

Annex B1.10

The Assessment of Iberian Sardine: A Bayesian State-Space Model Incorporating Migration and Spatially-Disaggregated Data

C.L. Cunningham¹ and B.A. Roel²

1: Marine Resource Assessment and Management Group, Department of Mathematics and Applied Mathematics, University of Cape Town, Private Bag X3, Rondebosch, 7701, South Africa. Tel: +27 31 2628102; Fax: +27 31 2628102; E-mail: c.l.cunningham@telkomsa.net. 2: Centre for Environment, Fisheries and Aquaculture Science, Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk, NR33 0HT, United Kingdom.

Introduction

One of the assessment models for Iberian sardine (*Sardina pilchardus*) to be considered as part of work package 7 of the EU-project *Sardine Dynamics and Stock Structure in the North-East Atlantic (SARDYN)*, is that of a Bayesian state-space model. This model, based on the one developed for the North East Atlantic mackerel population (Cunningham 2002), explicitly models the migration of the sardine between different areas during the year and incorporates, where possible, new data resulting from other SARDYN work packages. This model is used to evaluate an initial set of alternative hypotheses of stock-structure and migration.

This document describes the Bayesian state-space model developed for Iberian Sardine. The base case hypothesis assumes one sardine stock, while an alternative hypothesis assumes two stocks. The document is organised as follows. The characteristics of the Iberian sardine to be considered in the hypotheses are described, followed by a description of the Bayesian state-space model. The base case hypothesis, with robustness tests, is outlined and the alternative hypothesis is then described. The results at the posterior mode for the two hypotheses, together with the robustness tests are then given and the posterior probability density functions for the hypotheses are presented. A short discussion of these results follows.

Materials and Methods

When fitting time series models to fishery catch and abundance indices, two stochastic components should be considered. These are process error, the natural variability around the underlying population dynamics model, and observation error, the uncertainty in the observed abundance indices and harvest values due to measurement and sampling error (e.g., Schnute 1994; Meyer and Millar 1999).

State-space models (Carlin *et al.* 1992; Schnute 1994) have been recommended for the estimation of parameters in fisheries time series models for the following reason. They rigorously incorporate both process and observation error by relating time series observations to unobserved states through a stochastic observation model for the observations given the unobserved states. For example, in the context of fisheries population dynamics with lognormally distributed error, the unobserved states of biomass in year t , B_t , can be calculated from a function of the biomass in the previous year, and the process error parameters, u_t , i.e., $B_t = f(B_{t-1})e^{u_t}$, and the observed catch per unit effort in year t , I_t , can be calculated from a function of the biomass in that year, and the observation error parameters, v_t , i.e., $I_t = g(B_t)e^{v_t}$. Thus state-space models reflect the practical reality of most fisheries, in which an unseen population gives rise to collectable data (Schnute 1994).

Bayesian state-space fisheries models have, more recently, also been analysed (e.g., Carlin *et al.* 1992; Kinis 1996; Meyer and Millar 1999; Cunningham 2002).

Iberian Sardine

According to the Vigo Report (ICES 1998) four races for the Atlantic sardine can be identified: *saharienne*, *marocaine*, *iberique* or also called *meridional atlantic* whose distribution area spreads from Gibraltar up to the Cantabric coast and the *septentrional atlantic* from the Cantabric coast up to the British Islands. There was some consistency in the results from the SARDYN project identifying four sardine stocks: Azores, Africa, Mediterranean and NE Atlantic. Differences between stocks appear quite stable over the time of the study.

For the purposes of this model, a southern boundary to the Iberian sardine stock is assumed in the Gulf of Cadiz (ICES division IXa(south-cadiz)). Genetic results have indicated a separate sardine stock from the Gulf of

Cadiz northwards compared to Moroccan waters (SARDYN 2005). Environmental results confirm this. Although some mixing of Iberian and African coastal surface waters in the Gulf of Cadiz does occur, this mixing appears to be at a rather limited scale with the Gulf of Cadiz effectively separating Iberia and Northwest Africa into two parts between which continuity of flow is thought to be largely absent (Barton 1998; E. Mason pers. comm.). Studies using regional temperatures have also indicated the area off western Portugal to be separate from northern Morocco (SARDYN 2005).

The current assessment carried out by the ICES Working Group for the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy (WGMHSA) assumes a northern boundary in the stock between ICES divisions VIIIc(east) and VIIIb (ICES 2004a). Genetic analyses (using msDNA and allozymes) have suggested genetic homogeneity throughout the Atlantic European waters (SARDYN 2005), in agreement with morphometric results (Silva 2003). In addition, spring ichthyoplankton surveys since 1990 indicate a lack of discontinuity in the egg distribution at the inner Bay of Biscay between ICES divisions VIIIb and VIIIc (SARDYN 2005). French acoustic surveys in the past decade have also indicated a high biomass within France with no evidence of major gaps in the distribution at the proposed boundary. However, this above evidence does not exclude the possibility that the degree of mixing across the boundary is sufficient to lead to genetic homogeneity but insufficient to warrant a modification of the current boundary or to assume a substantial rate of immigration or emigration.

One uncertainty surrounding the Iberian sardine population is the number of potential stocks spawning in the area considered by this model. The Galicia Front, which separates Eastern North Atlantic Central Water off western Iberia and cooler, fresher North Atlantic Central Water, may act to produce a barrier between western and northern Iberia. Another physical feature that may act to produce a barrier in the circulation between the western and northern Iberian coasts is their sharply differing orientations and the resultant divergence in the hydro-dynamic response to the (generally homogeneous) wind forcing that occurs there (E. Mason pers. comm.). Discontinuities in the egg distribution during the late 1990s (Carrera and Porteiro 2003; SARDYN 2005) and emerging evidence for faster growth and maturation in northern Spain also suggest a boundary between ICES divisions IXa(north) and VIIIc(west), together with different N isotope ratios between Cantabria and Galicia (albeit for bigger fish), the difference in otolith chemistry between the Bay of Biscay (southern France and Cantabria) and northern Portugal (SARDYN 2005), and finally the later (and narrower) spawning season in the Cantabrian Sea (SARDYN 2005).

Data that potentially oppose such a boundary include the gradual northerly expansion of the 2000 year class that originated in northern Portugal (ICES 2003, 2004a), the lack of clear discontinuities in spawning grounds prior to 1992 (G. Stratoudakis pers comm.), the lack of genetic differences (SARDYN 2005) and the lack of morphometric differences between the Cantabrian Sea and western Iberia (Silva 2003). The most recent results from SARDYN suggest that despite the fact that there are consistent morphological differences between Cantabria and the South there is a continuous stock along the NE Atlantic and a degree of mixing taking place all along. However, fish in the North may have developed local adaptations in a few generations, which may explain genetic differences found (REF?) between sardine in the North Sea and in the Southern part of its distribution.

Base case hypothesis

Due to the lack of data (particularly catch-at-age) available for ICES division VIIIb, sardine north of VIIIc(east) could not be explicitly modelled. The base case hypothesis, H_0 , assumes one self-contained sardine stock extending from ICES division IXa(south-cadiz) in the south to VIIIc(east) in the north. As little information on a stock-recruitment relationship can be extracted from available data, a geometric mean is assumed for the base case.

Model Characteristics

The Bayesian state-space model, explicitly accounting for the assumed migratory characteristics of the population by allowing stock- and age-dependent movement between model divisions at the beginning of each quarter of the year, is detailed in Appendix A. The distribution of the sardine and the harvest rate is assumed to be uniform within each model division, while some model parameters (e.g. catch weights-at-age) differ between model divisions. The sardine are modelled to spawn at the beginning of the first quarter in more southerly divisions and at the beginning of the second quarter along the Cantabrian coast, while recruitment to the population is modelled to occur at the beginning of the third quarter. Catch is modelled to be taken at discrete times during the year using a harvest rate that is year-, quarter- and model division-dependent. Thus the rate of fishing mortality, F , is not explicitly modelled. Rather the catch from each stock is modelled to be proportional to the abundance of each stock's age group in each division, by quarter.

Although a 12+ group can be modelled from 1996 onwards, the lack of data for 6+ age groups in earlier years requires the plus group, $A(y)$ to be year dependent. Thus we have $A(y)=6$ for $y=1978,\dots,1990$, $A(1991)=7$, $A(1992)=8$, $A(1993)=9$, $A(1994)=10$, $A(1995)=11$ and $A(y)=12$ for $y=1996,\dots,2003$.

The model divisions (listed in Table B1.9.1) were determined by the availability of spatially-disaggregated data (in particular catch-at-age, which required ICES divisions VIIIc(east-east) and VIIIc(east-west) to be modelled as one model division) and to try to adequately describe the migration of the sardine (modelled between each model division at the beginning of each quarter). Tagging data (SARDYN, 2005) have indicated movement in both directions between the Algarve (ICES division IXa(south-algarve)) and the Gulf of Cadiz (ICES division IXa(south-cadiz)). Thus ICES divisions IXa(south-algarve) and IXa(south-cadiz) are assumed to be one model division with random movement therein.

The model is fitted to annual catch-at-age data for earlier years and quarterly catch-at-age data for latter years, to DEPM estimates of spawner biomass and to acoustic estimates of relative biomass and numbers-at-age by area (see Appendix A for equations and B for data).

Fixed parameter values and prior distributions for estimated parameters are detailed in Appendix B. Table B1.9.B14 summarises the various sources (eg expert opinion, available observed data, assumptions) used for these parameter values and prior distributions.

Robustness Tests

The robustness tests are listed in Table B1.9.2.

Biological data by country

Proportion mature-at-age and stock weight-at-age data are available by country from 1991-2003. These data were not used in the base case in order to preserve continuity in the SSB estimates between 1978-1990 and 1991-2003. In this robustness test, R_{data} , the effect of this updated data on the results was tested. These data are listed together with the data for the base case in Appendix B.

Plus group

In the base case, the maximum possible plus group, up to 12+ was assumed. However, precision in aging 6+ sardine is low. In this robustness test, R_{6+} , a plus group of age 6+ was assumed for all years, in accordance with that currently assumed by the WGMHSA. Any data available for ages 7 to 12+ were incorporated into the 6+ group (see Appendix B).

Natural mortality

The WGMHSA currently assumes a natural mortality of 0.33 per year for all ages for the Iberian sardine stock. This assumption is used in the base case hypothesis. Alternative estimates of natural mortality were calculated using a method based on growth parameters and water temperature (Pauly 1980) (see Table B1.9.3). Since a natural mortality of 0.7 is probably unrealistic, the second robustness test, R_M , therefore differs from the base case hypothesis in assuming $M(a) = 0.6$, $a = 0, \dots, A(y)$.

Stock recruitment

The base case hypothesis assumes no stock-recruitment relationship (i.e. recruitment distributed about a geometric mean, see Appendix A). As spawning may be negatively affected by high biomass (Myers *et al.* 1995; ICES 2004b), R_{Ricker} assumes a Ricker stock-recruitment relationship. In this case, equation (A.3) is replaced by

$$R_s(y) = \alpha_s SSB_s(y) \exp\{b SSB_s(y)\} \exp\{\epsilon_R(y)\} \quad (1)$$

where

α_s - denotes the slope at the origin of the stock-recruitment curve for stock s .

b - denotes the second Ricker stock-recruitment parameter

$SSB_s(y) = \sum_{d=1}^D SSB_s(y, d)$ - denotes the total SSB for stock s in year y .

$\epsilon_R(y)$ - denotes the lognormal process error (or recruitment residual) in recruitment.

In addition, equation (A.12) is replaced by

$$\bar{R}_s = \alpha_s \overline{SSB}_s \exp\{b \overline{SSB}_s\}, \quad \overline{SSB}_s = \sum_{a=1}^{A(y)} \bar{w}(a) \bar{P}(a) \bar{N}_s(1, a) \quad (2)$$

where

$\bar{w}(a)$ - denotes the equilibrium stock weights at age a .

$\bar{P}(a)$ - denotes the equilibrium proportion mature at age a .

For this robustness test, 1979, 1980 and 1983 were fixed as good recruitment year classes (to match that estimated for H_0) for the purposes of the migration matrices. An uninformative uniform prior distribution between 0 and 50 was assumed for α_s , while $b = 0.0000015$ was fixed externally as there was insufficient information to estimate this latter parameter.

Maximum age in Portuguese waters

Few 7+ sardine have been observed in Portuguese waters. In this robustness test R_7 , all sardine in ICES divisions IXa(central-north), IXa(central-south), IXa(south-algarve) and IXa(south-cadiz) (i.e., model divisions 4 to 6) are modelled to die as they reach age 7, so no 7+ sardine are modelled in these model divisions. In this case, equation (A.1) is modified as follows:

$$N_s(y, q, a, d) = \sum_{d_i=1}^D o_s(y, q, a, d_i, d) [N_s(y, q-1, a, d_i) - C_s(y, q-1, a, d_i)] \exp\left\{-\frac{1}{4}M(a)\right\}$$

$$q = 2, \dots, 4, \quad a = 1, \dots, A(y), \quad d = 1, \dots, D$$

$$N_s(y, 1, a, d) = \sum_{d_i=1}^D o_s(y, 1, a, d_i, d) [N_s(y-1, 4, a-1, d_i) - C_s(y-1, 4, a-1, d_i)] \exp\left\{-\frac{1}{4}M(a-1)\right\}$$

$$a = 1, \dots, A(y)-1, \quad d = 1, \dots, 3$$

$$N_s(y, 1, a, d) = \sum_{d_i=1}^D o_s(y, 1, a, d_i, d) [N_s(y-1, 4, a-1, d_i) - C_s(y-1, 4, a-1, d_i)] \exp\left\{-\frac{1}{4}M(a-1)\right\}$$

$$a = 1, \dots, 7, \quad d = 4, \dots, 6$$

$$N_s(y, 1, A(y), d) = \sum_{d_i=1}^D o_s(y, 1, A(y), d_i, d) [N_s(y-1, 4, A(y)-1, d_i) - C_s(y-1, 4, A(y)-1, d_i)] \exp\left\{-\frac{1}{4}M(A(y)-1)\right\}$$

$$+ \sum_{d_i=1}^D o_s(y, 1, A(y), d_i, d) [N_s(y-1, 4, A(y), d_i) - C_s(y-1, 4, A(y), d_i)] \exp\left\{-\frac{1}{4}M(A(y))\right\}$$

$$d = 1, \dots, 3$$

In addition, no movement is allowed for ages 8+ from model division 3 to model division 4 at the beginning of the third quarter (i.e. 100% of sardine in division 3 at the beginning of quarter 3 remain in division 3, as opposed to the 95% assumed for the base case, see Table B1.9.B1). Observed catch-at-age 8+ in model divisions 4 to 6 is added to catch-at-age 7. Thus, although the model still fits to proportions-at-age 8+ in the catch from 1998 to 2003 (equation A.13), these older age groups only consist of sardine from model divisions 1 to 3.

Immigration/emigration between ICES divisions VIIIc(east) and VIIIb

Robustness test $R_{\text{immigration}}$ represented a first attempt at modelling any potential immigration from ICES division VIIIb into the Iberian sardine stock in VIIIc(east) or emigration from VIIIc(east) to VIIIb. In this case an error term accounting for immigration/emigration between model division 1 and ICES division VIIIb was included at the beginning of each year:

$$N_s(y, 1, a=1, d=1) = \sum_{d_i=1}^D o_s(y, 1, 1, d_i, 1) [N_s(y-1, 4, 0, d_i) - C_s(y-1, 4, 0, d_i)] \exp\left\{-\frac{1}{4}M(0)\right\} \exp\{\varepsilon_{imm}\}$$

$$N_s(y, 1, a, 1) = \sum_{d_i=1}^D o_s(y, 1, a, d_i, 1) [N_s(y-1, 4, a-1, d_i) - C_s(y-1, 4, a-1, d_i)] \exp\left\{-\frac{1}{4}M(a-1)\right\} \exp\{\varepsilon_{em}\}$$

$$a = 2, \dots, A(y)-1$$

$$N_s(y, 1, A(y), 1) = \sum_{d_i=1}^D o_s(y, 1, A(y), d_i, 1) [N_s(y-1, 4, A(y)-1, d_i) - C_s(y-1, 4, A(y)-1, d_i)] \exp\left\{-\frac{1}{4}M(A(y)-1)\right\} \exp\{\varepsilon_{em}\}$$

$$+ \sum_{d_i=1}^D o_s(y, 1, A(y), d_i, 1) [N_s(y-1, 4, A(y), d_i) - C_s(y-1, 4, A(y), d_i)] \exp\left\{-\frac{1}{4}M(A(y))\right\} \exp\{\varepsilon_{em}\}$$

The same error term was used for all years, with a separate error for age 1 and ages 2+. Prior information suggested a net immigration into the Iberian sardine stock for age 1 and a net emigration for age 2+, therefore the prior distributions $\varepsilon_{imm} \sim N(0.1, \sigma_R^2)$ and $\varepsilon_{em} \sim N(-0.05, \sigma_R^2)$ were used.

Split of SSB at Equilibrium

As there was little prior information to determine the split of SSB between ICES divisions VIIIc(east) to IXa(north) and ICES divisions IXa(central-north) to IXa(south-cadiz) at equilibrium, two robustness tests were conducted to test the base case assumption of a ratio of 85% biomass in the Portuguese area compared to 15% in the Spanish area at equilibrium (cf pg 44). $R_{50:50}$ assumed a 50% split in the SSB at equilibrium, while $R_{70:30}$ assumed 70% of the biomass was distributed in ICES divisions IXa(central-north) to IXa(south-cadiz), while 30% was distributed in VIIIc(east) to IXa(north).

No Alternative Migration Matrices for Good Year Classes

In order to test the assumption in H_0 of alternative migration patterns for year classes of good recruitment, $R_{Migration}$ assumed that the same migration matrices of Table B.7.3.B1a applied to all year classes. Thus no distinction was made between normal/weak and good recruitment year classes in terms of their migration patterns.

Alternative Hypothesis

As mentioned above, the number of stocks occupying the area considered by this model is uncertain. Sardine from ICES division VIIIc(east), and in particular from VIIIc(east-east) have a different age-distribution to sardine from the rest of the Iberian coast, suggesting that sardine from this area may be of a different stock (ICES 1998, 2003, 2004a). Further, the observed age distribution in ICES division VIIIc(west) and IXa(north) are similar, suggesting sardine from these two divisions may be from the same stock (ICES 1998, 2003, 2004a). The alternative two-stock hypothesis, H_{2Stock} , considers a boundary assumed between ICES divisions VIIIc(west) and VIIIc(east). Thus the one stock is assumed to extend from ICES division IXa(south-cadiz) northwards to VIIIc(west) and the other stock is distributed throughout VIIIc(east).

An extra parameter, R_{max_2} is estimated in H_{2Stock} for the second stock (distributed throughout ICES division VIIIc(east)). The equilibrium catch was split between stocks assuming that the historic catch in ICES divisions VIIIc(east) and VIIIc(west) was, on average, equal. This gave $\bar{B}_1 = 123000$ and $\bar{B}_2 = 19000$. The split of adult sardine between areas at equilibrium and the percentage split of recruits by division were adjusted pro-rata, taking into account the fact that stock 1 (extending from IXa(south) to VIIIc(west)) is not assumed to be distributed in model division 1 (ICES division VIIIc(east)). Thus $SplitEq(1) = 0$, $SplitEq(2) = 0.1$, $SplitEq(3) = 0.02$, $SplitEq(4) = 0.35$, $SplitEq(5) = 0.18$ and $SplitEq(6) = 0.35$ for stock 1 and $SplitEq(1) = 1$ and $SplitEq(d) = 0$, $d = 2, \dots, 6$ for stock 2. Similarly $o_1^{Recruit}(y,1) = 0$, $o_1^{Recruit}(y,2) = 0.04$, $o_1^{Recruit}(y,3) = 0.11$, $o_1^{Recruit}(y,4) = 0.59$, $o_1^{Recruit}(y,5) = 0.08$ and $o_1^{Recruit}(y,6) = 0.18$ for stock 1 for normal year classes, while $o_1^{Recruit}(y,4) = 0.68$ and $o_1^{Recruit}(y,6) = 0.09$ for good year classes. $o_2^{Recruit}(y,1) = 1$ and $o_2^{Recruit}(y,d) = 0$, $d = 2, \dots, 6$ for stock 2 for all year classes.

Bayesian Integration

The posterior probability density functions (pdfs) were generated using the Sampling Importance Resampling (SIR) algorithm (e.g., Rubin 1988, Geweke 1989, West 1993), with a multivariate t-distribution importance function with 15 degrees of freedom. One million samples were run using this importance function with mean estimated by the joint posterior mode. As convergence to the posterior was initially slow, an adaptive step was taken (Kinas 1996). A sample was taken from this initial run to calculate a new mean and covariance matrix for an updated importance function. 20 million draws were then sampled to achieve acceptable convergence diagnostics (Table B1.9.4). The results presented in this document were calculated from 10 000 draws from the posterior probability density function using resampling without replacement

The marginal posterior probability for the two hypotheses were calculated using the method for importance sampling outlined in McAllister and Kirchner (2002), with both hypotheses assumed to have equal prior probabilities.

Results

Results at the Posterior Mode

Base case hypothesis

The base case hypothesis fits the observed DEPM estimates of SSB for Portuguese waters ($d = 4, \dots, 6$) well, but overestimates the observations for Spanish waters ($d = 1, \dots, 3$) (Figure B1.9.1). Immigration/emigration

between ICES divisions VIIIc(east) and VIIIb has been hypothesised. Such a hypothesis would seem to fit with these results, especially if movement was in a south-westerly direction in the late 1980s and in a north-easterly direction in the mid to late 1990s. However, immigration/emigration was not modelled as part of the base case hypothesis (see discussion for further explanation). A further reason for the over-estimation of Spanish SSB could be that migration patterns changed between the 1980s and the 1990s, or that the proportion of recruitment in Spanish waters, compared to Portuguese waters, has changed. There is currently insufficient information to further investigate such hypotheses.

The model is not able to fit the few observed proportions of SSB by division well, instead predicting proportions of SSB by division to remain relatively constant over the years (Figure B1.9.2). The SSB consists of a number of year classes. Although alternative movement matrices are assumed for good year classes, these matrices are only applied to three year classes in the base case (see below). Thus the same movement matrices are assumed for most adults, and especially so in the latter half of the time-series for which observed proportions of SSB by division are available. It is possible that the movement of the sardine differed from the 'norm' in some years, resulting in the observed distribution pattern. However, such information was not available for inclusion in this model.

The model fit to the annual and quarterly catch numbers (over all ages and model divisions) is good (Figure B1.9.3). The model fit to the annual and quarterly proportions-at-age in the catch is also good (see selected results in Figure B1.9.4). The only exception to this is between 1994-1996, when the model predicts a higher proportion-at-age 1 and 2 and a lower proportion-at-age 3 and 4. A single commercial selectivity curve is used for all years and quarters (equation A.4, Table B1.9.5, Figure B1.9.5), which appears sufficient for pre-1994 and post-1996. There may have been other external forces operating in these years such that a different selectivity was effectively applied by commercial fleets.

The model fit to the observed proportions-at-age in the Portuguese first and fourth quarter acoustic surveys are generally good (see selected results in Figures B1.9.6 and B1.9.7), as is the fit to the Spanish first quarter acoustic survey (see selected results in Figure B1.9.8). There appears to be a greater tendency to under- rather than over-estimate the proportion of 0-group in the fourth quarter and the proportion of 1-year-olds in the first quarter Portuguese surveys, while the model has a greater tendency to predict a higher proportion of 1-year-olds in the first quarter Spanish acoustic survey in division 3 than that observed, especially prior to 1992.

This may be a result of the estimated selectivity curve not allowing sufficient selectivity of 0-group sardine. As expected, the fitted acoustic selectivity curves are flatter than the commercial selectivity curves, with a greater selectivity of younger sardine prior to 1993 (Figure B1.9.5). Alternatively the model assumptions may not allocate sufficient recruits to the Portuguese areas (compared to the Spanish areas) together with a potential mismatch in the migration matrices for model division 3. As mentioned above, migration may also have changed over the years, for which there is no current information available to include in such a model. A final reason for the mismatch between observed and predicted proportions at younger ages could be differences in the acoustic selectivity between Spanish and Portuguese surveys.

Although the model is unable to fit the observed area-specific relative acoustic estimates of biomass closely in each year, the model predicted relative biomass by division averages through the observed data points (Figure B1.9.9). The observed absolute estimates of SSB from the DEPM surveys (Figure B1.9.1) are used to estimate the multiplicative bias factors for the acoustic survey estimates. Multiplicative bias for the Portuguese acoustic survey biomass is estimated at 1.9, i.e. observed indices almost double true biomass. In contrast, the model predicts that the observed Spanish acoustic survey biomass underestimates true biomass, with $q_{Sp,Ac} = 0.77$ (Table B1.9.5).

The geometric mean of recruitment, R_{max_s} , is estimated to be 8.0 billion (Table B1.9.5, Figure B1.9.10). For migration matrix purposes, a "good" recruitment year class was classified as one for which $\epsilon_R(y) > 0.2$ (cf pages 42-43). The model estimated 1979, 1980, 1981 and 1983 to be good recruitment year classes, while $\epsilon_R(1991)$ and $\epsilon_R(2000)$ were estimated just below 0.2. These latter two years have generally been recognised as "good" recruitment year classes. The model's preference for estimating these two year classes to be just below the cut-off for a "good" recruitment year class may indicate that the movement matrices assumed for normal and weak year classes better reflects the movement of these two year classes than that assumed for "good" recruitment year classes.

Biological data by country

The model predicted SSB in model divisions 1 to 3 for R_{data} differs from that for H_0 (Figure B1.9.1). This is primarily due to the higher stock weights for the Spanish area from 1991-1993 and 1996-2003, resulting in the sudden increase in the trajectory in 1991. The lack of data for the Spanish area in 1994 and 1995 result in a decrease in the SSB due to the lower stock weights for the full area. R_{max} is estimated to be lower at the posterior mode than that estimated for H_0 (Table B1.9.5). There is no noticeable difference in the model fit to the catch-at-age or total catch data, nor to the proportions-at-age in the acoustic surveys when compared to H_0 . The model fit to the acoustic relative biomass in ICES division IXa(north) differs from H_0 , again reflecting a higher biomass from 1991, with a dip in 1994 due to the stock weights for the Spanish area being higher than those for the total area (Figure B1.9.9).

Plus group

There are fewer data points for this robustness test, since the proportions-at-age for ages 6 to 12+ are now combined into 6+. There is little difference in the model fit to the data for R_{6+} compared to H_0 (Table B1.9.5).

Natural mortality

As expected, a much higher R_{max} was estimated under R_M compared to H_0 (Table B1.9.5), since a higher recruitment is required, given the higher natural mortality, in order for the same SSB to be predicted by the model. In addition, 1981 and 1991 were also estimated as good recruitment years, with $\varepsilon_R(1987)$, $\varepsilon_R(1992)$ and $\varepsilon_R(2000)$ estimated just below 0.2 (Table B1.9.5). The model fit to the DEPM estimates of SSB was slightly poorer than that for H_0 (Table B1.9.5, Figure B1.9.1).

The model fit to the annual and quarter catch numbers was improved from H_0 and there was an improvement in the overall fit to the proportions-at-age in the catch (although the fit in some individual years is poorer) (Table B1.9.5, Figure B1.9.4). The model predicted proportions-at-age in the quarterly catch for R_M are very similar to that for H_0 , with a slightly poorer fit for some of the younger ages (Figure B1.9.4). There is no improvement on the mismatch between model predicted and observed proportions-at-age in the catch from 1994 to 1996.

The estimated commercial selectivity curve is different for R_M compared to H_0 , with less selectivity on lower (more abundant) ages (Figure B1.9.5). Even though there is a change in the parameters estimated for acoustic selectivity (Table B1.9.5), the resultant curves for R_M are very similar to those for H_0 (Figure B1.9.5).

In general, a better fit to the proportions-at-age 0 and 1 in the Portuguese acoustic surveys was obtained under R_M compared to H_0 , but overall the fit to the proportions-at-age in the acoustic surveys was worse than that for H_0 (Table B1.9.5, Figures B1.9.6-8). The overall fit to the total relative biomass from acoustic surveys is not as good for R_M compared to H_0 (Table B1.9.5, Figure B1.9.9).

In summary, the assumptions for this robustness test appear to be in conflict with the data. By assuming $M = 0.6$, the model predicts fewer older sardine. These fewer older sardine result in a worse fit to the proportions-at-age in the catch and acoustic surveys. In order for the model to fit these data, the fit to the DEPM estimates of SSB is worse.

Stock recruitment

The model fit to the DEPM estimates of SSB is poorer for R_{Ricker} compared to H_0 (Table B1.9.5, Figure B1.9.1). In particular, the model predicted SSB is higher than that predicted under H_0 in the latter years. The overall fit to proportions-at-age in the catch and to the total catch is better than that for H_0 (Table B1.9.5, Figure B1.9.4).

The model fit to the proportions-at-age in the acoustic surveys is improved over that for H_0 (Table B1.9.5), although there is no single age or area of noticeable improvement in the fit (Figures B1.9.6-8). The acoustic selectivity curve for 1994 to 2003 differs from that estimated for H_0 , with a lower selectivity on older age groups (Figure B1.9.5). The fit to the relative acoustic biomass by division is also improved over that for H_0 (Table B1.9.5), particularly for ICES division IXa(north) (Figure B1.9.9).

The estimated stock-recruitment curve is shown in Figure B1.9.10, which doesn't show a large decrease in recruitment as SSB increases. The range of recruitment residuals is larger than that for H_0 , with the majority of $\varepsilon_R(y)$ parameters estimated to be higher under R_{Ricker} than H_0 . This needs to be viewed in the light of the fact that the "good" recruitment year classes were fixed for R_{Ricker} , while they were estimated under H_0 and, as mentioned above, some $\varepsilon_R(y)$ parameters were estimated just under 0.2 for H_0 .

Maximum age in Portuguese waters

The model predicted SSB trajectory for Portuguese waters under R_7 was slightly lower prior to 1995 compared to H_0 , but there was little difference in the fit to the observed data (Figure B1.9.1). R_{max} was estimated to be higher under R_7 compared to H_0 , due to the assumed shorter average life span of adults in Portuguese waters.

The model fit to proportions-at-age in the catch is improved from H_0 , especially for age 6+ from 1978 to 1997 (Figure B1.9.4) and the fit to the total catch is good (Table B1.9.5).

As expected, there is no noticeable difference in the model fit to the proportions-at-age in the Spanish acoustic surveys, nor in the model fit to the proportions-at-ages less than the plus group in the Portuguese acoustic surveys. The model fit to the observed proportions-at-age 6+ or 7+ are, however, improved under R_7 compared to H_0 (Figures B1.9.6 and B1.9.7), suggesting that either the sardine older than age 7 do disappear from Portuguese waters, or there is a tendency to underestimate the age of older year-classes. The model predicted acoustic relative biomass trajectory is slightly lower under R_7 than H_0 (Table B1.9.5).

Immigration/emigration between ICES divisions VIIIc(east) and VIIIb

The overall fit to the data for $R_{immigration}$ is better than that for H_0 (Table B1.9.5), mostly due to an improvement in the fit to the proportion-at-age in the catch (not plotted since difference is not noticeable) and the relative acoustic biomass from the Spanish surveys (Table B1.9.5 and Figure B1.9.9). R_{max_s} is estimated to be 7.7 million at the joint posterior mode, lower than that for H_0 , but ϵ_{imm} is estimated to be 0.31, i.e. an immigration of age 1 sardine into the stock from the north-east. These two parameters effectively balance each other such that the total SSB predicted by $R_{immigration}$ is similar to (slightly lower for the Portuguese area) that predicted by H_0 . ϵ_{em} was estimated to be 0.009 at the joint posterior mode, i.e. a very slight net immigration (as opposed to the prior assumption of a net emigration) of age 2+ sardine into the stock.

Split of SSB at equilibrium

There was little difference in the overall fit to the data for $R_{70:30}$ compared to H_0 , with the improved fit to the proportions-at-age in the acoustic surveys balanced by the worse fit to the proportions-at-age in the catch (Table B1.9.5). The fit to the proportions-at-age in the acoustic surveys for $R_{50:50}$ was an improvement over H_0 (Table B1.9.5), even though this is not noticeable in the plots (not shown).

There was little difference between the estimated parameter values for these two robustness tests compared to H_0 (Table B1.9.5), but the predicted SSB trajectories in early years differ due to change in the assumption of the split of SSB at equilibrium (Figure B1.9.1c,d). This difference affects the perception of the depletion of the stock. The greater the assumed proportion of SSB in Spanish waters at equilibrium, the greater the depletion (from exploited equilibrium in 1978 to 2003) in Spanish waters. However, the predicted total SSB (all model divisions) is unchanged between H_0 , $R_{70:30}$ and $R_{50:50}$ (Figure B1.9.11).

No alternative migration matrices for good year classes

There is no difference in the migration matrices for year classes for which $\epsilon_R(y) \leq 0.2$ and $\epsilon_R(y) > 0.2$ in $R_{Migration}$. The recruitment residuals estimated for $R_{Migration}$ differed from those for H_0 , resulting in an improved fit to the proportions-at-age in the catch (Figure B1.9.4) and acoustic surveys (Table B1.9.5). The fit to the SSB is worse, especially in recent years (Figure B1.9.1), and to the overall fit to the relative biomass from acoustic surveys (Table B1.9.5, Figure B1.9.9). However, the improvement in the fit to the proportions-at-age outweigh the fit of the model to these latter data resulting in a better fit overall (Table B1.9.5).

Maximum recruitment is estimated to be much lower under $R_{Migration}$ compared to H_0 , with greater variation in the recruitment residuals (Table B1.9.5). This indicates that creating a knife-edge 'cut-off' $\epsilon_R(y) > 0.2$ to define a good recruitment year class under H_0 may create some conflict with year classes that did not display a different migration pattern, but were above average recruitment. Alternative methods of testing this assumption could include increasing the cut-off value from 0.2 or fixing the year classes of good recruitment externally.

Alternative hypothesis

The overall log-likelihood value at the posterior mode for H_{2stock} is lower (i.e. worse fit) than for H_0 , however the joint prior distribution for H_{2stock} includes an extra prior distribution for the additional parameter R_{max_2} (Table B1.9.5). The model overestimated the total Spanish SSB, while the model predicted trajectory for SSB in Portuguese waters was lower than that for H_0 (Figure B1.9.12). The size of stock 2 (distributed in model division 1) needed to be sufficiently high to permit the observed historic catch. The proportion of SSB by model division was, however, a better fit in H_{2stock} compared to H_0 (Figure B1.9.13 compared to Figure B1.9.2, Table B1.9.5).

The overall model fit to the proportion-at-age in the commercial catch and the acoustic surveys and to the catch numbers was better for $H_{2\text{Stock}}$, compared to H_0 (Figure B1.9.14-17, Table B1.9.5). The geometric mean recruitment for both stocks was 7.6 billion for $H_{2\text{Stock}}$ compared to 8.0 billion for H_0 . The recruitment residuals estimated at the posterior mode also differed between hypotheses (having an impact on the fit to the observed proportions-at-age in the catch and acoustic surveys). However $\sum_{y=1978}^{2003} \varepsilon_R(y) = -1.52$ for $H_{2\text{Stock}}$, compared with

$\sum_{y=1978}^{2003} \varepsilon_R(y) = -5.07$ for H_0 . This indicates that $R_{\text{max}_1} + R_{\text{max}_2}$ in $H_{2\text{Stock}}$ is much closer to a geometric mean than R_{max} for H_0 . The recruitment residuals for “good” recruitment year classes are generally estimated to be much higher in $H_{2\text{Stock}}$ compared to H_0 (the exception being in 1981), with 1991 and 2000 being estimated as “good” recruitment year classes (i.e. $\varepsilon_R(y) > 0.2$) under $H_{2\text{Stock}}$, while not under H_0 (Table B1.9.5). The selectivity curves for $H_{2\text{Stock}}$ are very similar to those for H_0 (Table B1.9.5, figures not shown).

The fit to the relative biomass by division from the acoustic surveys was not as good as for H_0 (Figure B1.9.18), with the bias factors being estimated to be further away from unity (Table B1.9.5).

Bayesian Results

The six selectivity parameters were fixed at their estimated values at the posterior mode for all Bayesian integration (see Table B1.9.5 for values). These parameters, especially the acoustic selectivity parameters, were highly correlated (high correlation can hinder convergence on the posterior distribution). Thus the number of parameters estimated using SIR were 29 for H_0 and 30 for $H_{2\text{Stock}}$. Marginal posterior distributions were calculated from 10 000 draws sampled randomly without replacement from the 20 million draws.

Base case hypothesis

The geometric mean of annual recruitment, R_{max} , is estimated to range between 7 and 10 billion (Figure B1.9.19), with a mean of 8.1 billion (Table B1.9.6), which is close to the joint posterior mode (Table B1.9.5). The marginal posterior pdfs for the recruitment residuals are shown in Figure B1.9.20, with the marginal posterior pdf for some years of good recruitment and the year of poorest recruitment (2003) shown in Figure B1.9.22. 1979, 1980, 1981 and 1983 were estimated to be good recruitment year classes at the posterior mode, and this holds for the marginal posterior distribution. Above average recruitment was also estimated for 1978, 1987, 1991, 1992 and 2000, with posterior means below 0.2 (Table B1.9.6, Figure B1.9.20). As mentioned above, these latter three years have generally been recognised as “good” recruitment years.

The mean multiplicative bias for the Portuguese acoustic survey biomass was estimated at 2.0, compared to 0.8 for the Spanish acoustic survey biomass (Table B1.9.6). The range of the marginal posterior pdf for $q_{\text{Port.Ac}}$ is very high (with most of the weight between 1.6 and 2.7) indicating the model estimates the Portuguese acoustic surveys to substantially overestimate the true biomass (Figure B1.9.23). The marginal posterior pdf for $q_{\text{Sp.Ac}}$ ranges between about 0.6 and 1.1, with the majority of weight below 1, indicating the model estimates the Spanish acoustic surveys to underestimate true biomass (Figure B1.9.23).

The median SSB by model division is plotted in Figure B1.9.24, together with the 5% and 95% probability intervals. The probability intervals are quite tight around the median trajectories. An increase in the SSB was seen in the mid-1980s, particularly in the northerly model divisions 1 and 2 (ICES division VIIIc) and in model division 4 (ICES division IXa(central-north)), which accounted for the majority of the stock. This peak ended around the late 1980s / early 1990s. In the mid to late 1990s there was a smaller increase in the SSB in the southerly model divisions (4 to 6), which isn’t obvious in the more northerly divisions. In addition, the SSB in the northerly divisions is relatively constant over this period, suggesting that this increase in the southerly divisions was not a result of re-distribution of sardine from the northerly divisions. The estimated increase in SSB towards the end of the modelled period is seen in all divisions.

The depletion of the stock is estimated to range between 0.5 and 1 (Figure B1.9.25), where depletion is measured as total SSB (over all divisions) in 2003 as a proportion of that at unexploited equilibrium. This indicates that the stock as a whole is at a relatively healthy level. Of even less concern is the comparison between the SSB in 2003 and that in 1978, the initial year of this model for which an exploited equilibrium was assumed. The model only estimates a small depletion from exploited equilibrium (results not shown).

Alternative hypothesis

The geometric mean of annual recruitment is estimated to range between 5.75 and 8 billion for stock 1 and between 1 and 2.5 billion for stock 2 (Figure B1.9.19). As for H_0 , the means for these parameters (Table B1.9.6) are close to their values at the joint posterior mode (Table B1.9.5). The marginal posterior pdfs for the recruitment residuals are given in Figure B1.9.21, with the marginal posterior pdfs for some years of good recruitment and the year of poorest recruitment (2003) shown in Figure B1.9.22. 1979 to 1981, 1983, 1991 and 2000 were estimated to be good recruitment years at the posterior mode. This holds for the marginal posterior distribution. In particular, the increase in the estimated recruitment in 1991 and 2000 in $H_{2\text{Stock}}$ compared to H_0 is visible in Figures B7.2.21 and B7.2.22. 1978, 1987, 1992 and 2001 were also estimated to be years of above average recruitment, with the estimated mean recruitment residual for 2001 differing greatly from its estimate under H_0 .

The multiplicative bias for the Portuguese acoustic survey biomass was estimated to range over higher values (between 2 and 3.4) than under H_0 , indicating that the model estimates the Portuguese acoustic surveys to overestimate the true biomass even more substantially than under H_0 (Figure B1.9.23). The marginal posterior distribution for $q_{Sp,Ac}$ ranges between about 0.35 and 0.75, indicating that the model estimates the Spanish acoustic surveys to substantially underestimate true biomass (Figure B1.9.23), with the pdf almost mutually exclusive from that for H_0 .

Measuring depletion as total SSB (over all stocks and divisions) in 2003 as a proportion of that at unexploited equilibrium, the mean depletion of the population is estimated to be 0.89, which is very healthy (Table B1.9.6 and Figure B1.9.25). The population was estimated to be more depleted under H_0 .

Marginal posterior probability

The marginal posterior probability for H_0 was calculated to be 0.93, compared to 0.07 for $H_{2\text{Stock}}$. This is in line with the better fit to the model at the posterior mode for H_0 compared to $H_{2\text{Stock}}$ (Table B1.9.5). This model, together with the available data therefore suggest that the single stock hypothesis is much more likely than the two stock hypothesis, in which one stock was assumed to be distributed throughout ICES division VIIIc(east), separate from the stock extending from ICES division IXa(south-cadiz) northwards to VIIIc(west).

Discussion

This document has detailed a Bayesian state-space model of Iberian sardine, developed for the EU-project *Sardine Dynamics and Stock Structure in the North-East Atlantic (SARDYN)*. This model is able to model the migration of the sardine between divisions at the beginning of each quarter of the year and a two-stock hypothesis is considered. In addition, this model incorporates data not currently used by the WGMHSA.

Immigration/emigration between ICES divisions VIIIc(east) and VIIIb

In recognition of the potential extension of the sardine stock north of VIIIc(east), an attempt was made to model immigration/emigration of sardine between VIIIc(east) and VIIIb in H_0 . In this case an annual error to account for net immigration/emigration of 1-year-olds at the beginning of the year between VIIIc(east) and VIIIb was introduced, with uninformative prior distributions. There was, however, insufficient information in the data to warrant the estimation of these parameters, even in selected years, likely due to the data being used to estimate the annual recruitment residuals. However, using recent information from members of the SARDYN project, $R_{\text{immigration}}$ assumed the same net immigration/emigration for all years with a different parameter for age 1 (prior information suggesting immigration) and ages 2+ (prior information suggesting net emigration). This robustness test indicated that immigration of age 1 sardine from ICES division VIIIb is likely, with little movement of age 2+ sardine.

One versus two stocks

As a first attempt to model the Iberian sardine as more than one stock, we considered a two-stock hypothesis where one stock was assumed to extend from ICES division IXa(south-cadiz) northwards to VIIIc(west), while the second stock was assumed to be distributed throughout ICES division VIIIc(east). Although the model fit to the data was better under $H_{2\text{Stock}}$ for the proportion-at-age in the catch and acoustic surveys, as well as the proportion of SSB by division and the total catch numbers, the fit to SSB and relative acoustic biomass was worse compared to H_0 . The geometric mean of annual recruitment for both stocks under $H_{2\text{Stock}}$ was estimated to be much higher than $R \max_y$ for H_0 , having an impact on the perceived depletion of the stock from unexploited equilibrium. The multiplicative bias factors for the acoustic surveys were further from unity under $H_{2\text{Stock}}$ compared to H_0 . This latter result is concerning and a factor in the poorer fit to the relative acoustic biomass under $H_{2\text{Stock}}$. Had tighter prior distributions been assumed for $q_{Port,Ac}$ and $q_{Sp,Ac}$, these posterior distributions may not have extended so far from unity.

Making the prior assumption that both hypotheses were equally likely, the calculated marginal posterior probabilities indicated that H_0 was the more likely scenario. This does not, however, completely rule out the hypothesis of the Iberian Sardine consisting of more than one stock. Allowing the stock distributed throughout ICES division VIIIc(east) to extend northwards through, for example, a sensitivity test along the lines of $R_{\text{immigration}}$ for $H_{2\text{Stock}}$ may result in a better fit to the data. In particular, a net immigration of 1-year-olds into ICES division VIIIc(east) was estimated in $R_{\text{immigration}}$. An immigration of 1-year-olds into ICES division VIIIc(east) for $H_{2\text{Stock}}$ may allow for a lower estimate of R_{max_2} , and consequently a lower SSB trajectory for stock 2 and the total SSB for $H_{2\text{stock}}$. This may give an improved fit to the DEPM estimates of SSB. Alternatively different boundaries between the stocks may be considered.

Further research

Some reasons proposed for the potential mismatches between the model predicted results and the observed data raise some areas for potential future research. Reducing such uncertainties through further research may help scientists to better model the sardine using a model like the one presented in this document.

This document presents a first attempt to model the sardine using a Bayesian state-space model with migration matrices. The hope is that the results presented herein and the challenges faced in constructing this model will lead to further discussion and possibly further research on potential migration patterns, in particular w.r.t. any changes in migration over the years and the potential mismatch in the migration matrices for model division 3 (see results at posterior mode). In addition, could the assumption of a different migration pattern for 'good' recruitment year classes be improved upon, in particular w.r.t. the choice of 'good' recruitment year classes (fixed externally from the model or estimated within the model and the chosen cut-off point)?

The catch-at-age by division data are considered to be reliable (low misreporting). A follow-on from this work could therefore attempt to modify the multinomial likelihood functions (equations A.15) to fit the model predicted catch-at-age by division instead of the sum over all divisions.

Acknowledgements

Jose De Oliveira is thanked for his comments on earlier results and on this document. Members of the SARDYN project are thanked for their contribution towards defining the assumptions of the model and for providing data.

References

- Barton, E.D. 1998. Eastern boundary of the North Atlantic: Northwest Africa and Iberia coastal segment. *In* The Sea. *Edited by* Robinson, A.R., and Brink, K.H. John Wiley & Sons, Inc. pp 633-658.
- Carrera, Pa and C. Porteiro. 2003 - Stock dynamic of the Iberian sardine (*Sardina pilchardus*, W.) and its implication on the fishery off Galicia (NW Spain). *Scientia Marina* 67(Suppl. 1):245-258.
- Carlin, B.P., Polson, N.G., and Stoffer, D.S. 1992. A Monte Carlo Approach to Nonnormal and Nonlinear State-Space Modeling. *J. Am. Statist. Ass.* 87 : 493-500.
- Cunningham, C.L. 2002. Improved Management of North East Atlantic Mackerel, Using Bayesian Modelling Methodologies. PhD Thesis, University of London, United Kingdom.
- Geweke, J. 1989. Bayesian Inference in Econometric Models Using Monte Carlo Integration. *Econometrica*, 57: 1317-1339.
- International Council for the Exploration of the Seas (ICES). 1998. Report of the Sardine Study Group, Vigo (Spain) 4-8 May 1998.
- International Council for the Exploration of the Seas (ICES). 2003. Report of the Study Group on the Estimation of Spawning Stock Biomass of Sardine and Anchovy. ICES C.M. 2003/G:12.
- International Council for the Exploration of the Seas (ICES). 2004a. Report of the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy. ICES C.M. 2004/ACFM:08.
- International Council for the Exploration of the Seas (ICES). 2004b. ACFM Report 2004. ICES C.M. 2004/ACFM:2.
- Kinas, P.G. 1996. Bayesian fishery stock assessment and decision making using adaptive importance sampling. *Can. J. Fish. Aquat. Sci.* 53 : 414-423.
- McAllister, M.K., and Ianelli, J.N. 1997. Bayesian stock assessment using catch-age data and the sampling-importance resampling algorithm. *Canadian Journal of Fisheries and Aquatic Sciences*, 54: 284-300.
- McAllister, M., and Kirchner, C. 2002. Accounting for structural uncertainty to facilitate precautionary fishery management: illustration with Namibian orange roughy. *In* Targets, Thresholds and the Burden of Proof in Fisheries Management. *Edited by* M.Mangel. *Bulletin of Marine Science*, 70: 499-540.

- Meyer, R., and Millar, R.B. 1999. BUGS in Bayesian stock assessments. *Can. J. Fish. Aquat. Sci.* 56 : 1078-1086.
- Myers, R.A., Bridson, J., and Barrowman, N.J. 1995. Summary of Worldwide Spawner and Recruitment Data. Canadian Technical Report of Fisheries and Aquatic Sciences. No. 2024.
- Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *J. Cons. CIEM.* 39(2) : 175-192.
- Rubin, D.B. 1988. Using the SIR algorithm to simulate posterior distributions. *In Bayesian Statistics 3: Proceedings of the Third Valencia International Meeting, June 1-5, 1987.* pp. 385-402. *Edited by J.M. Bernardo, M.H. Degroot, D.V. Lindley, and A.M. Smith.* Clarendon Press, Oxford.
- SARDYN, 2005. SARDYN: Sardine dynamics and stock structure in the North-eastern Atlantic. Annual Report. January 2005.
- Schnute, J.T. 1994. A General Framework for Developing Sequential Fisheries Models. *Can. J. Fish. Aquat. Sci.* 51 : 1676-1688.
- Silva, A. 2003. Morphometric variation among sardine (*Sardina pilchardus*) populations from the northeastern Atlantic and the western Mediterranean. *ICES J. Mar. Sci.* 60(6) : 1352-1360.
- West, M. 1993. Approximating Posterior Distributions by Mixtures. *Journal of the Royal Statistical Society, B*, 55: 409-422.

Table B1.9.1. Model divisions

Model Division	ICES Division
1	VIIIc(east)
2	VIIIc(west)
3	IXa(north)
4	IXa(central-north)
5	IXa(central-south)
6	IXa(south-algarve) and IXa(south-cadiz)

Table B1.9.2. Summary of Model Hypotheses and Robustness Tests (blank cells indicate no change from H_0).

Hypothesis or Robustness Test	Number of Stocks	Stock Boundaries	Immigration /Emigration between VIIIc(east) and VIIIb	Stock-Recruitment Relationship	Natural Mortality	Plus-Group	Other
H_0	1	IXa(south-cadiz) to VIIIc(east)	No	Geometric Mean	$M(a) = 0.33$ for all ages	12+	
$H_{2\text{Stock}}$	2	i) IXa(south-cadiz) to VIIIc(west) ii) VIIIc(east)					
R_{data}							Maturity ogive and stock weights differ by country from 91-03
R_{6+} R_M					$M(a) = 0.6$ for all ages	6+	
R_{Ricker}				Ricker			
R_7							Adults in divisions 4 to 6 die after age 7.
$R_{\text{immigration}}$ $R_{50:50}$			Yes				Equilibrium SSB split equally between Spanish and Portuguese waters
$R_{70:30}$							Equilibrium SSB split with 70% in Portuguese waters and 30% in Spanish waters
$R_{\text{Migration}}$							No difference in migration matrices of 'good' recruitment year classes

Table B1.9.3. Estimates of natural mortality using Pauly (1980).

Sea Surface Temperature	M	Ln(M)	L_∞	K
7.5	0.5804	-0.5440	22.28	0.4023
10	0.6631	-0.4108	22.28	0.4023
12.5	0.7353	-0.3075	22.28	0.4023
15	0.8001	-0.2231	22.28	0.4023
17.5	0.8592	-0.1517	22.28	0.4023
20	0.9140	-0.0899	22.28	0.4023

Table B1.9.4. SIR convergence diagnostics.

Diagnostic	H_0	$H_{2\text{stock}}$
Maximum importance ratio as a proportion of the sum of all importance ratios	0.02	0.03
CV in the average importance ratio (McAllister and Kirchner 2002)	0.05	0.08
CV in the importance ratio (McAllister and Ianelli 1997)	230	363
CV in the importance ratio as a proportion of the CV in the likelihood function multiplied by the prior	0.78	0.90

Table B1.9.5. Log-Likelihood values (corresponding to equations (A.15) to (A.20)), the log of the posterior distribution, $\ln(L)$, (sum over $\ln(L_1)$ to $\ln(L_6)$) and $\ln(\text{Prior})$, the log of the joint prior distribution) and parameter estimates at the joint posterior mode for H_0 and the robustness tests. R_{\max} is reported in billions.

	H_0	R_{data}	R_{6+}	R_{M1}	R_{Raker}	R_7	$R_{\text{immigration}}$	$R_{50:50}$	$R_{70:30}$	$R_{\text{Migration}}$	$H_2\text{Stock}$
$\ln(L)$	-64.83	-80.75	25.25	-150.95	-17.83	-23.20	-57.02	-58.52	-65.83	-29.48	-75.65
$\ln(\text{Prior})$	-52.33	-52.34	-52.34	-48.42	-39.99	-52.35	-52.76	-52.33	-52.33	-60.17	-68.92
$\ln(L_1)$	-3473.81	-3472.53	-3424.66	-3470.74	-3445.98	-3443.93	-3467.73	-3476.38	-3479.23	-3437.77	-3459.46
$\ln(L_2)$	-0.64	-0.62	-0.74	-0.43	-0.52	-0.59	-0.60	-0.66	-0.67	-0.48	-0.55
$\ln(L_3)$	-86.44	-90.13	-87.29	-89.23	-90.99	-87.91	-86.60	-86.89	-86.67	-91.86	-105.64
$\ln(L_4)$	-38.70	-40.09	-38.47	-40.99	-38.83	-38.97	-38.03	-38.72	-38.71	-38.65	-36.15
$\ln(L_5)$	-1558.98	-1562.31	-1516.44	-1614.31	-1550.95	-1542.79	-1559.98	-1549.98	-1554.48	-1545.53	-1550.32
$\ln(L_6)$	-1253.93	-1262.73	-1254.82	-1286.83	-1250.57	-1256.66	-1251.32	-1253.57	-1253.73	-1255.03	-1254.61
R_{\max} / α	8.009	7.901	8.009	17.008	3.061	8.300	7.701	8.008	8.009	6.511	6.192
$R_{\max 2}$	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.359
α_i	1.469	1.469	1.469	1.681	1.302	1.467	1.467	1.468	1.468	1.301	1.372
α_i	1.025	1.025	1.025	1.390	1.212	1.025	1.029	1.025	1.025	1.227	1.192
α_i	0.678	0.678	0.678	0.701	0.643	0.677	0.677	0.677	0.677	0.589	0.672
α_i	0.953	0.954	0.953	1.027	0.911	0.953	0.953	0.953	0.953	2.019	0.950
α_i	0.392	0.392	0.392	0.414	0.288	0.391	0.391	0.392	0.392	0.262	0.370
α_i	1.445	1.445	1.445	1.520	1.378	1.445	1.445	1.445	1.445	2.411	1.438
q_{Port}	1.90	1.90	1.90	1.90	1.80	1.90	1.90	1.90	1.90	1.90	2.47
q_{Sp}	0.77	0.77	0.77	0.77	0.73	0.77	0.77	0.77	0.77	0.80	0.49
$\epsilon_R(1978)$	0.107	0.107	0.107	0.196	0.425	0.107	0.107	0.107	0.107	0.648	0.199
$\epsilon_R(1979)$	0.241	0.241	0.241	0.380	0.520	0.241	0.243	0.241	0.241	0.814	0.536
$\epsilon_R(1980)$	0.599	0.599	0.599	0.610	0.677	0.599	0.599	0.598	0.598	0.962	0.602
$\epsilon_R(1981)$	0.296	0.296	0.296	0.230	0.301	0.296	0.296	0.295	0.295	0.585	0.218
$\epsilon_R(1982)$	-0.156	-0.156	-0.156	-0.040	-0.104	-0.156	-0.156	-0.156	-0.156	0.155	-0.181
$\epsilon_R(1983)$	0.894	0.894	0.894	0.991	1.019	0.894	0.910	0.894	0.894	1.369	0.989
$\epsilon_R(1984)$	-0.051	-0.051	-0.051	0.020	0.080	-0.051	-0.048	-0.051	-0.051	0.348	-0.012

Table B1.9.5 (continued). Log-Likelihood values (corresponding to equations (A.15) to (A.20)), the log of the posterior distribution, $\ln(L)$, (sum over $\ln(L_1)$ to $\ln(L_6)$ and $\ln(\text{Prior})$), the log of the joint prior distribution) and parameter estimates at the joint posterior mode for H_0 and the robustness tests. R_{\max} is reported in billions.

	H_0	R_{data}	R_{6+}	R_M	R_{Raker}	R_7	$R_{\text{immigration}}$	$R_{50:50}$	$R_{70:30}$	$R_{\text{Migration}}$	$H_2\text{Stock}$
$\epsilon_R(1985)$	-0.470	-0.470	-0.470	-0.325	-0.289	-0.470	-0.468	-0.470	-0.470	-0.033	-0.228
$\epsilon_R(1986)$	-0.290	-0.290	-0.290	-0.225	-0.223	-0.290	-0.290	-0.290	-0.290	-0.007	-0.064
$\epsilon_R(1987)$	0.136	0.135	0.135	0.198	0.360	0.136	0.158	0.135	0.135	0.544	0.200
$\epsilon_R(1988)$	-0.450	-0.450	-0.450	-0.385	-0.380	-0.450	-0.440	-0.450	-0.450	-0.249	-0.552
$\epsilon_R(1989)$	-0.355	-0.355	-0.355	-0.319	-0.442	-0.355	-0.355	-0.355	-0.355	-0.326	-0.383
$\epsilon_R(1990)$	-0.591	-0.591	-0.591	-0.625	-0.569	-0.591	-0.591	-0.591	-0.591	-0.462	-0.520
$\epsilon_R(1991)$	0.199	0.199	0.199	0.275	0.501	0.199	0.200	0.199	0.199	0.576	0.312
$\epsilon_R(1992)$	0.158	0.159	0.158	0.198	0.317	0.158	0.179	0.158	0.159	0.421	0.200
$\epsilon_R(1993)$	-0.423	-0.423	-0.423	-0.280	-0.294	-0.423	-0.415	-0.423	-0.423	-0.183	-0.056
$\epsilon_R(1994)$	-0.455	-0.455	-0.455	-0.450	-0.435	-0.455	-0.453	-0.455	-0.455	-0.311	-0.393
$\epsilon_R(1995)$	-0.466	-0.466	-0.466	-0.620	-0.468	-0.466	-0.466	-0.466	-0.466	-0.327	-0.430
$\epsilon_R(1996)$	-0.473	-0.473	-0.473	-0.329	-0.254	-0.473	-0.465	-0.472	-0.472	-0.120	-0.210
$\epsilon_R(1997)$	-0.440	-0.440	-0.441	-0.595	-0.332	-0.441	-0.445	-0.440	-0.440	-0.218	-0.413
$\epsilon_R(1998)$	-0.552	-0.552	-0.552	-0.585	-0.248	-0.552	-0.552	-0.552	-0.552	-0.174	-0.394
$\epsilon_R(1999)$	-0.713	-0.713	-0.713	-0.781	-0.329	-0.713	-0.713	-0.713	-0.713	-0.267	-0.418
$\epsilon_R(2000)$	0.199	0.199	0.200	0.198	0.862	0.199	0.200	0.200	0.200	0.894	0.703
$\epsilon_R(2001)$	0.022	0.022	0.022	-0.245	0.331	0.022	0.019	0.022	0.022	0.505	0.199
$\epsilon_R(2002)$	-0.714	-0.714	-0.714	-0.675	-0.486	-0.714	-0.714	-0.714	-0.714	-0.150	-0.545
$\epsilon_R(2003)$	-1.320	-1.320	-1.320	-0.305	-0.661	-1.320	-1.320	-1.320	-1.320	-0.741	-0.880
ϵ_{imm}	N/A	N/A	N/A	N/A	N/A	N/A	0.310	N/A	N/A	N/A	N/A
ϵ_{em}	N/A	N/A	N/A	N/A	N/A	N/A	0.009	N/A	N/A	N/A	N/A

Table B1.9.6. Means and CVs of the marginal posterior distributions of parameter estimates and key model parameters for the alternative hypotheses (see Appendix A for parameter definitions). R_{\max} and $R_s(y)$ are reported in billions and SSB is reported in thousands of tonnes.

	H_0		H_{2Stock}	
	Mean	CV	Mean	CV
R_{\max}	8.113	0.05	6.377	0.05
$R_{\max 2}$	N/A	N/A	1.391	0.11
q_{Port}	2.00	0.10	2.52	0.09
q_{Sp}	0.79	0.10	0.48	0.11
$\varepsilon_R(1978)$	0.111	1.37	0.141	0.96
$\varepsilon_R(1979)$	0.219	0.69	0.480	0.34
$\varepsilon_R(1980)$	0.549	0.25	0.582	0.25
$\varepsilon_R(1981)$	0.291	0.44	0.283	0.53
$\varepsilon_R(1982)$	-0.163	0.92	-0.221	0.79
$\varepsilon_R(1983)$	0.877	0.11	0.933	0.09
$\varepsilon_R(1984)$	-0.049	2.40	-0.042	3.14
$\varepsilon_R(1985)$	-0.449	0.34	-0.290	0.48
$\varepsilon_R(1986)$	-0.307	0.46	-0.161	0.87
$\varepsilon_R(1987)$	0.125	0.81	0.158	0.63
$\varepsilon_R(1988)$	-0.448	0.35	-0.485	0.43
$\varepsilon_R(1989)$	-0.400	0.36	-0.404	0.37
$\varepsilon_R(1990)$	-0.602	0.26	-0.530	0.30
$\varepsilon_R(1991)$	0.173	0.51	0.274	0.33
$\varepsilon_R(1992)$	0.142	0.62	0.153	0.51
$\varepsilon_R(1993)$	-0.403	0.33	-0.128	0.88
$\varepsilon_R(1994)$	-0.474	0.23	-0.401	0.30
$\varepsilon_R(1995)$	-0.501	0.20	-0.447	0.24
$\varepsilon_R(1996)$	-0.449	0.23	-0.246	0.35
$\varepsilon_R(1997)$	-0.473	0.20	-0.423	0.23
$\varepsilon_R(1998)$	-0.549	0.17	-0.410	0.24
$\varepsilon_R(1999)$	-0.712	0.15	-0.477	0.23
$\varepsilon_R(2000)$	0.184	0.45	0.656	0.15
$\varepsilon_R(2001)$	-0.026	5.14	0.143	0.79
$\varepsilon_R(2002)$	-0.746	0.26	-0.522	0.38
$\varepsilon_R(2003)$	-1.237	0.32	-0.880	0.44
\overline{SSB}_1	1001	0.05	958	0.05
$\hat{I}_{Sp}(1978) + \hat{I}_{Por}(1978)$	618	0.10	554	0.12
$\hat{I}_{Sp}(2003) + \hat{I}_{Por}(2003)$	602	0.12	855	0.11
$(\hat{I}_{Sp}(2003) + \hat{I}_{Por}(2003)) / \sum_s \overline{SSB}_s$	0.60	0.12	0.89	0.10
$R_1(1978)$	9.151	0.15	9.009	0.14
$R_1(1980)$	14.149	0.13	13.989	0.12
$R_1(1981)$	10.907	0.11	10.371	0.12
$R_1(1983)$	19.532	0.08	19.771	0.07
$R_1(1991)$	9.666	0.08	10.234	0.08
$R_1(1992)$	9.368	0.08	9.067	0.08
$R_1(2000)$	9.773	0.08	15.044	0.11
$R_1(2003)$	2.545	0.41	3.469	0.41

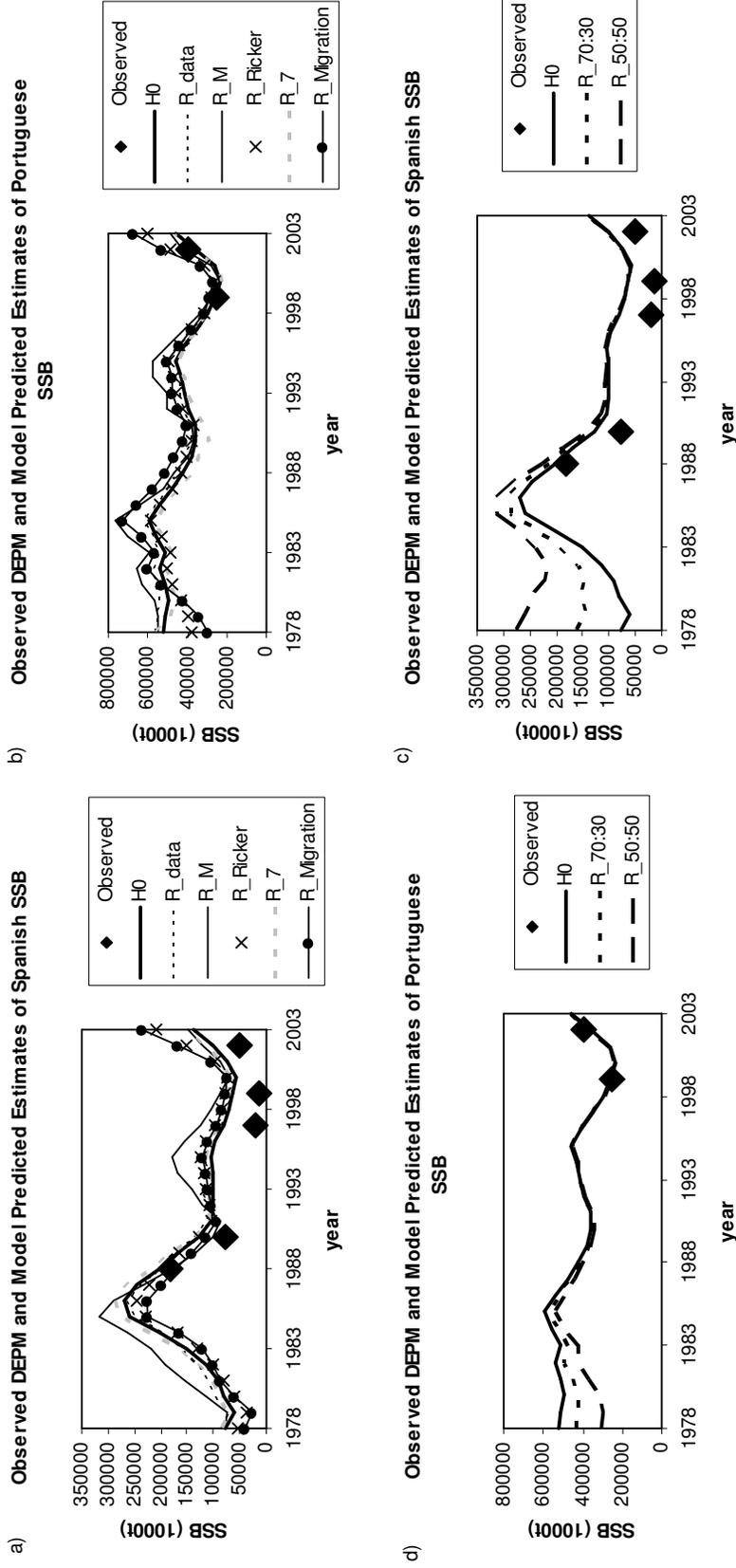
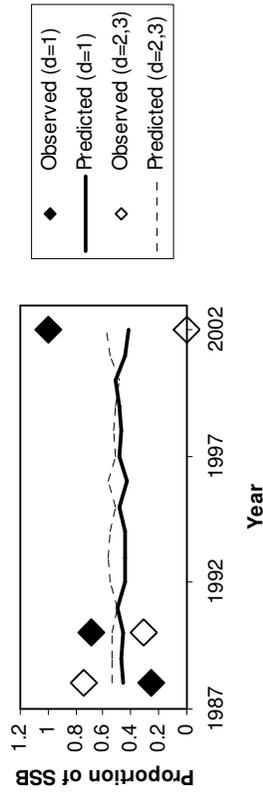


Figure BI.9.1. Observed and model predicted estimates of SSB for Spanish (a and c) and Portuguese (b and d) waters (model divisions 1-3 and 4-6, respectively) for H_0 and some robustness tests at the posterior mode.

Observed DEPM and Model Predicted Proportions of Spanish SSB by Division



Observed DEPM and Model Predicted Proportions of Portuguese SSB by Division

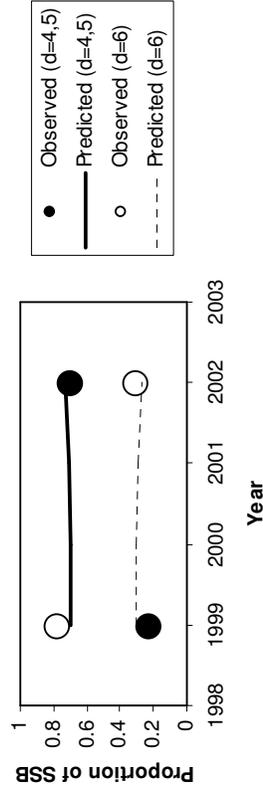
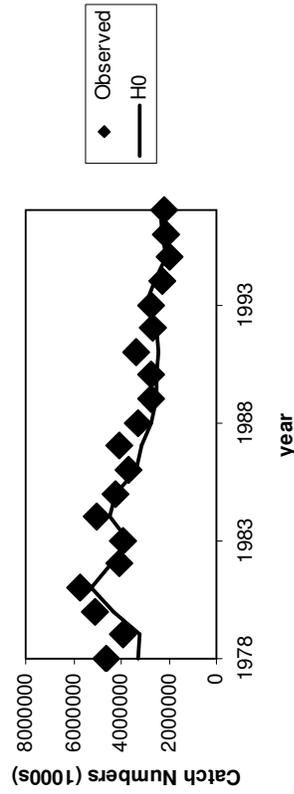


Figure B1.9.2. Observed and model predicted proportions of SSB by division for Spanish and Portuguese waters for H_0 at the posterior mode.

Observed and Model Predicted Annual Catch



Observed and Model Predicted Quarterly Catch

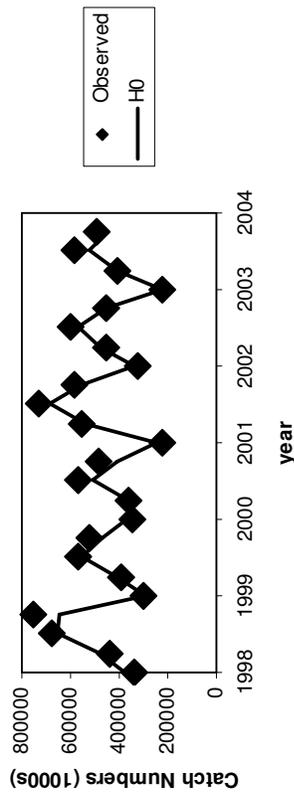


Figure B1.9.3. Observed and model predicted annual catch numbers from 1978 to 1997 and quarterly catch numbers from 1998 to 2003 for H_0 at the posterior mode.

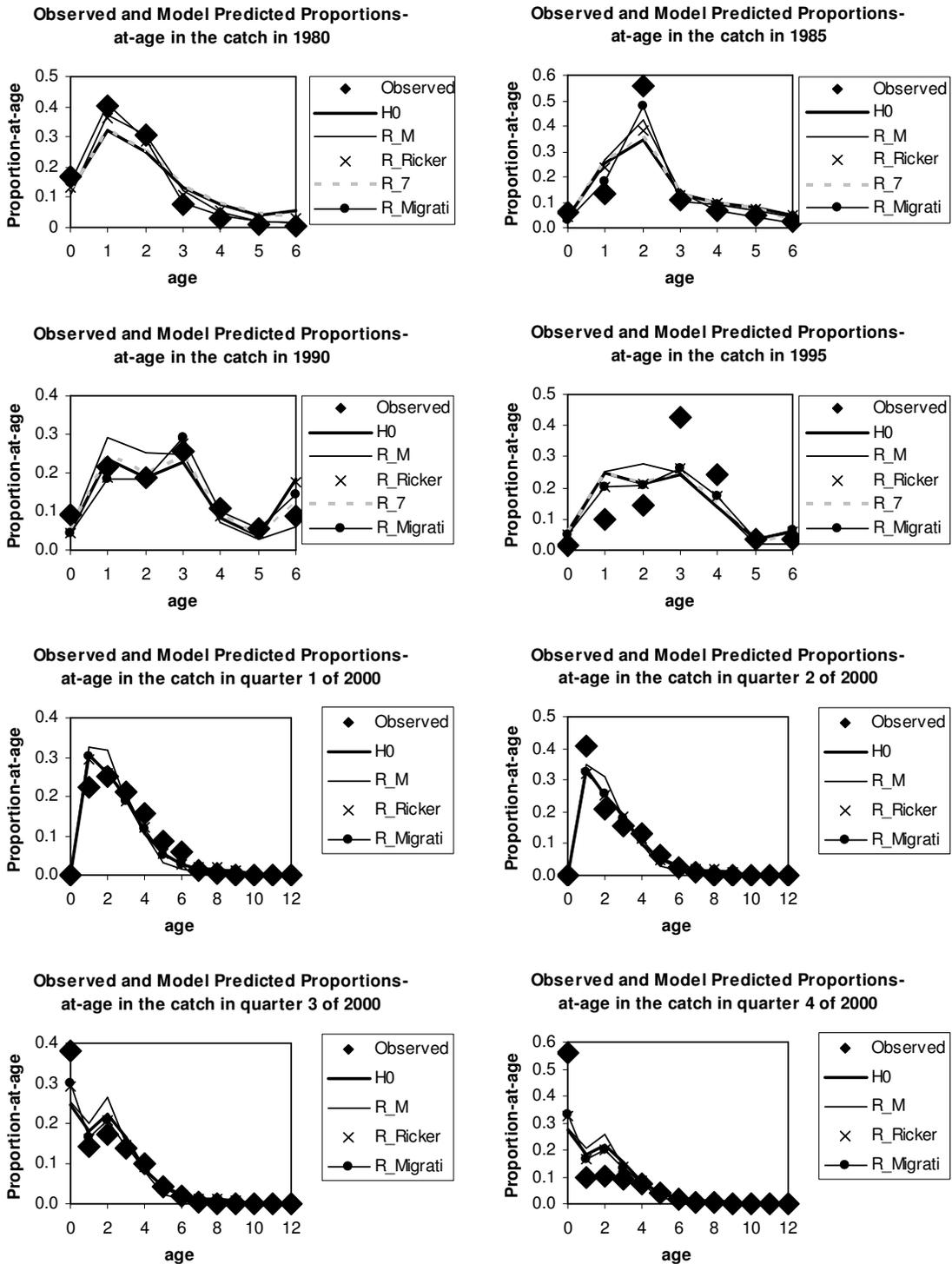


Figure B1.9.4. Observed and model predicted proportions-at-age in the annual and quarterly catch numbers for selected years for H_0 and some robustness tests at the posterior mode.

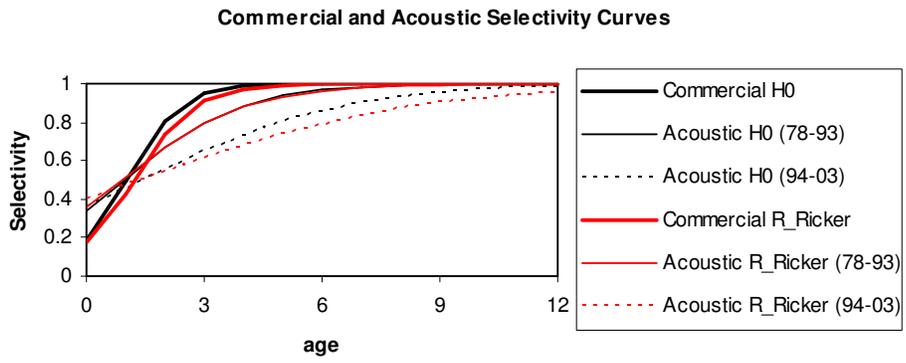
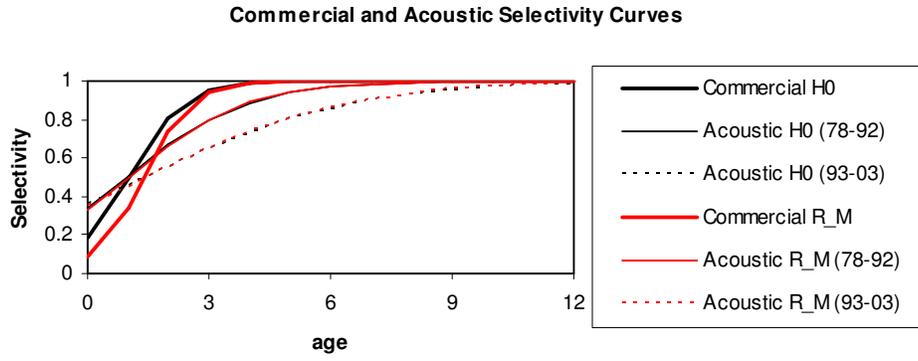
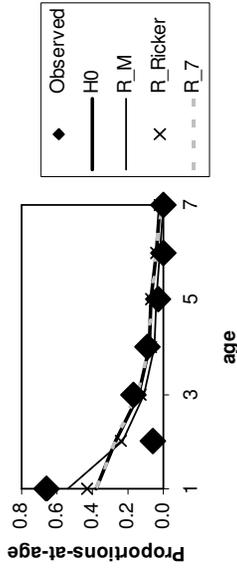
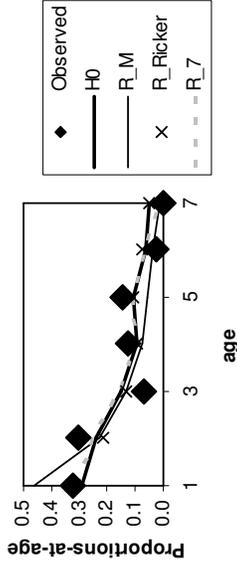


Figure B1.9.5. Model predicted commercial and acoustic selectivity curves for H_0 and R_M (upper panel) and H_0 and R_{Ricker} (lower panel).

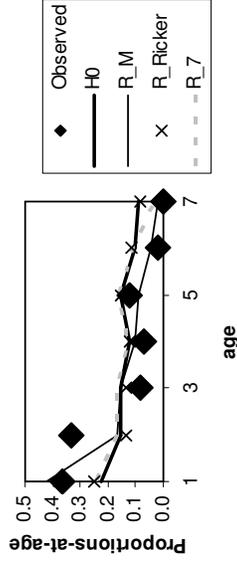
Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-north) in 1997



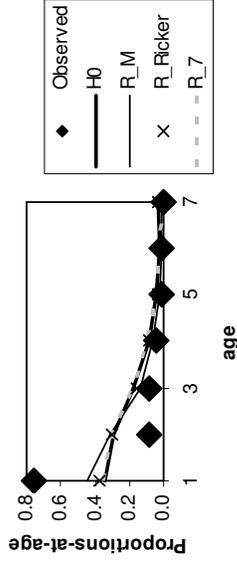
Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-south) in 1997



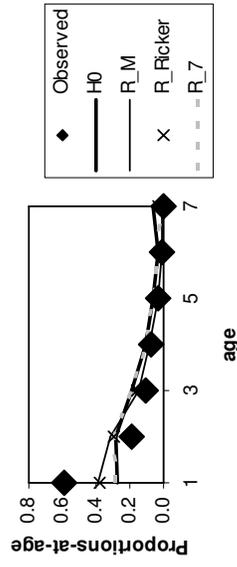
Observed Acoustic and Model Predicted Proportions-at-age in IXa(south) in 1997



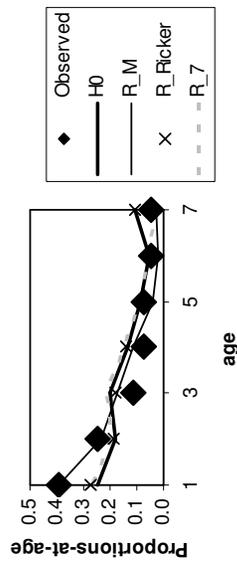
Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-north) in 2000



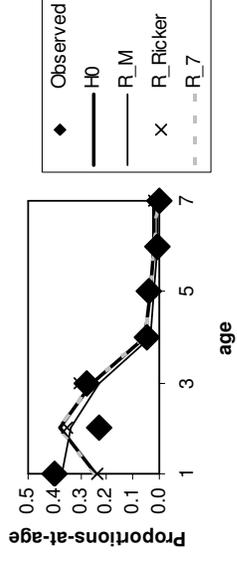
Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-south) in 2000



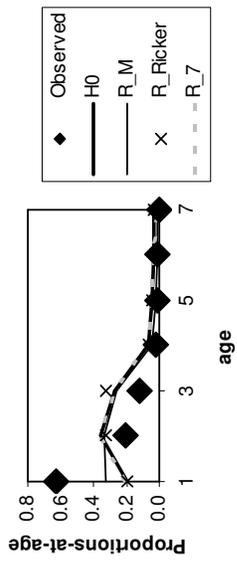
Observed Acoustic and Model Predicted Proportions-at-age in IXa(south) in 2000



Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-north) in 2003



Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-south) in 2003



Observed Acoustic and Model Predicted Proportions-at-age in IXa(south) in 2003

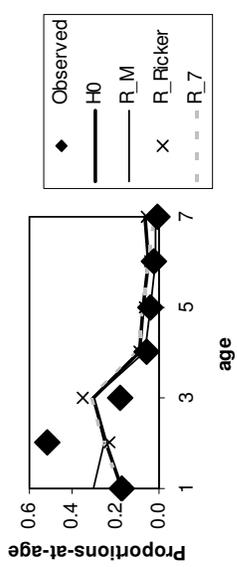
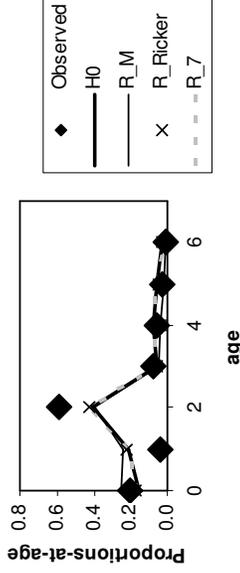
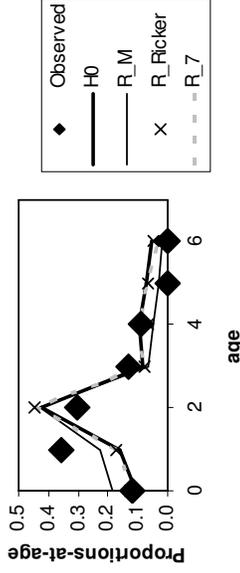


Figure B1.9.6. Observed and model predicted proportions-at-age in the first quarter Portuguese acoustic survey for selected years for H_0 and some robustness tests at the posterior mode.

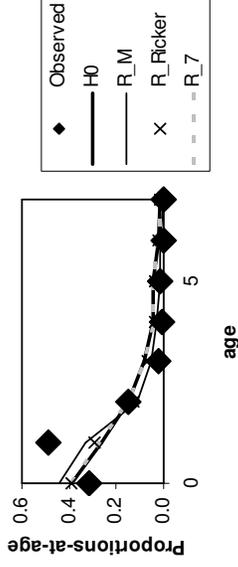
Observed Acoustic and Model Predicted
Proportions-at-age in IXa(central-north) in 1985



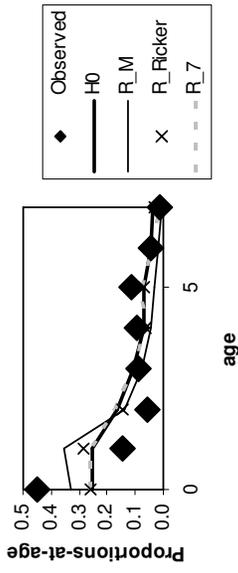
Observed Acoustic and Model Predicted
Proportions-at-age in IXa(central-south) in 1985



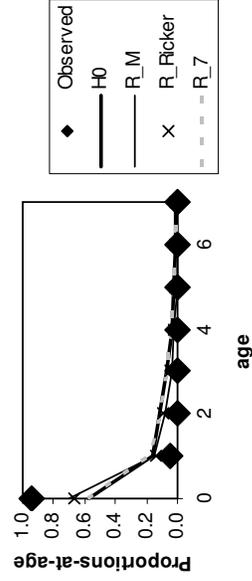
Observed Acoustic and Model Predicted
Proportions-at-age in IXa(central-north) in 1997



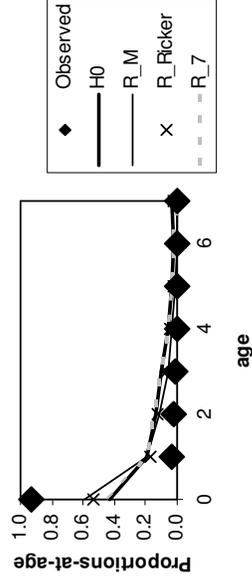
Observed Acoustic and Model Predicted
Proportions-at-age in IXa(central-south) in 1997



Observed Acoustic and Model Predicted
Proportions-at-age in IXa(central-north) in 2000



Observed Acoustic and Model Predicted
Proportions-at-age in IXa(central-south) in 2000



Observed Acoustic and Model Predicted
Proportions-at-age in IXa(south) in 2000

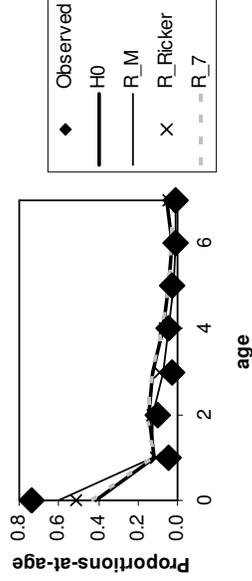


Figure B1.9.7. Observed and model predicted proportions-at-age in the fourth quarter Portuguese acoustic survey for selected years for H_0 and some robustness tests at the posterior mode.

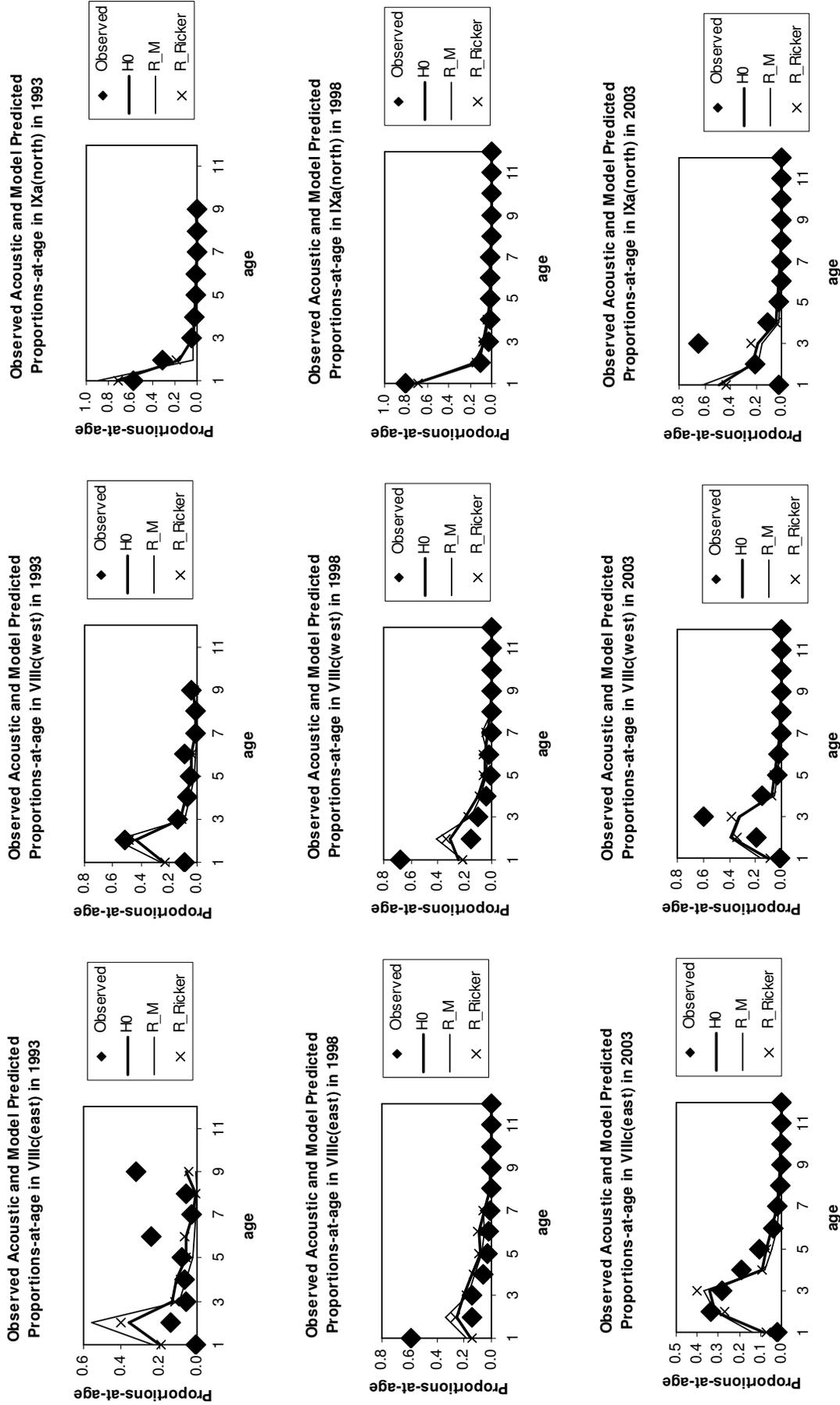


Figure B1.9.8. Observed and model predicted proportions-at-age in the first quarter Spanish acoustic survey for selected years for H_0 and some robustness tests at the posterior mode.

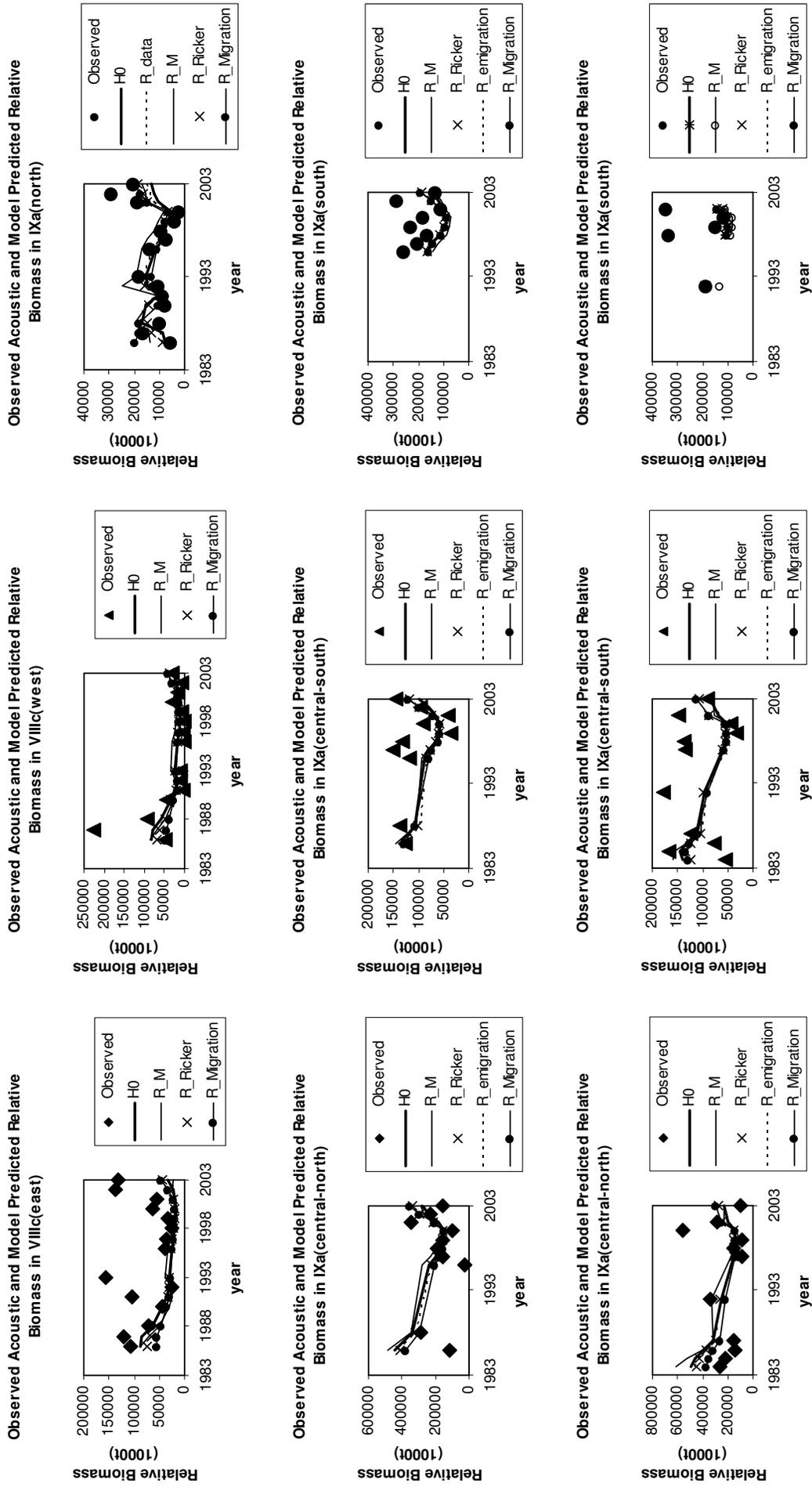


Figure B1.9.9. Observed and model predicted relative biomass by division in the Spanish first quarter acoustic survey (upper panel), Portuguese first quarter acoustic survey (middle panel) and Portuguese fourth quarter acoustic survey (lower panel) for H_0 and some robustness tests at the posterior mode.

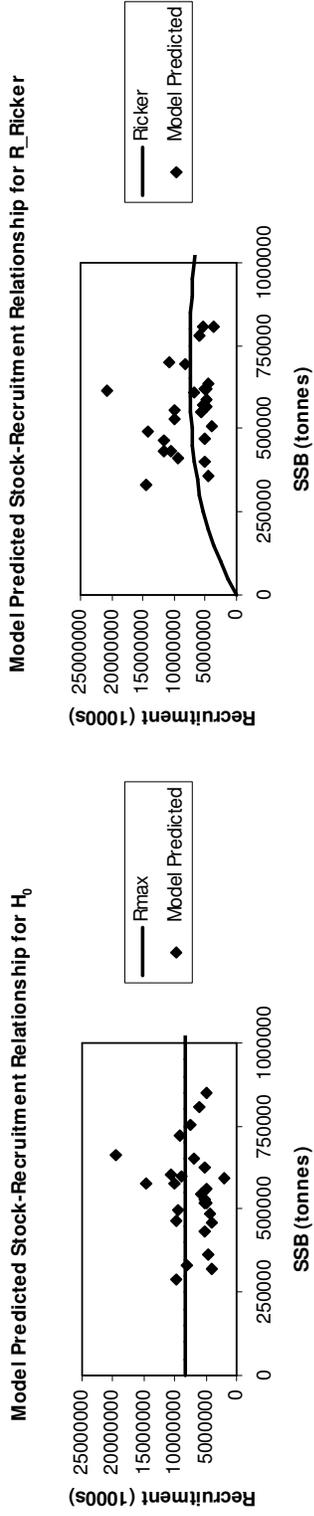


Figure B1.9.10. Model predicted stock-recruitment relationship for H_0 (assumed a geometric mean) and R_{Ricker} (assumed a Ricker curve).

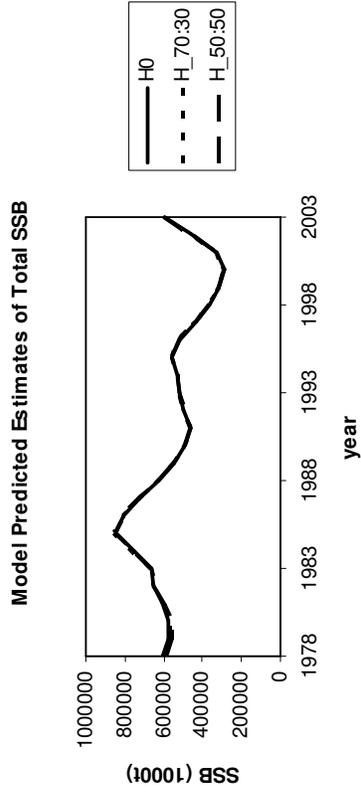


Figure B1.9.11. Model predicted estimates of SSB for all model divisions for H_0 and some robustness tests at the posterior mode.

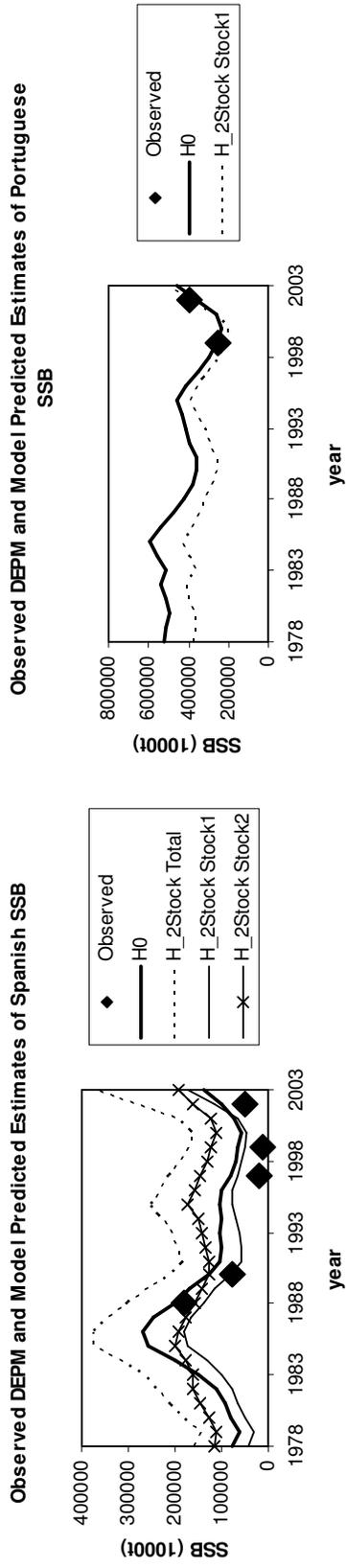


Figure B1.9.12. Observed and model predicted estimates of SSB for Spanish (a) and Portuguese (b) waters (model divisions 1-3 and 4-6, respectively) for H_0 and H_{2Stock} at the posterior mode.

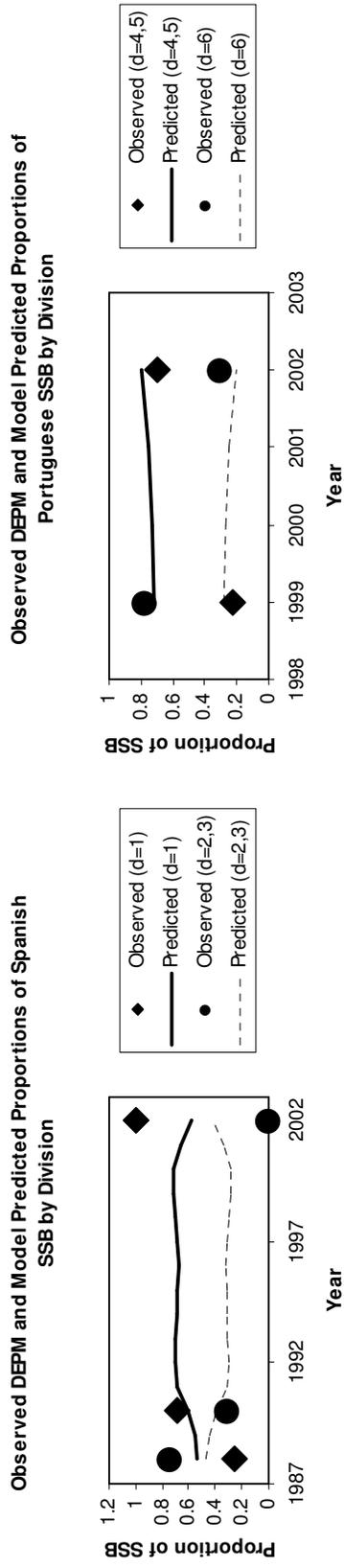


Figure B1.9.13. Observed and model predicted proportions of SSB by division for Spanish and Portuguese waters for H_{2Stock} at the posterior mode.

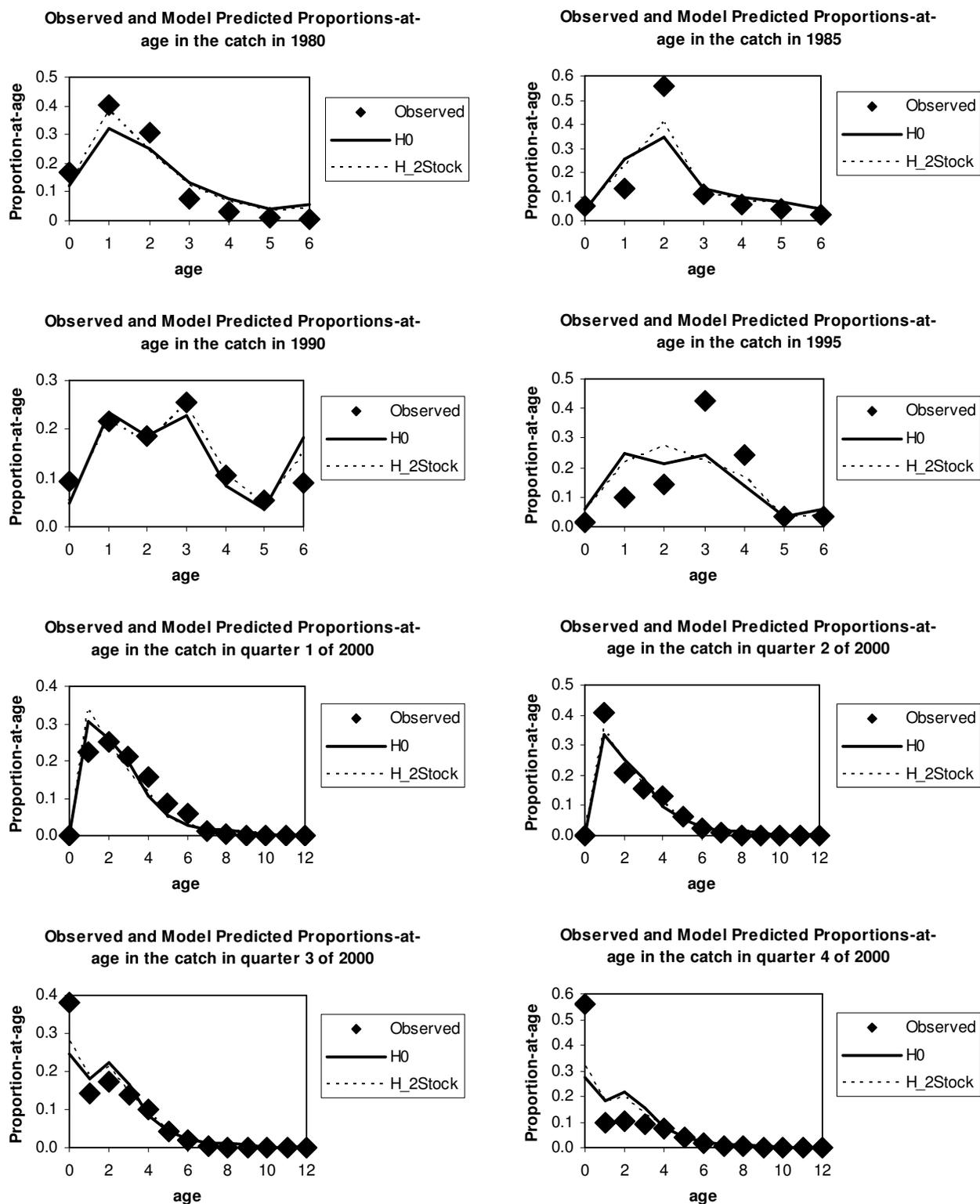


Figure B1.9.14. Observed and model predicted proportions-at-age in the annual and quarterly catch numbers for selected years for H_0 and H_{2Stock} at the posterior mode.

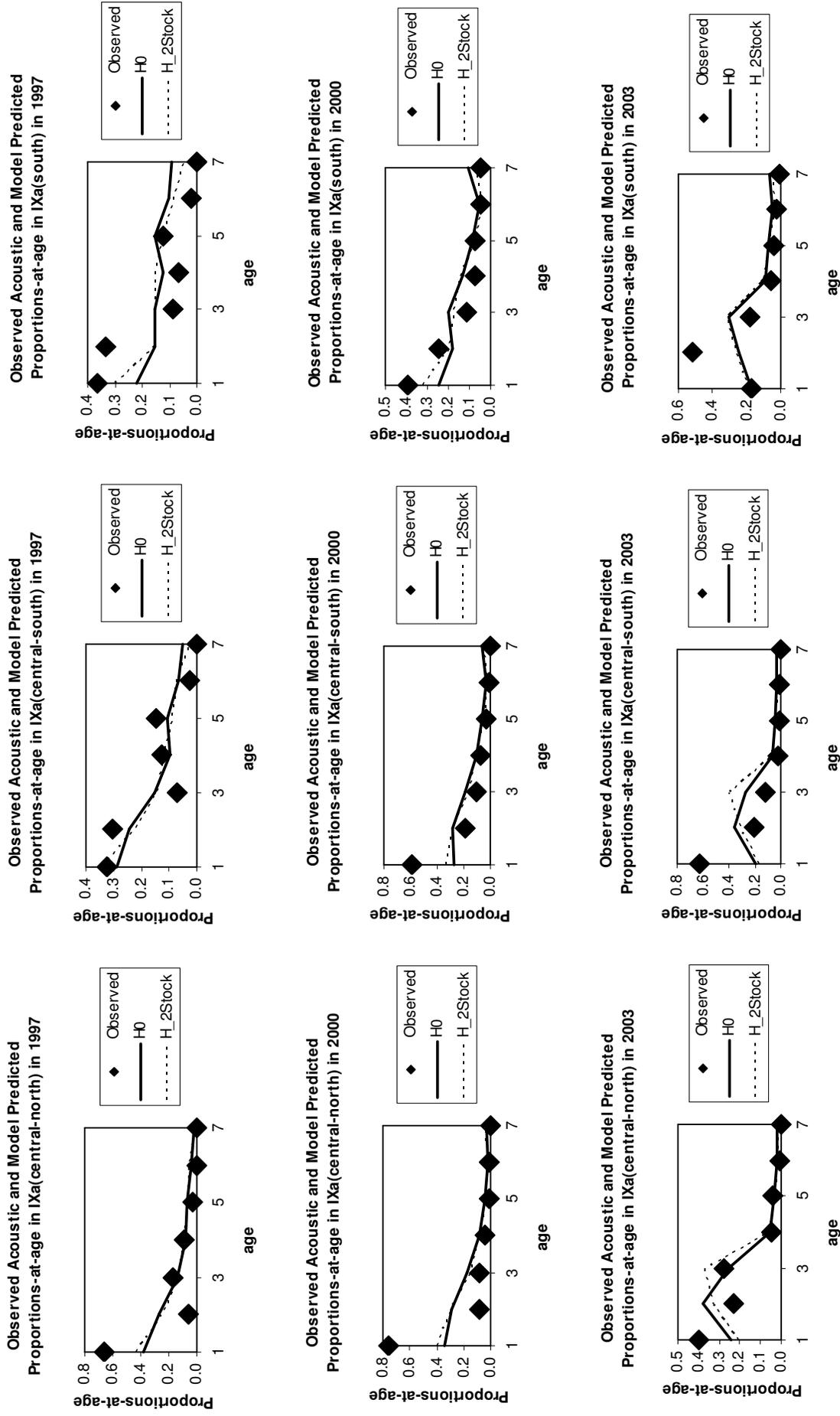
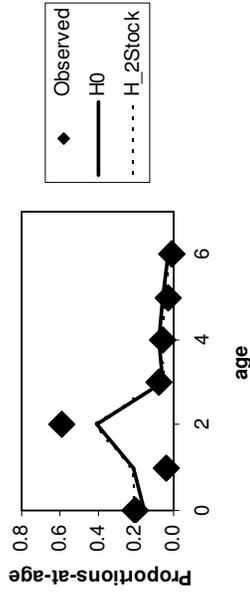
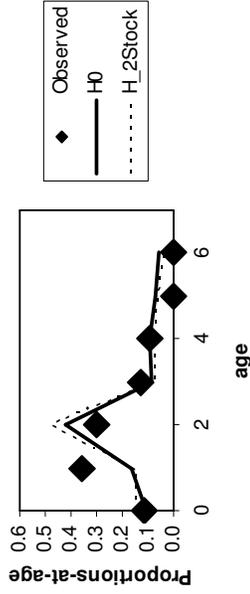


Figure B1.9.15. Observed and model predicted proportions-at-age in the first quarter Portuguese acoustic survey for selected years for H_0 and H_{2Stock} at the posterior mode.

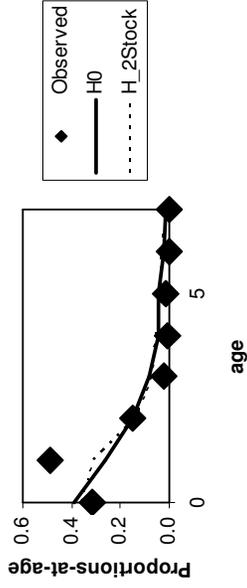
Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-north) in 1985



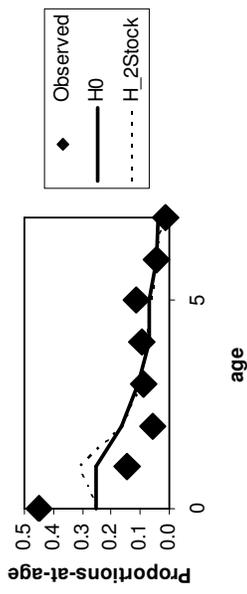
Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-south) in 1985



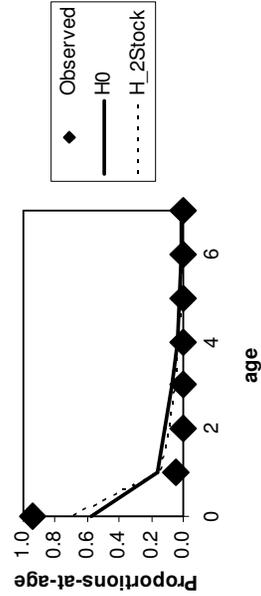
Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-north) in 1997



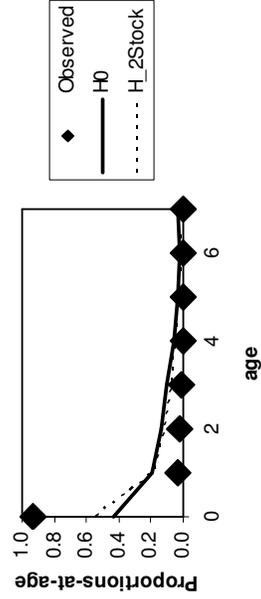
Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-south) in 1997



Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-north) in 2000



Observed Acoustic and Model Predicted Proportions-at-age in IXa(central-south) in 2000



Observed Acoustic and Model Predicted Proportions-at-age in IXa(south) in 2000

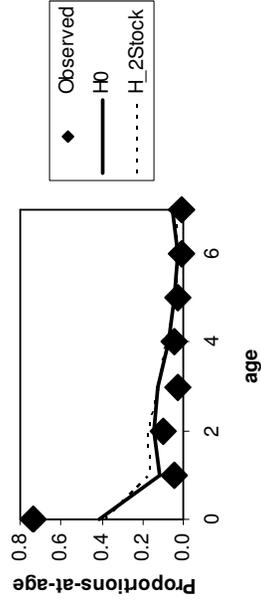


Figure BI.9.16. Observed and model predicted proportions-at-age in the fourth quarter Portuguese acoustic survey for selected years for H_0 and H_{2Stock} at the posterior mode.

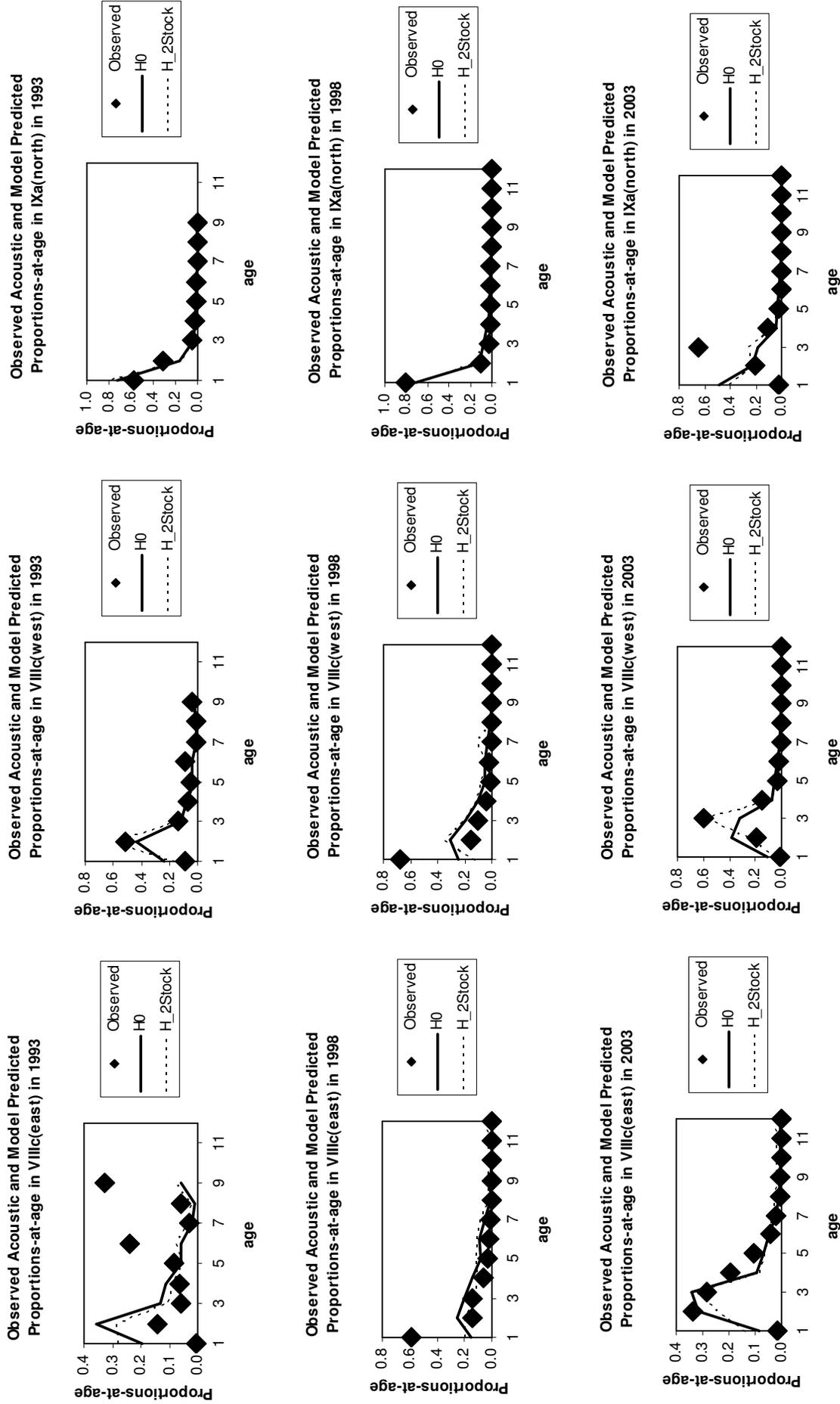


Figure B1.9.17. Observed and model predicted proportions-at-age in the first quarter. Spanish acoustic survey for selected years for H_0 and H_{2Stock} at the posterior mode.

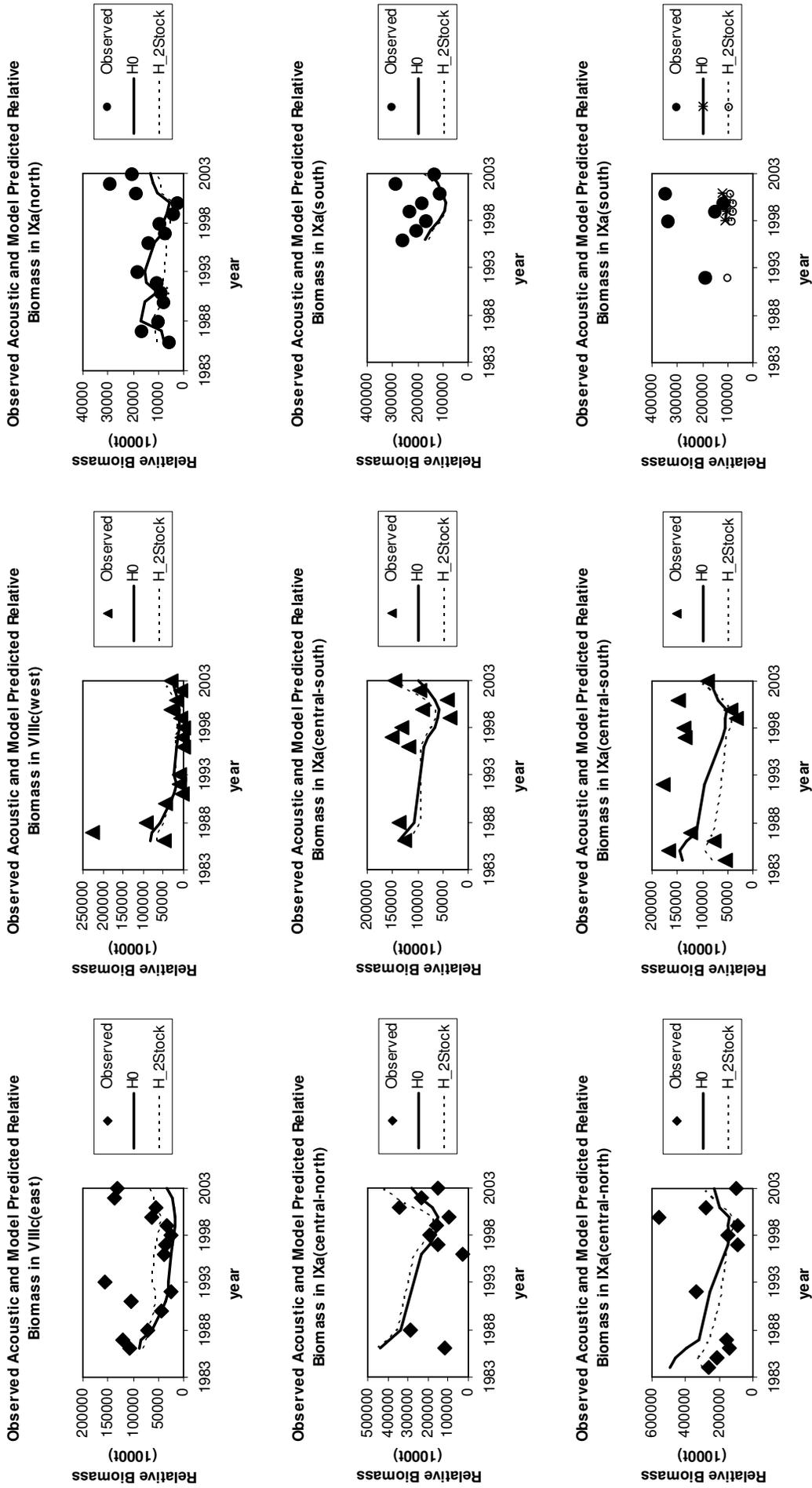


Figure B1.9.18. Observed and model predicted relative biomass by division in the Spanish first quarter acoustic survey (upper panel), Portuguese first quarter acoustic survey (middle panel) and Portuguese fourth quarter acoustic survey (lower panel) for H_0 and H_{2Stock} at the posterior mode.

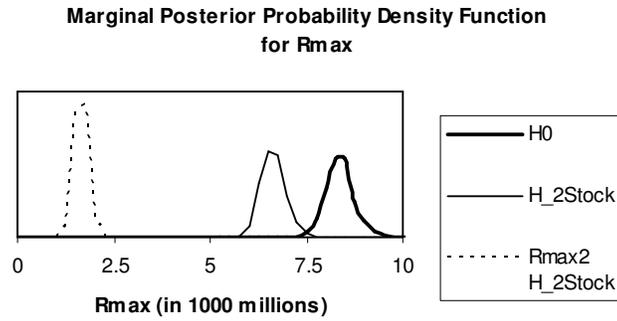


Figure B1.9.19. Marginal posterior probability density function distribution for $R \max_s$ for H_0 and H_{2Stock} .

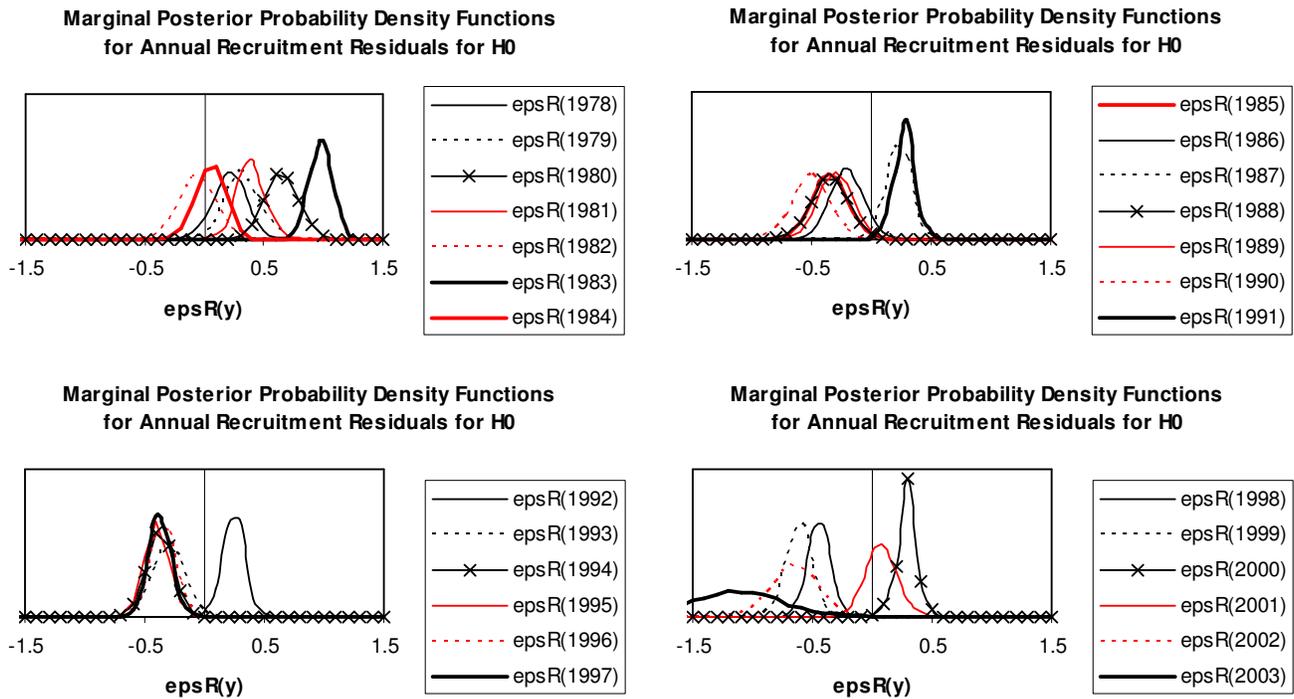


Figure B1.9.20. Marginal posterior probability density functions for recruitment residuals for H_0 .

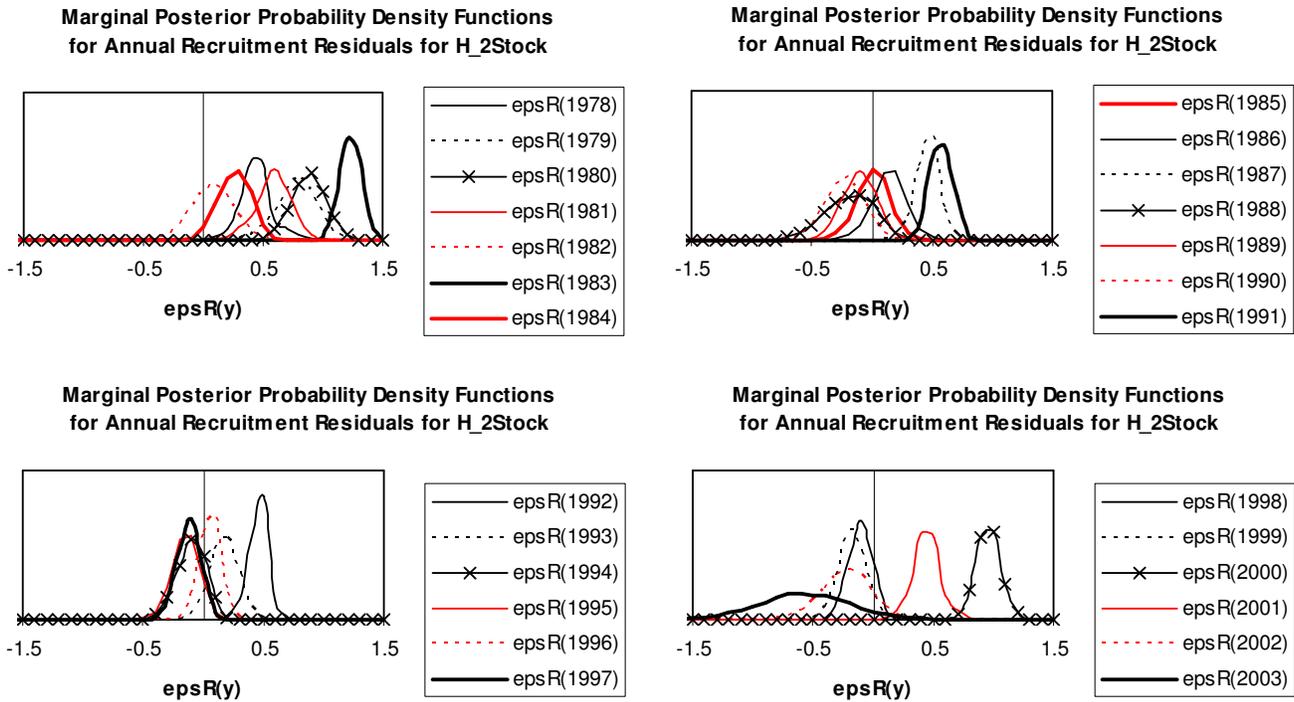


Figure B1.9.21. Marginal posterior probability density functions for recruitment residuals for H_{2Stock} .

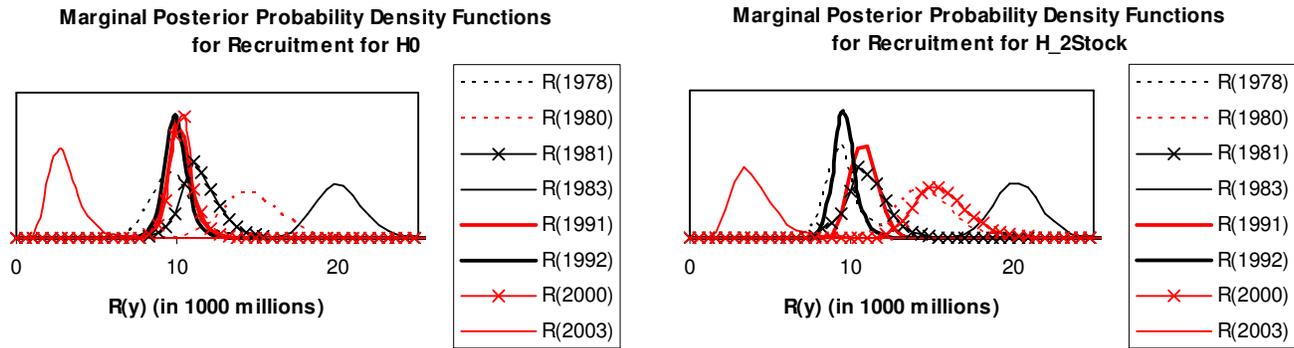


Figure B1.9.22. Marginal posterior probability density functions for recruitment in selected years for H_0 and H_{2Stock} .

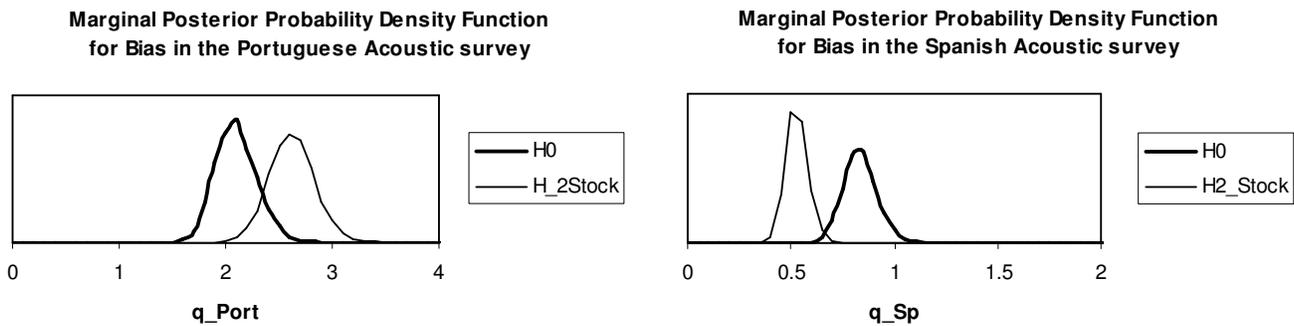


Figure B1.9.23. Marginal posterior probability density functions for bias factors in the acoustic surveys ($q_{Sp,Ac}$ and $q_{Port,Ac}$) for H_0 and H_{2Stock} .

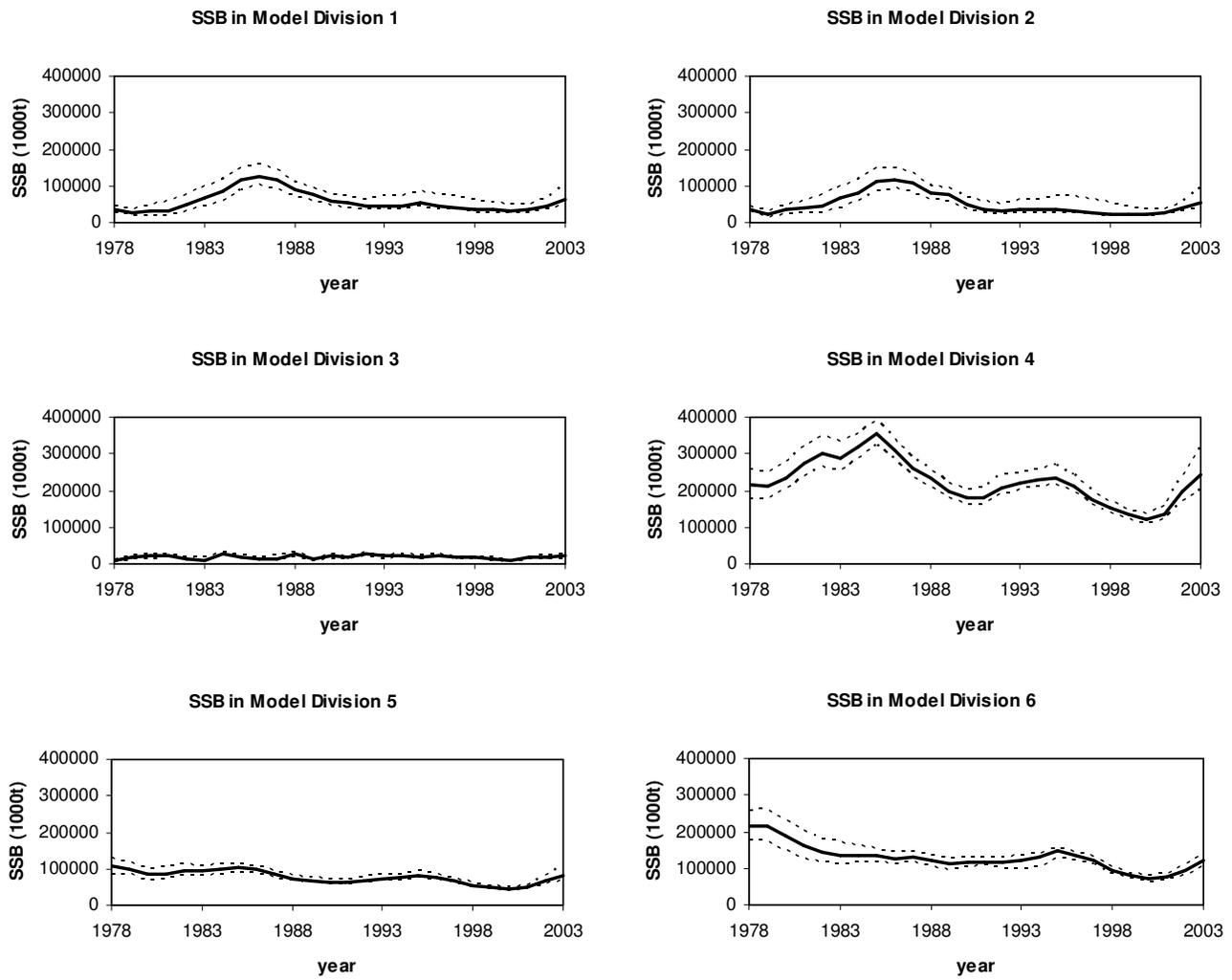


Figure B1.9.24. Median (solid line), 5 and 95 percentile (dotted lines) trajectories of SSB by model division for H_0 .

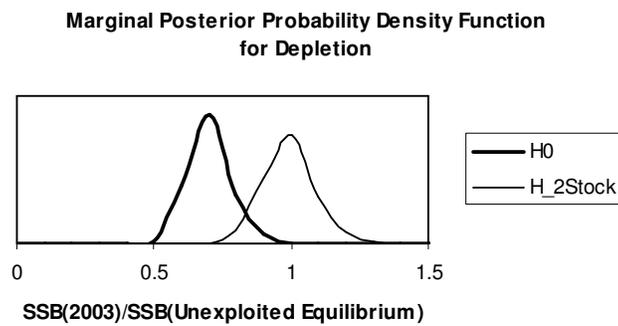


Figure B1.9.25. Marginal posterior probability density functions for depletion in SSB from unexploited equilibrium for H_0 and H_{2Stock} .

Appendix A: Bayesian State-Space Model

Assumptions

- 1.) Sardines are assumed to age on 1 January each year.
- 2.) A plus group of age 6 is assumed prior to 1991 and a plus group of age 12 is assumed after 1995. The plus group increases from 6 to 12 between 1990 and 1996.
- 3.) Migration is modelled to occur at the beginning of each quarter of the year.
- 4.) Catch is modelled to be taken at discrete times, at the beginning of each quarter of the year.
- 5.) Spawning Stock Biomass (SSB) for ICES divisions IXa(south-cadiz) to IXa(central-north) is calculated at the beginning of the first quarter of the year (corresponding to peak spawning in November), while SSB for ICES divisions IXa(north) to VIIIc(east) is calculated at the beginning of the second quarter of the year (corresponding to peak spawning in March).
- 7.) The March/April DEPM estimates of abundance are assumed to be absolute.
- 8.) Stock weights-at-age (Table B1.9.B4) are assumed to measure the average mass of sardine during all the surveys (First quarter DEPM; March acoustic and November acoustic surveys).
- 9.) Recruitment is based on a geometric mean.
- 10.) Although peak spawning is modelled to take place in winter and spring, recruitment to the fishery only occurs at the beginning of the third quarter (e.g., ICES 2004a). Recruitment to both the population and the fishery is therefore modelled to occur at the beginning of the third quarter. Movement of recruits between model divisions is modelled from the beginning of the fourth quarter.
- 11.) Recruitment residuals are assumed to be the same for all stocks (in $H_{2\text{Stock}}$). This implies, for example, that if favourable or unfavourable conditions affect recruitment in one stock, the same effect is seen in the other stocks.
- 12.) Selectivity in the commercial catch is assumed to be the same across all quarters and divisions, over all years. This reflects that similar gear and targeting strategies have been used in all divisions modelled over the time period considered. (Differences in the age-distribution of the landed catch between different areas and quarters therefore result from the age-distribution of the exploitable population, rather than fishing selectivity.) Some initial analyses suggest that commercial selectivity may differ by division and selectivity of 0-group may differ between quarters 3 and 4 (A. Uriarte pers. comm.). However, these analyses were too preliminary to be used as a basis for assuming different selectivity curves for different divisions, or quarters.
- 13.) Selectivity in the acoustic survey is also assumed to be the same across all quarters and divisions, but is assumed to have changed over time. This may be due to, for example, changes in gear or survey design. Selectivity is assumed to change between 1993 and 1994. (Differences in the age-distribution of the acoustic survey between different years may therefore result from the age-distribution of the exploitable population changing, in addition to changes in the selectivity.)
- 14.) The acoustic estimates of biomass are assumed to be relative (ICES 2004a).
- 15.) The distribution of the numbers at age by division at 1 January 1978 is based on the assumed proportion of adults in each model division during their spawning season.
- 16.) Observed annual and quarterly catch-at-age is assumed to differ from the model predicted annual and quarterly catch-at-age due to measurement error, and thus a multinomial likelihood function is used. A multinomial likelihood function is similarly assumed for the proportions of DEPM estimates of SSB by division and for the proportions-at-age by division in the acoustic surveys.
- 17.) A lognormal likelihood function is used to fit the model predicted Spanish SSB at the beginning of the second quarter, the Portuguese SSB at the beginning of the first quarter and to the observed biomass by area from the acoustic surveys.

Population Dynamics

Numbers at age

The numbers of sardine in spawning stock s (the number of stocks will depend on the chosen hypotheses) at age a , in division d , at the beginning of quarter q of year y , $N_s(y, q, a, d)$, are calculated by the following state equations:

$$N_s(y, q, a, d) = \sum_{d_i=1}^D o_s(y, q, a, d_i, d) [N_s(y, q-1, a, d_i) - C_s(y, q-1, a, d_i)] \exp\left\{-\frac{1}{4}M(a)\right\}$$
$$q = 2, \dots, 4, \quad a = 1, \dots, A(y), \quad d = 1, \dots, D$$
$$N_s(y, 1, a, d) = \sum_{d_i=1}^D o_s(y, 1, a, d_i, d) [N_s(y-1, 4, a-1, d_i) - C_s(y-1, 4, a-1, d_i)] \exp\left\{-\frac{1}{4}M(a-1)\right\}$$
$$a = 1, \dots, A(y)-1, \quad d = 1, \dots, D$$

$$N_s(y, 1, A(y), d) = \sum_{d_i=1}^D o_s(y, 1, A(y), d_i, d) [N_s(y-1, 4, A(y)-1, d_i) - C_s(y-1, 4, A(y)-1, d_i)] \exp\left\{-\frac{1}{4}M(A(y)-1)\right\} \\ + \sum_{d_i=1}^D o_s(y, 1, A(y), d_i, d) [N_s(y-1, 4, A(y), d_i) - C_s(y-1, 4, A(y), d_i)] \exp\left\{-\frac{1}{4}M(A(y))\right\} \\ d = 1, \dots, D \quad (\text{A.1})$$

Here

$o_s(y, q, a, d_i, d_j)$ - denotes the movement matrices, the proportion of sardine in stock s from division d_i , aged a moving from division d_i into division d_j at the beginning of quarter q of year y .

$M(a)$ - denotes the rate of natural mortality at age a for all stocks.

$C_s(y, q, a, d)$ - denotes the predicted catch-at-age a taken from stock s in division d and quarter q of year y .

SSB and recruitment

Letting $SSB_s(y, d)$ denote the SSB of stock s in division d in year y , we have

$$SSB_s(y, d) = \begin{cases} \sum_{a=1}^{A(y)} w(y, a, d) P(y, a, d) N_s(y, 1, a, d) & d = 4, \dots, D \\ \sum_{a=1}^{A(y)} w(y, a, d) P(y, a, d) N_s(y, 2, a, d) & d = 1, \dots, 3 \end{cases}$$

where

$w(y, a, d)$ - denotes the average stock weight at age a of an individual in division d in year y .

$P(y, a, d)$ - denotes the proportion mature at age a in division d in year y .

Since the observed DEPM estimates of abundance are assumed to be absolute estimates of SSB, the model-predicted SSB estimates are:

$$\hat{I}_{Sp}(y) = \sum_s \sum_{d=1}^3 SSB_s(y, d), \text{ and } \hat{I}_{Por}(y) = \sum_s \sum_{d=4}^6 SSB_s(y, d). \quad (\text{A.2})$$

There is no obvious stock-recruitment relationship in historically observed SSB and recruitment data for the Iberian sardine (ICES 2004b). Hence, as a base case option, recruitment to stock s in year y is based on a geometric mean.

$$R_s(y) = R \max_s \exp\{\varepsilon_R(y)\} \quad (\text{A.3})$$

where

$R \max_s$ - denotes the geometric mean of annual recruitment to stock s .

$\varepsilon_R(y)$ - denotes the lognormal process error (or recruitment residual) in recruitment.

0-group

Recruitment is modelled to occur at the beginning of the third quarter:

$$N_s(y, 3, 0, d) = R_s(y) o_s^{\text{Recruit}}(y, d) \quad d = 1, \dots, D$$

$$N_s(y, 4, 0, d) = \sum_{d_i=1}^D o_s(y, 4, 0, d_i, d) [N_s(y, 3, 0, d_i) - C_s(y, 3, 0, d_i)] \exp\left\{-\frac{1}{4}M(0)\right\} \quad d = 1, \dots, D \quad (\text{A.4})$$

where

$o_s^{\text{Recruit}}(y, d)$ - denotes the percentage split of recruits by division at the beginning of the third quarter.

Selectivity

A single selectivity curve for commercial catch is assumed for all divisions, defined by an increasing logistic function:

$$S(a) = \frac{1}{1 + \exp\{-sc(a - a_i)\}}, \quad a = 0, \dots, A(y) \quad (\text{A.5})$$

where

sc - denotes the slope of the commercial selectivity curve at 50% selected.

a_i - denotes the age at which 50% selectivity occurs.

Selectivity in the acoustic surveys is thought to have changed over the years, with change occurring between 1993/1994 (ICES 2004a). Although this is expected to be less selective, there is probably still a greater selectivity on older than younger ages, hence an increasing logistic function is also used:

$$S_t^{acoustic}(a) = \frac{1}{1 + \exp\left\{-sc_t^{acoustic}\left(a - a_{i,t}^{acoustic}\right)\right\}}, \quad a = 0, \dots, A(y) \quad (A.6)$$

where

$sc_t^{acoustic}$ - denotes the slope of the selectivity curve for the acoustic survey during period t ($t = 1978 - 1993$ and $1994 - 2003$) at 50% selected.

$a_{i,t}^{acoustic}$ - denotes the age at which 50% selectivity occurs in the acoustic survey during period t ($t = 1978 - 1993$ and $1994 - 2003$).

Total Biomass

The model predicted biomass to be used to fit the model to the relative acoustic estimates of biomass are calculated as follows:

$$\begin{aligned} \hat{I}_{Sp,Ac}(y, d) &= q_{Sp,Ac} \sum_s \sum_{a=1}^{A(y)} w(y, a, d) N_s(y, 2, a, d) & d = 1, \dots, 3 \\ \hat{I}_{Por1,Ac}(y, d) &= q_{Por,Ac} \sum_s \sum_{a=1}^{A(y)} w(y, a, d) N_s(y, 2, a, d) & d = 4, \dots, D \\ \hat{I}_{Por4,Ac}(y, d) &= q_{Por,Ac} \sum_s \sum_{a=1}^{A(y)-1} w(y+1, a+1, d) N_s(y, 4, a, d) + w(y+1, A(y), d) N_s(y, 4, A(y), d) & d = 4, \dots, D \end{aligned} \quad (A.7)$$

where

$q_{i,Ac}$ - denotes the multiplicative bias factor (constant of proportionality) for the Spanish ($i = Sp$) and Portuguese ($i = Por$) acoustic survey estimate of biomass.

Catch

The harvest rate in division d in quarter q of year y is the fraction of catch biomass to exploitable stock biomass, i.e.,

$$H(y, q, d) = \frac{B(y, q, d)}{\sum_s \sum_{a=0}^{A(y)} S(a) N_s(y, q, a, d) w_{catch}(y, q, a, d)}. \quad q = 1, \dots, 4, \quad d = 1, \dots, D \quad (A.8)$$

Here

$B(y, q, d)$ - denotes the observed catch biomass in division d in quarter q of year y .

$w_{catch}(y, q, a, d)$ - denotes the catch weight-at-age a in division d in quarter q of year y .

In years and divisions for which catch weight-at-age is not available by quarter, $w_{catch}(y, q, a, d)$ in the above equation is replaced by $w_{catch}(y, a)$. The catch from stock s of sardine aged a from division d in quarter q of year y is then calculated in proportion to the availability of sardine from that stock as follows:

$$C_s(y, q, a, d) = S(a) N_s(y, q, a, d) H(y, q, d) \quad q = 1, \dots, 4, \quad a = 0, \dots, A(y), \quad d = 1, \dots, D \quad (A.9)$$

Initial Conditions

The population is run from an exploitable equilibrium in 1978. Most of the data on the population are available from 1978, while some data are available in a more disaggregated form from 1991. Beginning the model at a later year, such as 1991, would result in valuable information from the 1980s being lost. Although annual landings (in tonnes) are recorded from 1940, little data on the population are available prior to 1978, and therefore modelling the population prior to 1978 would require a large number of assumptions to be made.

Unexploited equilibrium

The unexploited equilibrium population is calculated at the beginning of the third quarter, when recruitment to the population is modelled to occur. The numbers at age at unexploited equilibrium are derived from equilibrium recruitment (assumed to be the geometric mean for the base case) in the following manner:

$$\begin{aligned}
\bar{N}_s(0) &= \bar{R}_s = R \max_s \\
\bar{N}_s(1) &= \bar{R}_s \exp\{-0.5M(0)\} \exp\{-0.5M(1)\} \\
\bar{N}_s(a) &= \bar{R}_s \exp\{-0.5M(0)\} \exp\left\{-\sum_{i=1}^{a-1} M(i)\right\} \exp\{-0.5M(a)\} & a = 2, \dots, 5 \\
\bar{N}_s(6) &= \bar{R}_s \exp\{-0.5M(0)\} \exp\left\{-\sum_{i=1}^5 M(i)\right\} \exp\{-0.5M(6)\} \sum_{n=0}^{\infty} \exp\{-nM(6)\} \\
&= \bar{R}_s \exp\{-0.5M(0)\} \exp\left\{-\sum_{i=1}^5 M(i)\right\} \exp\{-0.5M(6)\} \sum_{n=0}^{\infty} (\exp\{-M(6)\})^n \\
&= \bar{R}_s \exp\{-0.5M(0)\} \exp\left\{-\sum_{i=1}^5 M(i)\right\} \exp\{-0.5M(6)\} \frac{1}{1 - \exp\{-M(6)\}}
\end{aligned} \tag{A.10}$$

Exploited equilibrium

The population numbers at age in all quarters at exploited equilibrium are calculated from the numbers at age at unexploited equilibrium, taking equilibrium catch into account. These equations are repeatedly calculated, beginning with numbers at age at unexploited equilibrium, (thus initially $\bar{N}_s(3, a) = \bar{N}_s(a)$, $a = 1, \dots, 6$ from unexploited equilibrium) until the total values in sequential years are less than 1% of each other.

$$\begin{aligned}
\bar{N}_s(3,0) &= \bar{R}_s \\
\bar{N}_s(4,0) &= [\bar{N}_s(3,0) - \bar{C}_s(3,0)] \exp\left[-\frac{1}{4}M(0)\right] \\
\bar{N}_s(q,a) &= [\bar{N}_s(q-1,a) - \bar{C}_s(q-1,a)] \exp\left\{-\frac{1}{4}M(a)\right\} & q = 2, \dots, 4, \quad a = 1, \dots, 6 \\
\bar{N}_s(1,a) &= [\bar{N}_s(4,a-1) - \bar{C}_s(4,a-1)] \exp\left\{-\frac{1}{4}M(a-1)\right\} & a = 1, \dots, 5 \\
\bar{N}_s(1,6) &= [\bar{N}_s(4,5) - \bar{C}_s(4,5)] \exp\left\{-\frac{1}{4}M(5)\right\} + [\bar{N}_s(4,6) - \bar{C}_s(4,6)] \exp\left\{-\frac{1}{4}M(6)\right\}
\end{aligned} \tag{A.11}$$

Recruitment at equilibrium for stock s is given by:

$$\bar{R}_s = R \max_s \tag{A.12}$$

The catch-at-age by quarter is calculated by $\bar{C}_s(q, a) = S(a)\bar{N}_s(q, a)\bar{H}_s(q)$ for $q = 1, \dots, 4$ and $a = 0, \dots, 6$. The equilibrium harvest rate for stock s is calculated by

$$\bar{H}_s(q) = \frac{Per_s(q)\bar{B}_s}{\sum_{a=0}^6 S(a)\bar{N}_s(q, a)\bar{w}_{catch,s}(a)} \quad q = 1, \dots, 4 \tag{A.13}$$

where

- \bar{B}_s - denotes the equilibrium yield for stock s .
- $Per_s(q)$ - denotes the estimated quarterly percentage of equilibrium yield for stock s .
- $\bar{w}_{catch,s}(a)$ - denotes the equilibrium catch weight at age a for stock s .

The numbers at age and by division in the first quarter of the initial year are then given by

$$N_s(1978, 1, a, d) = SplitEq(d) \times \bar{N}_s(1, a) \times \exp\{\bar{\varepsilon}(a)\} \quad a = 1, \dots, A(y), \quad d = 1, \dots, D \tag{A.14}$$

where

- $SplitEq(d)$ - denotes the estimated percentage of sardine in division d at the beginning of the year at exploited equilibrium.
- $\bar{\varepsilon}(a)$ - denotes the lognormal process error (or residual) of equilibrium numbers at age a .

Fitting the Model to Catch and Abundance Data

Catch-at-age data

Annual catch-at-age data are available by division from 1978 to 1990, and by quarter from 1991 to 2003, except in IXa(south-cadiz) where quarterly catch-at-age data are only available from 1998 to 2003. Since quarterly

catch-at-age data are only available for all divisions from 1998 to 2003, the model is fit to the annual catch-at-age data from 1978 to 1997, although the quarterly data are used in the calculation of the harvest rate (equation (A.8)).

The model is fit to observed annual, $C^{obs}(y, a)$, and quarterly, $C^{obs}(y, q, a)$, catch-at-age data as follows:

$$\ln(L_1) = \hat{N}_1 \sum_{y=1978}^{1997} \sum_{a=0}^{6+} p(y, a) \ln \hat{p}(y, a) + \hat{N}_2 \sum_{y=1998}^{2003} \sum_{q=1}^4 \sum_{a=0}^{12+} p(y, q, a) \ln \hat{p}(y, q, a). \quad (A.15)$$

Here

\hat{N}_i - denotes the estimated effective sample size for the total number of fish sampled each year ($i = 1$) or quarter ($i = 2$).

$p(y, a)$ - denotes the proportion at age in the sample in year y .

$$\hat{p}(y, a) = \frac{\sum_s \sum_{q=1}^4 \sum_{d=1}^D C_s(y, q, a, d)}{\sum_{a=0}^{6+} \sum_s \sum_{q=1}^4 \sum_{d=1}^D C_s(y, q, a, d)} \quad - \text{denotes the predicted proportion at age } a, \text{ in the commercial catch in year } y.$$

$p(y, q, a)$ - denotes the proportion at age in the sample in quarter q of year y .

$$\hat{p}(y, q, a) = \frac{\sum_s \sum_{d=1}^D C_s(y, q, a, d)}{\sum_{a=0}^{12+} \sum_s \sum_{d=1}^D C_s(y, q, a, d)} \quad - \text{denotes the predicted proportion at age } a, \text{ in the commercial catch in quarter } q \text{ of year } y.$$

As no catch (only proportions) was included in the above equation, we add the terms

$$\ln(L_2) = \lambda_1 \sum_{y=1978}^{1997} \left(\ln(C^{obs}(y)) - \ln(C(y)) \right)^2 + \lambda_2 \sum_{y=1998}^{2002} \left(\ln(C^{obs}(y, q)) - \ln(C(y, q)) \right)^2 \quad (A.16)$$

to the log-likelihood function to penalize deviations between predicted and observed catches and λ_1 and λ_2 are

set large enough in order that the predicted catch is close to the observed catch. Here $C^{obs}(y) = \sum_{a=0}^{6+} C^{obs}(y, a)$

and $C(y) = \sum_s \sum_{a=0}^{A(y)} \sum_{q=1}^4 \sum_{d=1}^D C_s(y, q, a, d)$; $C^{obs}(y, q) = \sum_{a=0}^{12+} \sum_{d=1}^D C^{obs}(y, q, a, d)$ and

$$C(y, q) = \sum_s \sum_{a=0}^{A(y)} \sum_{d=1}^D C_s(y, q, a, d).$$

Estimates of spawning abundance

Two series of daily egg production method based SSB estimates are available (ICES 2003, 2004a). The Spanish series of estimates are for Eastern Cantabria (ICES divisions VIIIc and IXa(north)) during March/April, while the Portuguese series covers the Portuguese coast (ICES divisions IXa(central-north), IXa(central-south) and IXa(south-algarve)) and the Gulf of Cadiz (ICES division IXa(south-cadiz)) and took place during January. The likelihood function used to fit the model to these data is as follows:

$$\begin{aligned} \ln(L_3) = & -\frac{1}{2} n_{Sp,SSB} \ln(2\pi) - \sum_{y=88,90,97,99,02} \ln(\sigma_{Sp,SSB}^2(y) I_{Sp,SSB}(y)) - \frac{1}{2} \sum_{y=88,90,97,99,02} \frac{(\ln(I_{Sp,SSB}(y)) - \ln(\hat{I}_{Sp}(y)))^2}{\sigma_{Sp,SSB}^2(y)} \\ & -\frac{1}{2} n_{Por,SSB} \ln(2\pi) - \sum_{y=99,02} \ln(\sigma_{Por,SSB}^2(y) I_{Por,SSB}(y)) - \frac{1}{2} \sum_{y=99,02} \frac{(\ln(I_{Por,SSB}(y)) - \ln(\hat{I}_{Por}(y)))^2}{\sigma_{Por,SSB}^2(y)} \end{aligned} \quad (A.17)$$

where

$n_{i,SSB}$ - denotes the total number of $I_{i,SSB}(y)$ observations, $i = Sp, Por$.

- $\sigma_{i,SSB}(y)$ - denotes the standard deviation in the log of the DEPM estimates of abundance for Eastern Cantabria ($i = Sp$) and for the Portuguese coast and the Gulf of Cadiz ($i = Por$) in year y .
- $I_{i,SSB}(y)$ - denotes the observed DEPM estimate of abundance for Eastern Cantabria ($i = Sp$) and for the Portuguese coast and the Gulf of Cadiz ($i = Por$) in year y .

In addition to the DEPM estimates of SSB for the total Eastern Cantabria area used above, estimates of SSB are available by region in some of the years. Similarly, estimates of SSB for the Portuguese surveys are available by region. The model is fit to these data as follows:

$$\ln(L_4) = \hat{N}_{DEPM_Sp} \sum_{y=88,90,02} \left\{ propI_{Sp,SSB}(y,1) \ln \hat{propI}_{Sp,SSB}(y,1) + propI_{Sp,SSB}(y,2+3) \ln \hat{propI}_{Sp,SSB}(y,2+3) \right\} \\ + \hat{N}_{DEPM_Por} \sum_{y=99,02} \left\{ propI_{Por,SSB}(y,4+5) \ln \hat{propI}_{Por,SSB}(y,4+5) + propI_{Por,SSB}(y,6) \ln \hat{propI}_{Por,SSB}(y,6) \right\} \quad (A.18)$$

where

\hat{N}_{DEPM_i} - denotes the estimated effective sample size for the total abundance sampled each survey, ($i = Sp, Por$).

$propI_{i,SSB}(y,d)$ - denotes the observed proportion of abundance by division d in year y , ($i = Sp, Por$).

$\hat{propI}_{i,SSB}(y,d)$ - denotes the predicted proportion of abundance by division d , in year y , ($i = Sp, Por$).

The observed proportion for ICES divisions IXa(north) and VIIIc(west) is combined and therefore the predicted proportion for model divisions 2 and 3 is combined. Similarly, the observed proportion for ICES divisions IXa(central-north) and IXa(central-south) is combined and therefore the predicted proportion for model divisions 4 and 5 is combined. Thus we have:

$$\hat{propI}_{Sp,SSB}(y,1) = \frac{\sum_s SSB_s(y,1)}{\sum_s \sum_{d=1}^3 SSB_s(y,d)} \quad \text{and} \quad \hat{propI}_{Sp,SSB}(y,2+3) = \frac{\sum_s SSB_s(y,2) + SSB_s(y,3)}{\sum_s \sum_{d=1}^3 SSB_s(y,d)}$$

$$\hat{propI}_{Por,SSB}(y,4+5) = \frac{\sum_s SSB_s(y,4) + SSB_s(y,5)}{\sum_s \sum_{d=4}^6 SSB_s(y,d)} \quad \text{and} \quad \hat{propI}_{Por,SSB}(y,6) = \frac{\sum_s SSB_s(y,6)}{\sum_s \sum_{d=4}^6 SSB_s(y,d)} .$$

Estimates of total abundance

Three series of acoustic estimates of abundance are available (ICES 2003, 2004a). The Spanish first quarter acoustic surveys cover Eastern Cantabria (ICES divisions VIIIc and IXa(north)) during March/April. The Portuguese first quarter acoustic surveys cover the Portuguese coast and Gulf of Cadiz (ICES divisions IXa(central-north), IXa(central-south), IXa(south-algarve) and IXa(south-cadiz)) during March. Lastly, the Portuguese fourth quarter acoustic surveys cover the Portuguese coast, and in some years, the Gulf of Cadiz during November. The log-likelihood function is given by:

$$\ln(L_5) = \hat{N}_{Ac_Sp} \sum_y \sum_d \sum_{a=0}^{A(y)} propN_{Sp}(y,2,a,d) \ln \hat{propN}_{Sp}(y,2,a,d) \\ + \hat{N}_{Ac_Por1} \sum_y \sum_d \sum_{a=0}^{7+} propN_{Por}(y,2,a,d) \ln \hat{propN}_{Por}(y,2,a,d) * \\ + \hat{N}_{Ac_Por4} \sum_y \sum_d \sum_{a=0}^{7+} propN_{Por}(y,4,a,d) \ln \hat{propN}_{Por}(y,4,a,d) \quad (A.19)$$

Here

\hat{N}_i - denotes the estimated effective sample size for the total number of fish sampled each

* In the second and third terms of this equation, the sum over ages is to a maximum of 6+ for years prior to 1991.

survey, $i = Ac_Sp, Ac_Por1, Ac_Por4$.

$propN_i(y, 2, a, d)$ - denotes the proportion of numbers at age in the sample from the first quarter survey i ,
 $i = Sp, Por$ in division d in year y .

$propN_{Por}(y, 4, a, d)$ - denotes the proportion of numbers at age in the sample from the fourth quarter Portuguese survey, in division d in year y .

$$\hat{propN}_{Sp}(y, 2, a, d) = \frac{\sum_s S_t^{acoustic}(a) \times N_s(y, 2, a, d)}{\sum_s \sum_{a=1}^{A(y)} S_t^{acoustic}(a) \times N_s(y, 2, a, d)}$$

- denotes the predicted proportion of numbers at age in division d at the beginning of quarter 2 in year y to match the Spanish survey.

$$\hat{propN}_{Por}(y, 2, a, d) = \frac{\sum_s S_t^{acoustic}(a) \times N_s(y, 2, a, d)}{\sum_s \sum_{a=1}^{7+} S_t^{acoustic}(a) \times N_s(y, 2, a, d)}$$

- denotes the predicted proportion of numbers at age in division d at the beginning of quarter 2 in year y to match the Portuguese first quarter survey.

$$\hat{propN}_{Por}(y, 4, a, d) = \frac{\sum_s S_t^{acoustic}(a) \times N_s(y, 4, a, d)}{\sum_s \sum_{a=1}^{7+} S_t^{acoustic}(a) \times N_s(y, 4, a, d)}$$

- denotes the predicted proportion of numbers at age in division d at the beginning of quarter 4 in year y to match the Portuguese fourth quarter survey.

The model is fit to the observed biomass by area as follows:

$$\begin{aligned} \ln(L_6) = & -\frac{1}{2} n_{Sp,Ac} \ln(2\pi) - \sum_y \sum_d \ln(\sigma_{Sp,Ac}^2 I_{Sp,Ac}(y, d)) - \frac{1}{2} \sum_y \sum_d \frac{(\ln(I_{Sp,Ac}(y, d)) - \ln(\hat{I}_{Sp,Ac}(y, d)))^2}{\sigma_{Sp,Ac}^2} \\ & - \frac{1}{2} n_{Por1,Ac} \ln(2\pi) - \sum_y \sum_d \ln(\sigma_{Por,Ac}^2 I_{Por1,Ac}(y, d)) - \frac{1}{2} \sum_y \sum_d \frac{(\ln(I_{Por1,Ac}(y, d)) - \ln(\hat{I}_{Por1,Ac}(y, d)))^2}{\sigma_{Por,Ac}^2} \\ & - \frac{1}{2} n_{Por4,Ac} \ln(2\pi) - \sum_y \sum_d \ln(\sigma_{Por,Ac}^2 I_{Por4,Ac}(y, d)) - \frac{1}{2} \sum_y \sum_d \frac{(\ln(I_{Por4,Ac}(y, d)) - \ln(\hat{I}_{Por4,Ac}(y, d)))^2}{\sigma_{Por,Ac}^2} \end{aligned} \quad (A.20)$$

Here

$n_{i,Ac}$ - denotes the total number of $I_{i,Ac}(y, d)$ observations, $i = Sp, Por1, Por4$.

$\sigma_{i,Ac}$ - denotes the assumed standard deviation in the log of the acoustic estimates of abundance ($i = Sp, Por$).

$I_{i,Ac}(y, d)$ - denotes the observed acoustic estimate of abundance ($i = Sp, Por1, Por4$) in division d of year y .

Appendix B: Model Parameters and Observed Data

Fixed Parameter Values

Movement matrices

The movement matrices, $o_s(y, q, a, d_i, d_j)$, were assigned fixed values as there are insufficient data to estimate the age- and division-dependent movement (Table B1.9.B1). These values were based on expert advice from members of the SARDYN project, using knowledge gained from tagging studies, surveys and commercial catches (with the reservation that the reported catches show the distribution of the fishery and not necessarily the sardine population). The movement of adults was assumed to be age-independent from age 2 upwards. The movement of 1-year-olds and the recruits (0-group) were modelled separately and since the 0-group were assumed to recruit to the population at the beginning of the third quarter, only one migration matrix at the beginning of the fourth quarter is required. In addition, the migration pattern of sardine from good recruitment year classes is assumed to differ from that of normal or weaker year classes (Table B.7.3.B1b).

0-group

Initial tagging evidence seems to support the idea that little directional movement of recruits occurs at the beginning of the fourth quarter. However, some diffusion of recruits in northern Portugal and western Galicia may occur (e.g., as observed during 2004). Thus 5% of recruits in model division 3 were assumed to move to model division 4 and vice versa and 5% of recruits in model division 4 were assumed to move to model division 5 and vice versa (see Table B1.9.1 for ICES divisions corresponding to model divisions).

There is currently no information on which to base a change in the migration pattern of these recruits during a year of good recruitment.

1-year-olds

The 1-year-olds are assumed to generally remain in the area to which they recruited. At the beginning of the first quarter, some further diffusion of recruits between model divisions is assumed by modelling 5% of 1-year-olds to move into their neighbouring divisions. No migration is modelled to occur at the beginning of the second and fourth quarters.

As there may be some northerly movement of the juveniles, it was assumed that at the beginning of the third quarter, 10% of sardine in each model division move into the neighbouring model division to the north or east. The exception was that only 80% of the 1-year-olds in model division 3 were assumed to remain in that division, while 10% were assumed to move into model division 2 and 10% into model division 1, corresponding to the migration of the adults from model division 3 (see below).

There is currently no information on which to base a change in the migration patterns of 1-year-olds between good recruitment year classes and normal or weak year classes.

Adults

The spawning season in Portuguese waters begins around October/November each year. The sardine in model divisions 4 to 6 were therefore assumed to move into their spawning areas at the beginning of the fourth quarter. The sardine spawning within Portuguese waters were assumed to be distributed, on average, with about 40% of the spawning biomass in model division 4, 20% in model division 5 and 40% in model division 6. In addition, the percentage split of SSB between model divisions has been observed in limited years (Table B1.9.B7). This information was used in initial model testing to help establish reliable movement rates between model divisions 4 and 5 and between 5 and 6 at the beginning of the fourth quarter. These initial tests pointed towards the majority of adults in division 4 at the beginning of quarter 4 remaining there for spawning, with 30% of the adults in division 5 moving to division 4. In addition, the majority of adults in division 6 at the beginning of quarter 4 were assumed to remain there for spawning.

These sardine were assumed to stay in their spawning areas during the first half of the year and thus and no directional movement at the beginning of the first and second quarters was modelled.

Spawning in the Spanish waters of model divisions 1 to 3 was assumed to occur at the beginning of April. These adults were assumed to move into their spawning areas from the beginning of the year, and no movement at the beginning of the second quarter was modelled. As for the distribution of SSB in Portuguese waters, the migration rates between model divisions 1 and 2 and between 2 and 3 at the beginning of the first quarter were fixed after initial model testing using information that, on average, about 10% of the adults distributed throughout model divisions 1 to 3 were found in model division 3 and the remaining adults were split equally between model divisions 1 and 2, together with the observed percentage split of SSB between model divisions

in limited years (Table B1.9.B6). These initial tests pointed towards the majority of adults in division 1 at the beginning of quarter 1, staying in division 1 for spawning and the majority of adults in division 2 moving into division 1. In addition, about 70% of the adults in model division 3 at the beginning of the first quarter were assumed to move into division 2 for spawning.

Both spawning and recruitment occur in model division 6 and the feeding conditions in these areas are good. These combined areas are generally thought to remain stable, and thus only a 5% northerly migration into model division 5 was assumed once a year, at the beginning of the third quarter.

There is some indication that there is a small southerly migration of adults from IXa(north) down to IXa(south-algarve) and IXa(south-cadiz). This was incorporated in the model by allowing 5% of the adults in model divisions 2 to 5 to move into the south-neighbouring model division at the beginning of the third quarter. In addition, 15% of adult sardine were assumed to move from model division 4 northwards into model division 3 at the beginning of the third quarter. This directional movement was greater for good recruitment year classes (see below), but was not assumed to disappear altogether for normal or weak recruitment year classes. (In fact, initial model testing revealed worse fits to the data if a smaller percentage of northerly migration was assumed.)

Adults in ICES division VIIIc have been observed to move to IXa(north) for feeding. Therefore at the beginning of the third quarter, 65% of adults in model division 2 were assumed to move into model division 3 and 40% of adults in model division 1 were assumed to move into model division 2 and 20% into model division 3.

The larger of these adults in IXa(north) were assumed to migrate back to VIIIc before the smaller adults move at the beginning of the first quarter. To allow for this, some of the adults (10%) were assumed to move from model division 2 into model division 1 at the beginning of the fourth quarter. In addition, 10% of the adults in model division 3 were assumed to move into model division 1 and 10% into model division 2 at the beginning of the fourth quarter. No other movement was assumed to occur at the beginning of the fourth quarter.

The distribution of the adult sardine at peak spawning was assumed to remain unchanged for good recruitment year classes compared to normal and weak recruitment year classes.

The small southerly migration of 5% of adults between neighbouring model divisions at the beginning of the third quarter from model division 3 down to model division 6 was assumed to remain unchanged for good recruitment year classes. However, the good recruitment year classes have demonstrated a greater northerly migration. Therefore, in addition to this southerly movement, 10% of the adults in model division 6 were assumed to move into model division 5, 10% of the adults in model division 5 move north to model division 4 and 25% of the adults in model division 4 move north to model division 3. Note that although this northerly migration may only appear to be modelled as far north as ICES division IXa(north), adults in model division 3 move into model divisions 1 and 2 at the beginning of the fourth and first quarters, thereby completing the assumed north-eastwards movement of adults from good recruitment year classes.

Distribution of recruits

The percentage split of recruits by division at the beginning of the third quarter, $o_s^{Recruit}(y, d)$, was also based on expert opinion (Table B1.9.B2). The majority (57%) of recruits were assumed to be distributed in model division 4, with a large portion (17%) in model division 6 and 13% in model division 3. The remaining 13% were spread throughout the remaining three model divisions.

In years of good recruitment, the recruitment in model division 4 is more prominent (65%), while that in model division 6, especially ICES division IXa(south-cadiz), is less important and therefore only 9% of the recruits were assumed to be distributed in model division 6.

Natural mortality

Natural mortality at age is assumed to be constant for all ages (ICES 2004a), $M(a) = 0.33$, $a = 0, \dots, A(y)$.

Maturity ogives

Maturity ogives, $P(y, a, d)$, $d = 1, \dots, D$ are given in Table B1.9.B3. From 1991 to 2003 these values are available separately for Portuguese and Spanish waters. These area-disaggregated data were used in robustness test R_{data} . Maturity ogives at equilibrium, $\bar{P}(a)$, used in the robustness test R_{Ricker} were based on an average from 1978 to 1985.

Stock weights at age

Stock weights at age, $w(y, a, d)$, $d = 1, \dots, D$ are given in Table B1.9.B4. From 1991 to 2003 these values are available separately for Portuguese and Spanish waters (excluding 1994 and 1995 for Spanish waters for which the weights at age for the entire area were used) and were used in robustness test R_{data} . These values were assumed to reflect the average mass at spawning and the average mass during the November acoustic survey of the previous year. Stock weights at age at equilibrium, $\bar{w}(a)$, used in the robustness test R_{Ricker} , were based on an average from 1978 to 1985.

Observed catch biomass

The observed catch biomass in division d in quarter q of year y , $B(y, q, d)$, used in calculating the harvest rate was calculated by multiplying the observed catch-at-age data and the observed catch weight-at-age data. From 1978 to 1990 and from 1991 to 1996 in model division 6, only annual catch-at-age and catch weight-at-age data are available. The observed annual catch-at-age were therefore split into quarters based on the quarterly split observed between 1991 and 2003 for model divisions 1 to 5 and 1997 to 2003 for model division 6. In addition, annual catch-at-age is only available jointly for model divisions 1 and 2 between 1978 and 1990. This observed annual catch-at-age was therefore split equally between the two model divisions. This was based on the percentage split observed between 1991 and 2003, which although differing between years, did not deviate greatly from 0.5. Thus we have

$$B(y, q, d) = \begin{cases} 0.5 \times C^{obs}(y, a, 1+2) \times w_{catch}(y, a) \times splitQ(q, a, d) & \text{if } (y \leq 1990) \text{ and } (d = 1, 2) \\ C^{obs}(y, a, d) \times w_{catch}(y, a) \times splitQ(q, a, d) & \text{if } (y \leq 1990 \text{ and } d \neq 1, 2) \text{ and } (1991 \leq y \leq 1997 \text{ and } d = 6) \\ C^{obs}(y, q, a, d) \times w_{catch}(y, q, a, d) & \text{if } (1991 \leq y \leq 1997 \text{ and } d \neq 6) \text{ and } (y \geq 1998) \end{cases}$$

where

$splitQ(q, a, d)$ - denotes the approximate split of annual catch biomass for age a in division d between quarters (Table B1.9.B5).

Equilibrium yield and distribution

The average total catch for ICES divisions VIIIc and IXa (excluding the Gulf of Cadiz) between 1968 and 1977 was 142 thousand tonnes. This was assumed to be the equilibrium catch, \bar{B}_s . In the absence of any available quarterly data in the 1970s, the equilibrium yield was split equally between quarters (i.e. $Per_s(q) = 0.25$, $q = 1, \dots, 4$). The catch weight-at-age was unchanged between 1978 and 1988 (SARDYN database; SARDYN 2005) and therefore the same catch weight-at-age was assumed for equilibrium, $\bar{w}_{catch,s}(a)$.

At the beginning of the initial year, the adult sardine are in their spawning areas and thus the assumed distribution of the SSB between the model divisions was used (cf pg 42-43). In addition it was assumed that the sardine were distributed with a 15:85 split between ICES divisions VIIIc(east) to IXa(north) and ICES divisions IXa(central-north) to IXa(south-cadiz). This split was arrived at through initial testing of the model with alternative values. Thus we have: $SplitEq(1) = 0.15 \times 0.45 = 0.09$, $SplitEq(2) = 0.15 \times 0.45 = 0.09$, $SplitEq(3) = 0.15 \times 0.1 = 0.02$, $SplitEq(4) = 0.85 \times 0.4 = 0.32$, $SplitEq(5) = 0.85 \times 0.2 = 0.16$ and $SplitEq(6) = 0.85 \times 0.4 = 0.32$.

The lognormal equilibrium numbers at age process error parameters were fixed $\bar{\epsilon}(a) = 0$. Initial testing of the model indicated that there were insufficient data to estimate these parameters together with the remaining model parameters.

Weightings

The number of observations used in the lognormal likelihoods are as follows: $n_{Sp,SSB} = 5$, $n_{Por,SSB} = 2$, $n_{Sp,Ac} = 45$, $n_{Por1,Ac} = 28$ and $n_{Por4,Ac} = 27$. In the absence of any recorded CVs for the observed acoustic estimates of biomass, $\sigma_{Sp,Ac} = \sigma_{Por,Ac} = 0.5$ such that the estimates are not given too much weighting. The weighting for fitting the predicted annual and quarterly catches to the observed values is $\lambda_1 = \lambda_2 = 1$. No closer fit to these catch biomass data was obtained by increasing this weighting. The effective sample size for the total number of fish sampled each survey for the proportions of DEPM estimated abundance by division were set to $\hat{N}_{DEPM_Sp} = \hat{N}_{DEPM_Por} = 10$ and the effective sample size for the total number of fish sampled each survey for the proportions of acoustic numbers-at-age were set to $\hat{N}_{Ac_Sp} = \hat{N}_{Ac_Por1} = \hat{N}_{Ac_Por4} = 10$. The effective

sample size for the total number of fish sampled each year for the proportions-at-age in the commercial catch were set to $\hat{N}_1 = \hat{N}_2 = 50$. Lower values resulted in high correlations between model parameters, especially amongst the recruitment residuals and between the recruitment residuals and $R \max_s$, while higher values resulted in too great a weighting to the catch-at-age data in comparison to the observed DEPM estimates of SSB.

Estimated Parameters and their Prior Distributions

An uninformative prior distribution was assumed for the geometric mean of annual recruitment, with boundaries exceeding the range in recruitment recorded by Myers *et al.* (1995), i.e. $R \max_s \sim U(0,40000)$ million.

The lognormal recruitment process error parameters (or recruitment residuals) were assumed to be normally distributed, $\varepsilon_R(y) \sim N(0, \sigma_R^2)$. The standard deviation of the log of the process error in stock-recruitment, σ_R^2 , was fixed at a value of 0.453 obtained from a lognormal distribution fit to the stock-recruitment data on Spanish Sardine (Myers *et al.*, 1995). Years for which $\varepsilon_R(y)$ was estimated to be > 0.2 were defined as being good recruitment years. This affects the distribution of the recruits during this year and the movement of the year class (see migration matrices and distribution of recruits above).

The parameters for the slope of the selectivity curves at 50% selected were assigned lognormal prior distributions, $sc, sc_{78-93}^{acoustic}, sc_{94-03}^{acoustic} \sim \log N(2, 0.4^2)$, where 2 is the median of the distribution, while the parameters for the age at 50% selected in the selectivity curves were assigned truncated normal prior distributions: $a_i \sim truncN(2, 10^2)$ and $a_{i,78-93}^{acoustic} \sim truncN(1, 2^2)$, with $a_{i,94-03}^{acoustic} = a_{i,78-93}^{acoustic} + x$, where $x \sim U(0,1)$ to reduce correlation between the estimated parameters.

The multiplicative bias factors for the acoustic survey estimates of biomass were assigned normal distributions around 1 (no bias), i.e. $q_{Sp,Ac} \sim q_{Por,Ac} \sim N(1, 0.5^2)$.

Data Used to Fit the Model

Annual catch-at-age data, $C^{obs}(y, a)$, and corresponding catch weights-at-age, $w_{catch}(y, a)$, are available in the SARDYN database (SARDYN 2005) for ages 0 to 6+ from 1978 to 1990 for ICES divisions VIIIc, IXa(north), IXa(central-north), IXa(central-south), IXa(south-algarve) and IXa(south-cadiz) and from 1991 to 1997 for IXa(south-cadiz). Quarterly catch-at-age data, $C^{obs}(y, q, a)$, and catch weights-at-age, $w_{catch}(y, q, a, d)$, are available in the SARDYN database (SARDYN 2005) for ages 0 to 12+ from 1991 to 2003 for ICES divisions VIIIc(east), VIIIc(west), IXa(north), IXa(central-north), IXa(central-south) and IXa(south-algarve) and from 1998 to 2002 for IXa(south-cadiz). The observed proportions-at-age $p(y, a)$ and $p(y, q, a)$ used in equation (A.15) are calculated from these observed data using the same formulae as for the predicted proportions-at-age (cf pg 39).

Tables B1.9.B6 and B1.9.B7 list the data from the DEPM surveys, while Tables B1.9.B8 to B1.9.B13 list the data from the acoustic surveys.

Table B1.9.B1a. Migration matrices for normal and weak recruitment year classes.

		Movement into model divisions																						
		Age 0						Age 1						Age 2+										
		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6					
Movement from model divisions	Quarter 1	1	0	0	0	0	0	0.95	0.05	0	0	0	0	0.9	0.1	0	0	0	0.8	0.15	0	0	0	0
		2	0	0	0	0	0	0.05	0.9	0.05	0	0	0	0	0.8	0.05	0	0	0	0.15	0.05	0	0	0
		3	0	0	0	0	0	0	0.05	0.9	0.05	0	0	0	0	0.7	0.3	0	0	0.7	0.3	0	0	0
		4	0	0	0	0	0	0	0	0.05	0.9	0.05	0	0	0	0	0	1	0	0	0	1	0	0
		5	0	0	0	0	0	0	0	0	0.05	0.9	0.05	0	0	0	0	0	0	0	0	0	1	0
		6	0	0	0	0	0	0	0	0	0	0.05	0.95	0	0	0	0	0	0	0	0	0	0	1
	Quarter 2	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	
		2	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	
		3	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	
		4	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	
		5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	
		6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
	Quarter 3	1	0	0	0	0	0	1	0	0	0	0	0.4	0.4	0.2	0	0	0	0.4	0.2	0	0	0	
		2	0	0	0	0	0	0.1	0.9	0	0	0	0	0.35	0.65	0	0	0	0.35	0.65	0	0	0	
		3	0	0	0	0	0	0.1	0.1	0.8	0	0	0	0	0.95	0.05	0	0	0	0.95	0.05	0	0	
		4	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0.15	0.8	0.05	0	0	0.15	0.8	0.05	0	
		5	0	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0	0	0.95	0.05	
		6	0	0	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0	0.95	0.05	
	Quarter 4	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	
		2	0	0	0	0	0	0	1	0	0	0	0	0.9	0	0	0	0	0.9	0	0	0	0	
		3	0	0	0.05	0	0	0	0	1	0	0	0	0.1	0.8	0	0	0	0.1	0.8	0	0	0	
		4	0	0	0.9	0.05	0	0	0	0	1	0	0	0	0	0.8	0.2	0	0	0	0.8	0.2	0	
		5	0	0	0	0.05	0	0	0	0	0	1	0	0	0	0	0.1	0	0	0	0	0.1	0.6	
		6	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	

Table B1.9.B1b. Migration matrices for good recruitment year classes.

		Movement into model divisions																							
		Age 0						Age 1						Age 2+											
		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6						
Movement from model divisions	Quarter 1	1	0	0	0	0	0	0.95	0.05	0	0	0	0	0	0.1	0	0	0	0	0.9	0.1	0	0	0	0
		2	0	0	0	0	0	0.05	0.9	0.05	0	0	0	0.8	0.15	0.05	0	0	0	0.8	0.15	0.05	0	0	0
		3	0	0.95	0	0	0	0	0.05	0.9	0.05	0	0	0	0.7	0.3	0	0	0	0	0.7	0.3	0	0	0
		4	0	0	0	0	0	0	0	0.05	0.9	0.05	0	0	0	0	1	0	0	0	0	0	1	0	0
		5	0	0	0	0	0	0	0	0	0.05	0.9	0.05	0	0	0	0	0	1	0	0	0	0	1	0
		6	0	0	0	0	0	0	0	0	0	0.05	0.95	0	0	0	0	0	0	0	0	0	0	0	1
	Quarter 2	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	
		2	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	
		3	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	
		4	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	
		5	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	
		6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1		
	Quarter 3	1	0	0	0	0	0	1	0	0	0	0	0.4	0.4	0.2	0	0	0	0.4	0.4	0.2	0	0	0	
		2	0.1	0.9	0	0	0	0.1	0.9	0	0	0	0	0.35	0.65	0	0	0	0	0.35	0.65	0	0	0	
		3	0.1	0.1	0.8	0	0	0.1	0.1	0.8	0	0	0	0	0.95	0.05	0	0	0	0	0.95	0.05	0	0	
		4	0	0	0.1	0.9	0	0	0	0.1	0.9	0	0	0	0.25	0.7	0.05	0	0	0	0.25	0.7	0.05	0	
		5	0	0	0	0.1	0.9	0	0	0	0.1	0.9	0	0	0	0.1	0.85	0.05	0	0	0	0.1	0.85	0.05	
		6	0	0	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0.1	0.9	0	0	0	0	0.1	0.9	
	Quarter 4	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	
		2	0	0	0	0	0	0	1	0	0	0	0.1	0.9	0	0	0	0	0.1	0.9	0	0	0	0	
		3	0	0.95	0	0	0	0	0	1	0	0	0.1	0.1	0.8	0	0	0	0.1	0.1	0.8	0	0	0	
		4	0	0.05	0.9	0.05	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	
		5	0	0	0	0.05	0.95	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	
		6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1		

Table B1.9.B1c. Migration matrices for normal and weak recruitment year classes for stock 1 in H_{2stock} (To ease comparison, the shaded cells are those changed from $H_{0..}$)

		Movement into model divisions																	
		Age 0						Age 1						Age 2+					
		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Movement from model divisions	Quarter 1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		2	0	0.95	0	0	0	0	0.95	0	0	0	0	0	0.95	0	0	0	0
		3	0	0.05	0.9	0.05	0	0	0.05	0.9	0.05	0	0	0	0.7	0.3	0	0	0
		4	0	0	0.05	0.9	0.05	0	0	0.05	0.9	0.05	0	0	0	0	1	0	0
		5	0	0	0	0.05	0.9	0	0	0	0.05	0.9	0.05	0	0	0	0	1	0
		6	0	0	0	0	0.05	0	0	0	0	0.05	0.95	0	0	0	0	0	1
Movement from model divisions	Quarter 2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
		3	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0
		4	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0
		5	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0
		6	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Movement from model divisions	Quarter 3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	1	0	0	0	0	1	0	0	0	0	0	0.35	0.65	0	0	0
		3	0	0.2	0.8	0	0	0	0.2	0.8	0	0	0	0	0	0.95	0.05	0	0
		4	0	0	0.1	0.9	0	0	0	0.1	0.9	0	0	0	0	0.15	0.8	0.05	0
		5	0	0	0	0.1	0.9	0	0	0	0.1	0.9	0	0	0	0	0	0.95	0.05
		6	0	0	0	0	0.1	0	0	0	0	0.1	0.9	0	0	0	0	0.05	0.95
Movement from model divisions	Quarter 4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
		3	0	0	0.95	0.05	0	0	0	0.95	0.05	0	0	0	0.2	0.8	0	0	0
		4	0	0	0.05	0.9	0.05	0	0	0.05	0.9	0.05	0	0	0	0	0.8	0.2	0
		5	0	0	0	0.05	0.95	0	0	0	0.05	0.95	0	0	0	0	0	0.3	0.1
		6	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.2	0.8

Table B1.9.B1d. Migration matrices for good recruitment year classes for stock 1 in H_{2Stock} . To ease comparison, the shaded cells are those changed from $H_{0..}$

		Movement into model divisions																	
		Age 0						Age 1						Age 2+					
		1	2	3	4	5	6	1	2	3	4	5	6	1	2	3	4	5	6
Movement from model divisions	Quarter 1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		2	0	0.95	0	0	0	0	0.05	0	0	0	0	0	0	0.95	0	0	0
		3	0	0.05	0.9	0.05	0	0	0.05	0.9	0.05	0	0	0	0.7	0.3	0	0	0
		4	0	0	0.05	0.9	0.05	0	0	0.05	0.9	0.05	0	0	0	0	1	0	0
		5	0	0	0	0.05	0.9	0	0	0	0.05	0.9	0.05	0	0	0	0	1	0
		6	0	0	0	0	0.05	0	0	0	0.05	0.95	0	0	0	0	0	0	1
Movement from model divisions	Quarter 2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
		3	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0
		4	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0
		5	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0
		6	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1
Movement from model divisions	Quarter 3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	1	0	0	0	0	1	0	0	0	0	0	0.35	0.65	0	0	0
		3	0	0.2	0.8	0	0	0	0.2	0.8	0	0	0	0	0	0.95	0.05	0	0
		4	0	0	0.1	0.9	0	0	0	0.1	0.9	0	0	0	0	0.25	0.7	0.05	0
		5	0	0	0	0.1	0.9	0	0	0	0.1	0.9	0	0	0	0	0.1	0.85	0.05
		6	0	0	0	0	0.1	0	0	0	0.1	0.9	0	0	0	0	0	0.1	0.9
Movement from model divisions	Quarter 4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		2	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0
		3	0	0	0.95	0.05	0	0	0	1	0	0	0	0	0.2	0.8	0	0	0
		4	0	0	0.05	0.9	0.05	0	0	0	1	0	0	0	0	0	0.8	0.2	0
		5	0	0	0	0.05	0.95	0	0	0	0	1	0	0	0	0	0	0.1	0.6
		6	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0.2	0.8

Table B1.9.B3a. Proportion mature at age for all model divisions (SARDYN database; SARDYN, 2005).

Year	Age						Year	Age					
	1	2	3	4	5	6+		1	2	3	4	5	6+
Equilib	0.650	0.950	1.000	1.000	1.000	1.000	1991	0.740	0.910	0.960	0.970	1.000	1.000
1978	0.650	0.950	1.000	1.000	1.000	1.000	1992	0.790	0.910	0.950	0.980	1.000	1.000
1979	0.650	0.950	1.000	1.000	1.000	1.000	1993	0.470	0.930	0.940	0.970	0.990	1.000
1980	0.650	0.950	1.000	1.000	1.000	1.000	1994	0.800	0.890	0.960	0.960	0.970	1.000
1981	0.650	0.950	1.000	1.000	1.000	1.000	1995	0.730	0.980	0.970	0.990	1.000	1.000
1982	0.650	0.950	1.000	1.000	1.000	1.000	1996	0.830	0.890	0.920	0.960	1.000	1.000
1983	0.650	0.950	1.000	1.000	1.000	1.000	1997	0.727	0.918	0.950	0.972	0.993	1.000
1984	0.650	0.950	1.000	1.000	1.000	1.000	1998	0.720	0.924	0.956	0.987	0.995	1.000
1985	0.650	0.950	1.000	1.000	1.000	1.000	1999	0.619	0.911	0.987	0.995	1.000	1.000
1986	0.650	0.950	1.000	1.000	1.000	1.000	2000	0.257	0.910	0.947	0.950	1.000	1.000
1987	0.650	0.950	1.000	1.000	1.000	1.000	2001	0.391	0.902	0.962	0.989	1.000	1.000
1988	0.650	0.950	1.000	1.000	1.000	1.000	2002	0.496	0.936	0.964	0.985	0.987	1.000
1989	0.230	0.830	0.910	0.920	0.940	0.977	2003	0.500	0.964	0.988	0.997	0.999	1.000
1990	0.600	0.810	0.880	0.890	0.940	0.987							

Table B1.9.B3b. Proportion mature at age for all model divisions for Robustness Test R_{data} (SARDYN database; SARDYN, 2005).

Year	Model Divisions 1-3 (Spanish waters)						Model Divisions 4-6 (Portuguese waters)										
	1	2	3	4	5	6	7+	1	2	3	4	5	6	7	8	9	10+
1991	0.767	0.988	1.000	1.000	1.000	1.000	1.000	0.725	0.925	0.947	0.938	1.000	1.000	1.000	1.000	1.000	1.000
1992	0.993	0.907	1.000	1.000	1.000	1.000	1.000	0.829	0.902	0.940	0.975	1.000	1.000	1.000	1.000	1.000	1.000
1993	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.301	0.918	0.935	0.966	0.991	1.000	1.000	1.000	1.000	1.000
1994	0.800	1.000	1.000	1.000	1.000	1.000	1.000	0.850	0.870	0.950	0.940	0.950	1.000	1.000	1.000	1.000	1.000
1995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.380	0.970	0.980	0.980	1.000	1.000	1.000	1.000	1.000	1.000
1996	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.812	0.945	0.962	0.970	1.000	1.000	1.000	1.000	1.000	1.000
1997	0.944	1.000	1.000	1.000	1.000	1.000	1.000	0.424	0.894	0.944	0.986	0.988	1.000	1.000	1.000	1.000	1.000
1998	0.721	1.000	1.000	1.000	1.000	1.000	1.000	0.500	0.715	0.924	0.956	0.987	0.995	0.989	1.000	1.000	1.000
1999	0.802	1.000	1.000	1.000	1.000	1.000	1.000	0.595	0.903	0.985	0.953	0.955	0.983	1.000	1.000	1.000	1.000
2000	1.000	1.000	1.000	1.000	0.989	1.000	1.000	0.240	0.890	0.920	0.930	1.000	1.000	1.000	1.000	1.000	1.000
2001	0.538	0.983	1.000	1.000	1.000	1.000	1.000	0.390	0.860	0.930	0.940	0.950	0.960	0.960	0.980	0.980	1.000
2002	1.000	1.000	0.997	1.000	1.000	1.000	1.000	0.487	0.929	0.951	0.975	0.976	0.977	0.975	0.972	0.973	1.000
2003	0.879	1.000	0.996	1.000	1.000	1.000	1.000	0.497	0.956	0.982	0.994	0.998	0.998	1.000	1.000	1.000	1.000

Table B1.9.B4a. Stock weights at age (kgs), for all model divisions (SARDYN database; SARDYN, 2005).

Year	Age						Year	Age					
	1	2	3	4	5	6+		1	2	3	4	5	6+
Equilib	0.015	0.038	0.050	0.064	0.067	0.100	1991	0.019	0.042	0.050	0.064	0.071	0.100
1978	0.015	0.038	0.050	0.064	0.067	0.100	1992	0.027	0.036	0.050	0.062	0.069	0.100
1979	0.015	0.038	0.050	0.064	0.067	0.100	1993	0.022	0.045	0.057	0.064	0.073	0.100
1980	0.015	0.038	0.050	0.064	0.067	0.100	1994	0.031	0.040	0.049	0.060	0.067	0.100
1981	0.015	0.038	0.050	0.064	0.067	0.100	1995	0.029	0.050	0.062	0.072	0.079	0.100
1982	0.015	0.038	0.050	0.064	0.067	0.100	1996	0.036	0.047	0.061	0.069	0.075	0.100
1983	0.015	0.038	0.050	0.064	0.067	0.100	1997	0.025	0.050	0.058	0.068	0.074	0.100
1984	0.015	0.038	0.050	0.064	0.067	0.100	1998	0.023	0.041	0.053	0.061	0.067	0.100
1985	0.015	0.038	0.050	0.064	0.067	0.100	1999	0.020	0.039	0.054	0.062	0.068	0.100
1986	0.015	0.038	0.050	0.064	0.067	0.100	2000	0.017	0.043	0.059	0.064	0.067	0.100
1987	0.015	0.038	0.050	0.064	0.067	0.100	2001	0.017	0.042	0.058	0.075	0.080	0.100
1988	0.015	0.038	0.050	0.064	0.067	0.100	2002	0.020	0.044	0.060	0.071	0.078	0.100
1989	0.015	0.038	0.050	0.064	0.067	0.100	2003	0.027	0.054	0.064	0.075	0.082	0.100
1990	0.015	0.038	0.050	0.064	0.067	0.100							

Table B1.9.B4b. Stock weights at age (kgs), for all model divisions for Robustness Test R_{data} (SARDYN database; SARDYN, 2005).

Year	Model Divisions 1-3 (Spanish waters)						Model Divisions 4-6 (Portuguese waters)							
	1	2	3	4	5	6	7+	1	2	3	4	5	6	7+
1991	0.039	0.060	0.075	0.081	0.092	0.100	0.100	0.019	0.039	0.044	0.052	0.062	0.067	0.100
1992	0.042	0.070	0.079	0.086	0.091	0.090	0.100	0.028	0.043	0.056	0.067	0.072	0.076	0.100
1993	0.042	0.064	0.071	0.078	0.089	0.094	0.100	0.022	0.046	0.058	0.064	0.072	0.077	0.100
1994	0.031	0.040	0.049	0.060	0.067	0.100	0.100	0.031	0.038	0.047	0.059	0.066	0.069	0.100
1995	0.029	0.050	0.062	0.072	0.079	0.100	0.100	0.030	0.052	0.057	0.068	0.078	0.081	0.100
1996	0.046	0.059	0.068	0.072	0.077	0.081	0.100	0.036	0.046	0.058	0.063	0.067	0.069	0.100
1997	0.032	0.061	0.074	0.079	0.086	0.089	0.100	0.025	0.050	0.058	0.068	0.073	0.082	0.100
1998	0.033	0.056	0.067	0.079	0.087	0.088	0.100	0.022	0.035	0.049	0.056	0.064	0.070	0.100
1999	0.025	0.062	0.070	0.078	0.087	0.084	0.100	0.019	0.038	0.052	0.059	0.067	0.072	0.100
2000	0.044	0.062	0.074	0.081	0.085	0.090	0.100	0.017	0.039	0.051	0.057	0.062	0.066	0.100
2001	0.030	0.053	0.089	0.096	0.100	0.104	0.100	0.017	0.037	0.048	0.057	0.067	0.070	0.100
2002	0.033	0.052	0.070	0.079	0.086	0.090	0.100	0.020	0.043	0.057	0.065	0.071	0.074	0.100
2003	0.045	0.060	0.066	0.077	0.087	0.090	0.100	0.027	0.053	0.064	0.073	0.079	0.081	0.100

Table B1.9.B2. Percentage split of recruits by division at the beginning of the third quarter.

Model division	Normal / weak recruitment	Good recruitment
1	0.04	0.04
2	0.04	0.04
3	0.10	0.10
4	0.57	0.65
5	0.08	0.08
6	0.17	0.09

Table B1.9.B5. Average percentage split of catch between quarters for each model division for ages 0, 1, 2 and 3+.

Division	1	2	3	4	5	6
Age 0						
Quarter 3	0.330	0.438	0.451	0.380	0.604	0.660
Quarter 4	0.670	0.562	0.549	0.620	0.396	0.340
Age 1						
Quarter 1	0.228	0.104	0.075	0.205	0.079	0.399
Quarter 2	0.224	0.240	0.297	0.257	0.411	0.216
Quarter 3	0.169	0.457	0.291	0.194	0.378	0.202
Quarter 4	0.379	0.199	0.337	0.344	0.133	0.182
Age 2						
Quarter 1	0.263	0.067	0.052	0.201	0.102	0.167
Quarter 2	0.200	0.313	0.222	0.180	0.427	0.325
Quarter 3	0.164	0.403	0.440	0.372	0.343	0.323
Quarter 4	0.373	0.216	0.285	0.248	0.127	0.186
Age 3+						
Quarter 1	0.416	0.126	0.076	0.310	0.130	0.197
Quarter 2	0.176	0.352	0.215	0.249	0.390	0.335
Quarter 3	0.144	0.308	0.426	0.250	0.297	0.276
Quarter 4	0.264	0.214	0.282	0.191	0.182	0.191

Table B1.9.B6. Daily Egg Production Method Estimates of Spawning Biomass (in thousand tonnes, $I_{Sp,SSB}(y)$), with CVs ($\sigma_{Sp,SSB}(y)$) in brackets, from Spanish First Quarter Surveys (ICES 2003, 2004a). The proportion of estimated SSB by region, $propI_{Sp,SSB}(y, d)$, is also given.

Year	Proportion of SSB			SSB
	Model Divisions 2&3		Model Division 1	Total Region
	Galicia (IXa(north) + VIIIc(west))	West Cantabria (VIIIc(east-west))	East Cantabria (VIIIc(east-east))	
1988	0.745	0.186	0.069	180.2 (50)
1990	0.312	0.593	0.095	77.7 (45)
1997				20.7 (84)
1999				13.4 (77)
2002	0	0.815	0.185	50.7 (33)

Table B1.9.B7. Daily Egg Production Method Estimates of Spawning Biomass (in thousand tonnes, $I_{Por,SSB}(y)$), with CVs ($\sigma_{Por,SSB}(y)$) in brackets, from Portuguese First Quarter Surveys (ICES 2003, 2004a). The proportion of estimated SSB by region, $propI_{Por,SSB}(y, d)$, is also given.

Year	Proportion of SSB		SSB
	Model Divisions 4&5	Model Division 6	Total
	West (IXa(central-north) + IXa(central-south))	South (IXa(south-algarve)+IXa(south-cadiz))	
1999	0.220	0.780	255.6 (38)
2002	0.695	0.305	391.9 (31)

Table B1.9.B8. Proportion of Numbers-at-age, $propN_{sp}(y,2,a,d)$, from Spanish first quarter acoustic surveys (SARDYN database; SARDYN, 2005). When proportions for two plus-groups are given in the same year, the 6+ proportion is used in R_{6+} .

Year	Age	Proportion of Abundance			Year	Age	Proportion of Abundance		
		VIIIc(east) ¹	VIIIc(west)	IXa(north)			VIIIc(east)	VIIIc(west)	IXa(north)
1986	1	0.029	0.008	0.049	1999	1	0.239	0.485	0.424
	2	0.005	0.009	0.057		2	0.219	0.210	0.248
	3	0.414	0.480	0.753		3	0.200	0.171	0.102
	4	0.097	0.094	0.036		4	0.186	0.094	0.179
	5	0.188	0.173	0.048		5	0.046	0.030	0.003
	6+	0.266	0.236	0.057		6	0.055	0.005	0.000
1987	1	0.010	0.144	0.413	2000	7	0.047	0.004	0.044
	2	0.032	0.045	0.177		8	0.000	0.000	0.000
	3	0.003	0.004	0.030		9	0.002	0.000	0.000
	4	0.484	0.476	0.257		10	0.006	0.000	0.000
	5	0.154	0.102	0.048		11	0.000	0.000	0.000
	6+	0.316	0.230	0.074		12+	0.000	0.000	0.000
1988	1	0.065	0.099	0.317	2001	6+	0.110	0.009	0.044
	2	0.020	0.029	0.074		1	0.078	0.000	0.507
	3	0.004	0.043	0.116		2	0.284	0.048	0.376
	4	0.008	0.040	0.056		3	0.301	0.432	0.091
	5	0.421	0.393	0.259		4	0.164	0.252	0.019
	6+	0.481	0.396	0.179		5	0.136	0.180	0.002
1990	1	0.048	0.001	0.336	1991	6	0.024	0.062	0.003
	2	0.047	0.027	0.146		7	0.006	0.023	0.002
	3	0.230	0.224	0.362		8	0.007	0.003	0.000
	4	0.047	0.048	0.047		9	0.001	0.000	0.000
	5	0.078	0.089	0.036		10	0.000	0.000	0.000
	6+	0.549	0.611	0.073		11	0.000	0.000	0.000
1991	1	0.007	0.021	0.105	1992	12+	0.000	0.000	0.000
	2	0.104	0.169	0.472		6+	0.038	0.089	0.005
	3	0.112	0.135	0.121		1	0.024	0.707	0.970
	4	0.289	0.327	0.186		2	0.222	0.225	0.030
	5	0.046	0.046	0.024		3	0.284	0.026	0.000
	6	0.059	0.043	0.014		4	0.214	0.024	0.000
1992	7+	0.384	0.259	0.078	2001	5	0.152	0.012	0.000
	6+	0.442	0.302	0.092		6	0.052	0.003	0.000
	1	0.090	0.032	0.675		7	0.026	0.001	0.000
	2	0.153	0.078	0.118		8	0.017	0.000	0.000
	3	0.203	0.116	0.079		9	0.008	0.000	0.000
	4	0.066	0.068	0.022		10	0.002	0.000	0.000
1992	5	0.235	0.331	0.063	11	0.000	0.000	0.000	
	6	0.051	0.071	0.014	12+	0.000	0.000	0.000	
	7	0.047	0.046	0.010	6+	0.104	0.005	0.000	
	8+	0.156	0.258	0.019					
	6+	0.253	0.375	0.043					

¹ Data for ICES divisions VIIIc(east-east) and VIIIc(east-west) are available separately in the SARDYN database (SARDYN, 2005), but are combined here to correspond with the chosen model divisions.

Table B1.9.B8 (cont.).

Year	Age	Proportion of Abundance			Year	Age	Proportion of Abundance		
		VIIIc(east)	VIIIc(west)	IXa(north)			VIIIc(east)	VIIIc(west)	IXa(north)
1993	1	0.005	0.087	0.572	2002	1	0.089	0.056	0.155
	2	0.141	0.518	0.311		2	0.158	0.273	0.697
	3	0.057	0.136	0.055		3	0.195	0.206	0.094
	4	0.064	0.067	0.027		4	0.310	0.308	0.055
	5	0.081	0.048	0.012		5	0.162	0.120	0.000
	6	0.239	0.087	0.017		6	0.068	0.020	0.000
	7	0.027	0.008	0.002		7	0.013	0.013	0.000
	8	0.061	0.009	0.001		8	0.004	0.003	0.000
	9+	0.325	0.042	0.003		9	0.000	0.001	0.000
	6+	0.652	0.145	0.023		10	0.000	0.000	0.000
	1996	1	0.010	0.004		0.025	2003	11	0.000
2		0.046	0.054	0.140	12+	0.000		0.000	0.000
3		0.115	0.106	0.138	6+	0.085		0.037	0.000
4		0.467	0.481	0.479	1	0.017		0.012	0.018
5		0.322	0.317	0.198	2	0.334		0.187	0.210
6		0.024	0.021	0.008	3	0.285		0.595	0.646
7		0.010	0.013	0.010	4	0.193		0.148	0.104
8		0.005	0.004	0.001	5	0.103		0.032	0.017
9		0.000	0.000	0.000	6	0.041		0.023	0.005
10		0.000	0.000	0.000	7	0.019		0.004	0.000
11		0.000	0.000	0.000	8	0.003		0.000	0.000
12+	0.000	0.000	0.000	9	0.003	0.000	0.000		
6+	0.039	0.038	0.019	10	0.001	0.000	0.000		
1997	1	0.037	0.017	0.316	2003	11	0.000	0.000	0.000
	2	0.472	0.067	0.114		12+	0.000	0.000	0.000
	3	0.184	0.200	0.158		6+	0.067	0.027	0.005
	4	0.164	0.350	0.149					
	5	0.080	0.167	0.123					
	6	0.042	0.117	0.079					
	7	0.011	0.067	0.026					
	8	0.009	0.017	0.009					
	9	0.001	0.000	0.026					
	10	0.000	0.000	0.000					
	11	0.000	0.000	0.000					
12+	0.000	0.000	0.000						
6+	0.063	0.200	0.140						
1998	1	0.591	0.674	0.801					
	2	0.145	0.150	0.108					
	3	0.140	0.100	0.030					
	4	0.057	0.039	0.016					
	5	0.031	0.010	0.018					
	6	0.022	0.020	0.016					
	7	0.009	0.005	0.011					
	8	0.002	0.001	0.000					
	9	0.002	0.001	0.000					
	10	0.000	0.000	0.000					
	11	0.000	0.000	0.000					
12+	0.000	0.000	0.000						
6+	0.036	0.027	0.027						

Table B1.9.B9. Proportion of Numbers-at-age, $propN_{Por}(y,2,a,d)$, from Portuguese first quarter acoustic surveys (SARDYN database; SARDYN, 2005). When proportions for two plus-groups are given in the same year, the 6+ proportion is used in R_{6+} .

Year	Age	Proportion of Abundance			Year	Age	Proportion of Abundance		
		IXa(central-north)	IXa(central-south)	IXa(south) ²			IXa(central-north)	IXa(central-south)	IXa(south)
1986	1	0.327	0.058		1999	1	0.522	0.343	0.489
	2	0.440	0.508			2	0.190	0.096	0.256
	3	0.145	0.289			3	0.183	0.111	0.087
	4	0.057	0.034			4	0.026	0.195	0.089
	5	0.026	0.111			5	0.034	0.192	0.045
	6+	0.006	0.000			6	0.036	0.055	0.026
1988	1	0.723	0.075		6+	0.045	0.062	0.034	
	2	0.076	0.392		7+	0.009	0.007	0.008	
	3	0.053	0.199		1	0.760	0.594	0.396	
	4	0.070	0.179		2	0.082	0.188	0.248	
	5	0.054	0.071		3	0.085	0.105	0.114	
	6+	0.024	0.084		4	0.043	0.076	0.072	
1996	1	0.579	0.238	0.067	2000	5	0.015	0.027	0.074
	2	0.385	0.083	0.257		6	0.010	0.007	0.049
	3	0.028	0.147	0.350		6+	0.015	0.010	0.097
	4	0.009	0.436	0.302		7+	0.005	0.003	0.048
	5	0.000	0.094	0.023		1	0.938	0.963	0.749
	6	0.000	0.002	0.001		2	0.034	0.018	0.060
	6+	0.000	0.002	0.001		3	0.014	0.007	0.065
	7+	0.000	0.000	0.000		4	0.010	0.005	0.040
1997	1	0.657	0.326	0.366	2001	5	0.003	0.004	0.048
	2	0.058	0.303	0.336		6	0.000	0.002	0.027
	3	0.171	0.072	0.086		6+	0.000	0.003	0.037
	4	0.085	0.128	0.069		7+	0.000	0.000	0.011
	5	0.029	0.146	0.124		1	0.500	0.812	0.640
	6	0.000	0.026	0.019		2	0.487	0.076	0.228
	6+	0.000	0.026	0.019		3	0.004	0.014	0.069
	7+	0.000	0.000	0.000		4	0.005	0.034	0.035
1998	1	0.125	0.222	0.097	2002	5	0.002	0.025	0.015
	2	0.518	0.246	0.221		6	0.002	0.020	0.010
	3	0.134	0.171	0.287		6+	0.003	0.038	0.013
	4	0.086	0.132	0.172		7+	0.001	0.018	0.003
	5	0.066	0.109	0.149		1	0.397	0.632	0.169
	6	0.065	0.110	0.058		2	0.230	0.208	0.515
	6+	0.071	0.120	0.075		3	0.277	0.116	0.182
	7+	0.007	0.011	0.017		4	0.049	0.024	0.061
1999					2003	5	0.037	0.011	0.039
						6	0.010	0.007	0.027
						6+	0.010	0.009	0.034
						7+	0.000	0.002	0.007

² Acoustic abundance indices are available separately for IXa(south-algarve) and IXa(south-cadiz) from 1996 to 2003 in the SARDYN database (SARDYN 2005), but were combined here to correspond to model division 6. In addition, although abundance indices are available for IXa(south-algarve) in 1986 and 1988, since IXa(south-cadiz) was not surveyed in these years, these data were not used.

Table B1.9.B10. Proportion of Numbers-at-Age, $propN_{Por}(y,4,a,d)$, from Portuguese fourth quarter acoustic surveys (SARDYN database; SARDYN, 2005). When proportions for two plus-groups are given in the same year, the 6+ proportion is used in R_{6+} .

Year	Age	Proportion of Abundance			Year	Age	Proportion of Abundance		
		IXa(central-north)	IXa(central-south)	IXa(south) ³			IXa(central-north)	IXa(central-south)	IXa(south)
1984	0	0.007	0.717		1997	0	0.315	0.447	
	1	0.779	0.164			1	0.491	0.144	
	2	0.110	0.060			2	0.152	0.058	
	3	0.066	0.055			3	0.021	0.088	
	4	0.038	0.005			4	0.006	0.095	
	5	0.000	0.000			5	0.013	0.112	
	6+	0.000	0.000			6	0.002	0.047	
1985	0	0.202	0.117		6+	0.004	0.057		
	1	0.034	0.358		7+	0.001	0.010		
	2	0.588	0.301		0	0.777	0.530	0.617	
	3	0.078	0.130		1	0.162	0.076	0.127	
	4	0.057	0.092		2	0.043	0.183	0.050	
	5	0.027	0.002		3	0.012	0.126	0.078	
	6+	0.013	0.001		4	0.002	0.038	0.053	
1986	0	0.358	0.510		5	0.003	0.034	0.055	
	1	0.290	0.124		6	0.001	0.011	0.015	
	2	0.228	0.242		6+	0.001	0.013	0.020	
	3	0.089	0.074		7+	0.000	0.002	0.005	
	4	0.026	0.027		0	0.705	0.791	0.057	
	5	0.005	0.018		1	0.190	0.022	0.222	
	6+	0.003	0.006		2	0.091	0.048	0.168	
1987	0	0.444	0.379		3	0.014	0.054	0.164	
	1	0.155	0.386		4	0.001	0.052	0.198	
	2	0.175	0.111		5	0.000	0.023	0.131	
	3	0.071	0.081		6	0.000	0.011	0.046	
	4	0.123	0.022		6+	0.000	0.011	0.060	
	5	0.027	0.013		7+	0.000	0.000	0.015	
	6+	0.004	0.008		0	0.944	0.927	0.735	
1992	0	0.567	0.275	0.405	1	0.050	0.030	0.045	
	1	0.305	0.496	0.415	2	0.004	0.028	0.100	
	2	0.039	0.121	0.100	3	0.001	0.008	0.030	
	3	0.049	0.079	0.063	4	0.001	0.005	0.042	
	4	0.029	0.025	0.016	5	0.001	0.002	0.028	
	5	0.009	0.004	0.002	6	0.000	0.001	0.013	
	6	0.001	0.000	0.000	6+	0.000	0.002	0.021	
6+	0.002	0.000	0.000	7+	0.000	0.000	0.008		
2001	0	0.362	0.770	0.692	0	0.362	0.770	0.692	
	1	0.579	0.094	0.181	1	0.579	0.094	0.181	
	2	0.043	0.045	0.051	2	0.043	0.045	0.051	
	3	0.011	0.062	0.036	3	0.011	0.062	0.036	
	4	0.002	0.011	0.025	4	0.002	0.011	0.025	
	5	0.002	0.012	0.011	5	0.002	0.012	0.011	
	6	0.000	0.004	0.003	6	0.000	0.004	0.003	
6+	0.000	0.005	0.004	6+	0.000	0.005	0.004		
7+	0.001	0.001	0.001	7+	0.000	0.001	0.001		

³ Acoustic abundance indices are available for IXa(south-algarve) from 1984 to 1987, in 1997 and in 2002 in the SARDYN database (SARDYN, 2005), but were not used here since IXa(south-cadiz) was not surveyed in these years.

Table B1.9.B11. Observed Biomass ($I_{Sp,Ac}(y, d)$, in tonnes) from Spanish first quarter acoustic surveys (SARDYN database; SARDYN, 2005).

Year	VIIIc(east)	VIIIc(west)	IXa(north)
1986	106070.8	49553.0	5540.5
1987	121730.6	225094.6	16596.2
1988	71868.7	92521.1	9873.0
1990	43175.3	45456.1	7868.5
1991	104985.6	3889.3	9017.6
1992	25507.5	9393.5	10410.2
1993	156029.4	9098.2	17952.9
1996	38478.0	1117.5	13577.8
1997	36222.0	4805.9	7344.5
1998	25194.2	655.0	9455.6
1999	33498.7	5435.2	3842.1
2000	62974.5	31427.0	1943.7
2001	54675.5	18205.8	18527.0
2002	137251.3	7836.7	29269.9
2003	132353.6	32115.9	20424.8

Table B1.9.B12. Observed Biomass ($I_{Por1,Ac}(y, d)$, in tonnes) from Portuguese first quarter acoustic surveys (SARDYN database; SARDYN, 2005).

Year	IXa(central-north)	IXa(central-south)	IXa(south-algarve) & IXa(south-cadiz)
1986	113027	124986	
1988	290391	138153	
1996	27518	117894	259859
1997	153297	151837	202897
1998	190667	130736	162120
1999	157557	34562	230104
2000	97704	90328	181730
2001	343981	40121	111901
2002	232869	96185	286507
2003	153480	145376	133267

Table B1.9.B13. Observed Biomass ($I_{Por4,Ac}(y, d)$, in tonnes) from Portuguese fourth quarter acoustic surveys (SARDYN database; SARDYN, 2005).

Year	IXa(central-north)	IXa(central-south)	IXa(south-algarve) & IXa(south-cadiz)
1984	260600	53580	
1985	216918	166996	
1986	140907	77198	
1987	152939	123424	
1992	334709	179008	188874
1997	87018	135379	
1998	150806	136889	333186
1999	89323	32360	150619
2000	555026	42736	112868
2001	280944	146722	347232
2003	94804	89892	

Table B1.9.B14. Summary of source of information for parameter values and prior distributions.

Parameter Value / Prior Distribution	Observed Data	Expert Advice	Initial Testing of the Model	Other models	Derived from Calculations Based on Observed Data	Comments
Movement matrices		✓	✓			
Distribution of recruits at the beginning of the third quarter		✓				
Natural mortality				✓		
Maturity ogives	✓					
Stock weights at age	✓					
Observed catch biomass					✓	The split of catch biomass between model divisions in early years was based on the observed average split between 1991 and 2003. The catch biomass was assumed to be split equally between model divisions 1 and 2 for 1978 to 1990.
Equilibrium yield					✓	
Split of equilibrium yield by quarter					✓	
Equilibrium catch weight-at-age					✓	
Split of equilibrium SSB between Portuguese and Spanish waters			✓			
Lognormal equilibrium numbers-at-age process error			✓			
Number of observations in lognormal likelihoods	✓					
CV's for observed acoustic estimates of biomass		✓				
Weighting for fitting predicted annual and quarterly catches to observed values			✓			
Effective sample size for the total number of fish sampled each survey or year (commercial catch)			✓			
Geometric mean of annual recruitment						
Recruitment process error				✓	✓	Uninformative prior distribution
Selectivity parameters			✓	✓		Relatively uninformative prior distributions
Multiplicative bias factors for the acoustic survey estimates of biomass		✓				