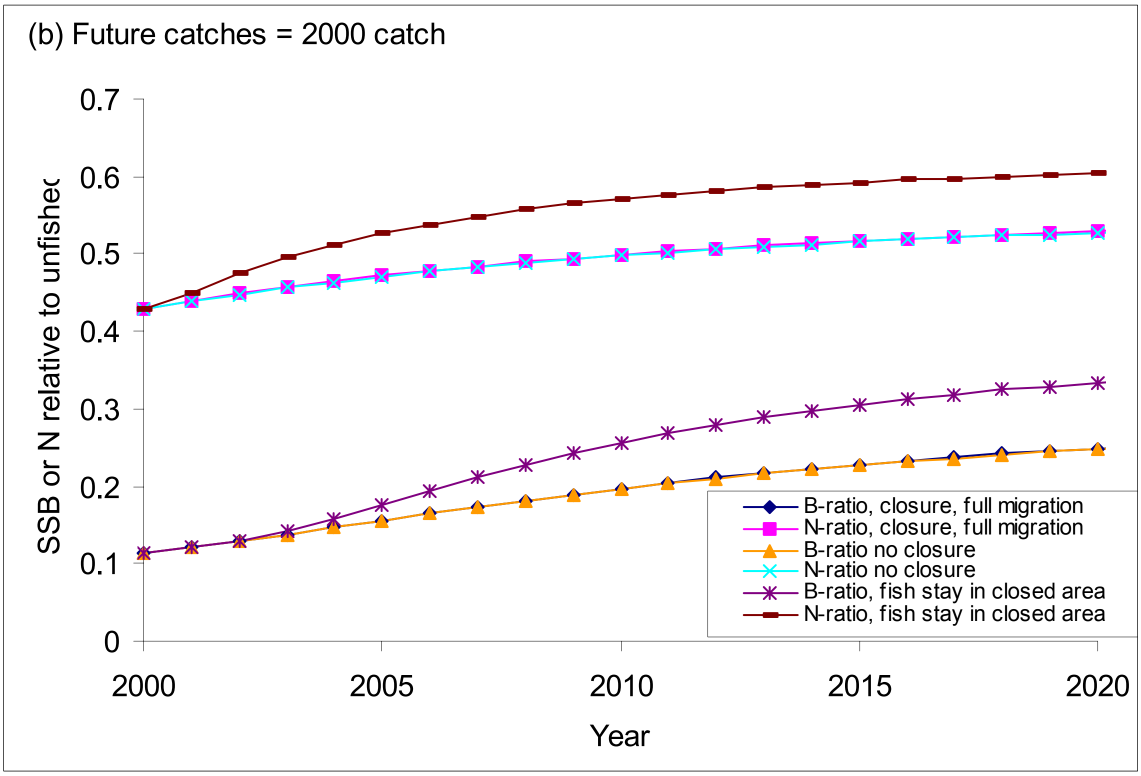


Figure 6 a & b. Deterministic projections at the mode of the posterior distribution of spawning stock biomass and total numbers relative to unfished levels with the U.S. closed areas (Fig. 3) and two different assumptions for future catches.

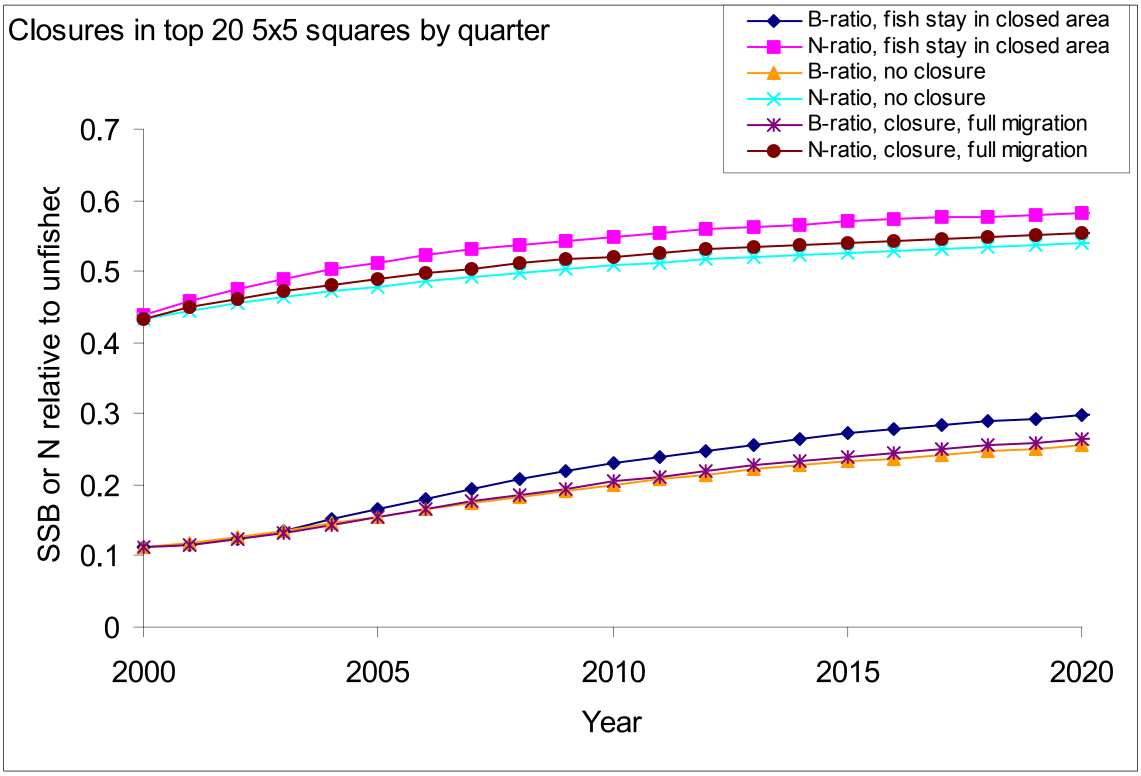


Figure 7. Deterministic projections at the mode of the posterior distribution of spawning stock biomass and total numbers relative to unfished levels with the international closed area. Catches in 2001 and later equal the year 2000 catch.