Stock Annex: Southern Horse Mackerel (hom 27.9.a)

Stock	Horse Mackerel in ICES Division 9a (Southern horse mackerel)
Working Group	Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA)
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A. General

A.1. Stock definition

Stock units

Prior to 2004 horse mackerel stocks in the north east Atlantic were separated into three stocks according to the identification of spawning areas based on egg distribution, resulting in: a "Western stock" (northeast continental shelf of Europe, from France to Norway); a "North Sea stock" (North Sea area) and a "Southern stock" (Atlantic waters of the Iberian Peninsula). However, there is no recognizable boundary in the distribution of eggs between the putative western and southern horse mackerel stocks (ICES, 1999).

A study of stock structure of horse mackerel in the North Atlantic and Mediterranean Sea from a holistic point of view was carried out in a EU funded HOMSIR project (QLK5-CT1999-01438) in 2000-03. This multidisciplinary project included various genetic approaches, the use of parasites as biological tags, body morphometrics, otolith shape analysis and the comparative study of life history traits (growth, reproduction and distribution). As result of this project the former boundary of the "Southern" and "Western" stocks was moved from Cape Breton Canyon (southeast of Bay of Biscay) to the northwest of Iberian Peninsula (Galician coasts: Cape Finisterre at 43º N latitude) in 2004. Therefore, the current distribution area of the Southern stock is the ICES Division 9.a (The Iberian coast from the Strait of Gibraltar to Cape Finisterre in Galician waters).

Moreover, horse mackerel length-at-age data analysis (2004–2016), showed similar growth patterns along ICES Division 9.a which also supports the current stock boundaries (ICES, 2017a). The analysis of spatial distribution by size and age from the Portuguese and Spanish IBTS survey time-series and from the fishery show that all ages are found within Division 9.a indicating that migration outside the area, if it occurs, is negligible thus also supporting the current stock boundaries (Azevedo and Silva, 2016; Mendes *et al*., 2017).

A.2. Fishery

The southern horse mackerel in Division 9.a is exploited by six fleets, defined by the gear type (bottom trawl, purse-seine and artisanal) and country (Portugal and Spain). The Portuguese bottom-trawl demersal fish fleet, the Portuguese purse-seine fleet and the Spanish purse-seine fleet show a similar exploitation pattern with greater presence of juveniles and low abundance of adults. The Portuguese artisanal fleet is mainly composed by small size vessels licensed to operate with several gears (gill and trammel-nets, purse-seine and lines). Catches of horse mackerel from the Portuguese artisanal fleet are mainly from trips operating with nets showing the presence of larger/adult fish while the catches from trips operating with purse-seine show the presence of small/juveniles. The Spanish bottom trawl fleet catches mainly adults. Horse mackerel is the main target species in the Portuguese bottom trawl demersal fish fleet, while in Spain main catches are from the Purse-seine fleet. Spanish and Portuguese artisanal fishery are considerably smaller. In recent years, and due to the lower catch opportunities for the Iberian sardine stock (sar8.c–9.a), the relative importance in the annual catches of the purse-seine fleets has increased, both in Portugal and in Spain.

The catches of horse mackerel in Division 9.a comprise the following four subdivisions: 9.aNorth (9.a.n: Spain - Galicia), 9.aCentral-North (9.a.c.n: Portugal – Caminha to Figueira da Foz), 9.aCentral-South (9.a.c.s: Portugal – Nazaré to Sines) and 9.aSouth (9.a.s: Portugal – Sagres to V. Real Santo António) and are allocated to the Southern horse mackerel stock (hom 27.9.a). In the years before 2004 the catches from Subdivision 8.c, were also considered to belong to the southern horse mackerel stock. Spanish catches from the Gulf of Cádiz (Subdivision 9.a.s) are available since 2002 but they are scarce, representing less than the 5% of the total catch and, therefore, are not included in the assessment to avoid a possible bias in the assessment results. Horse mackerel catches from Division 9.a are used for human consumption.

Catches statistics of horse mackerel in Division 9.a are therefore allocated to the Southern Horse mackerel Stock. Before 2004, the catches from Division 8.c were considered in the southern horse mackerel stock. These catches were removed from previous total catches to obtain the current historical series of stock catches. However, the definition of the Subdivisions was set quite recently and some of the previous catch statistics came from an area that comprised more than one Subdivision. This is the case of the Galician coasts where the Subdivision 8.c West and Subdivision 9.a North are located. That is the reason why the time-series of catch statistics for southern stock is only from 1992 onwards.

Although Portuguese catches are available since 1927, in the case of Spanish catches the allocation of catches to Subdivisions 9.a North and Subdivision 8.c West before 1992, has not yet been possible. People who compiled that information are not working anymore and that historical information has not been recovered.

A.3. Ecosystem aspects

Influence of environmental drivers on the stock dynamic

The western and southern Atlantic coasts of the Iberian Peninsula are in a biogeographic transition zone, between temperate and subtropical waters and are part of a more general upwelling system that extend southward, the Canary Current Large Marine Ecosystem. These geographic and oceanographic characteristics where the northern or southern distribution limits of several stocks can be found, including horse mackerel, make this area more vulnerable to the effects of changing climatic conditions which will most likely affect the abundance, distribution and composition of fisheries catches (Brander *et al*., 2010; Vinagre *et al*., 2011; Gamito *et al*., 2013).

There is evidence in the literature that horse mackerel recruitment is influenced by environmental drivers. Santos *et al*. (2001) showed that upwelling events observed off Portugal during winter months had a negative impact on recruitment. This effect on recruitment could be due to an increase in conditions favourable to the offshore transport of larvae and consequently an increase in their mortality. A negative relationship between SST, winter NAO and horse mackerel LPUE was also observed which might indicate a negative effect of winter upwelling and temperatures on recruitment of horse mackerel (Gamito *et al*., 2015; Teixeira *et al*., 2016). Exploratory analysis carried out under the INEXFISH project (Frid *et al*., 2009; West Iberian Sea Case study) showed that Portuguese historical landings of horse mackerel suffered great fluctuations throughout the 20th century, which is likely to have been caused by both human and environmental factors. Modeling analysis revealed that non-linear combinations of NAO and upwelling indices were able to explain the strength of past recruitments. NAO acted as a proxy for climate forcing with apparently more significance than other more reliable and biologically important factors as the local sea surface temperature or seasonal upwelling. General climate indices, like NAO, correlate to a number of potentially important factors such as temperature, salinity, wind and currents. It is then possible that this type of global index gives stronger relations than any of the factors separately, because the stock is simultaneously influenced by the combination of these different factors.

While statistical broad trends are evident, the mechanisms by which the environment affects stock productivity are poorly understood and should be further explored before taken into account in stock assessment.

Role of multispecies interactions

Horse mackerel is a schooling species and often close to the sea floor. Shelf attachment is a predominant distributional pattern for this stock. Therefore, horse mackerel is in relation with other fish and invertebrate species that are usually caught during the bottom-trawl surveys and share the same habitat. These species are mainly: snipefish, boarfish, blue whiting, European hake, sardine, blue jack mackerel, squid and pelagic crabs (Sousa *et al*., 2006). These species are found together in the stock area and most of them are commercially exploited, hence fishing mortality for horse mackerel could affect the yield of all other species and vice versa.

The nature of the interactions between these species as well as the variation in spatial overlap between these stocks is not fully explored but habitat migratory movements of the horse mackerel are mostly driven by feeding and spawning requirements (Murta *et al*., 2008).

Trophic interactions

Young horse mackerel, despite being a feeding resource consumed by several demersal, benthic and pelagic predators present in the distribution area like hake, monkfish, rays and dolphins, does not seem to be the favoured prey among the area predators (Cabral and Murta, 2002; Farias *et al*., 2006; Pierce and Santos, 2000, project MARPRO). Some recent unpublished work suggests an increase in the predation pressure from hake on small to medium-size horse mackerel probably reflective of the recovery of the hake stock coupled with the high abundance levels of horse mackerel.

Horse mackerel is mainly a zooplanktivorous species. Diet variations with fish length and water depth are correlated: small fish are closely associated with coastal areas where they feed primarily on copepods. Horse mackerel can prey on fish as they grow but show a comparatively lower consumption of fish, being euphausids (*Meganyctiphanes norvegica* and *Nyctiphanes couchi*) and decapods (*Pasiphaea sivado*) the most important preys (Cabral and Murta, 2002). They become ichthyophagic when they reach large sizes also being less targeted by predators. No signs of cannibalism are found for this species.

B. Data

B.1. Biological

Age sampling and reading protocol

The annual age sampling data and intensity of the commercial catches of southern horse mackerel stock (hom 27.9.a) is carried out from at-market sampling (EU Data Collection Framework, DCF) on a quarterly basis from Portugal and on a semester basis from Spain (ICES, 2017a). Sampling intensity provides a good and reliable coverage of the national length composition of the catches (annual age sampling around 1200 otoliths for Spanish catches and around 2500 for the Portuguese catches) and there are no differences in the stock growth-at-age either by zone (Spain-9.a.n; Portugal – 9.a.c.n, 9.a.c.s, 9.a.s) nor by time period (quarter/semester). The analysis carried out by Azevedo *et al*. (2016) indicates that a lower sampling intensity for age determination can provide similar precision ad accuracy levels.

Age reading protocol for horse mackerel (*Trachurus trachurus*) otoliths follows the guidelines from the most recent ICES age reading workshop (ICES, 2015; ICES, 2018). Precision in age reading of horse mackerel, evaluated during the workshop, indicated good and acceptable levels with an above-average percentage of agreement between readers. Recognizing that otoliths from older fish became thicker with time and thus presenting more difficulties for age determination, a plus group at age 11+ is set for the catch-at-age of the southern horse mackerel stock (hom 27.9.a).

Maturity-at-age

The maturity ogive corresponds to females. Horse mackerel is a multiple spawner (ICES, 2008) and hence maturity ogives should be based on histological analysis of the gonads which provide a correct and precise means to follow the development of both ovaries and testes (Costa, 2009). Therefore, microscopical analysis of the gonads collected during the triennial AEPM/DEPM surveys for horse mackerel carried out in 2004, 2007 and 2010 (1st quarter of the year) were used to estimate the proportion of mature females at length. The proportion of mature females-at-age in 2004, 2007 and 2010 was obtained by applying to the length composition the quarterly catch age–length key (ALK) of the same year. A logistic model was fitted to the proportion mature-at-age by pooling together the data from the three surveys (Murta *et al*., 2011). The predicted proportion-at-age is given in the text table below (7+: age 7 and older fish) and was adopted by ICES (2017a) for assessment.

Age	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7+**
Proportion mature	0.0	0.0	0.36	0.82	0.95	0.97	0.99	1.0

The maturity ogive could not be updated with the 2013 DEPM survey since, due to logistic problems, the adult samples were obtained by the commercial fleet and smaller/younger fish (likely corresponding to the immature/maturing individuals) could not be collected (Costa *et al*., 2017). The sampling strategy during future DEPM surveys will be adapted to allow accurate estimation of maturity ogives. The maturity ogive will be updated every three years if the proportion-at-age from data collected during the triannual DEPM surveys fell outside the confidence bounds (95%CI) of the current predicted values.

Natural mortality (M)

The fixed value of the natural mortality of 0.15 for all ages and adopted for all horse mackerel stocks since 1992 was considered an underestimation for this particular horse mackerel stock in the last benchmark. Moreover, the assumption that natural mortality is the same for all ages was highly unrealistic. It is generally accepted that natural mortality is very high during larval stages and decreases as the age of the fish increases, approaching a steady rate (Jennings *et al.*, 2001).

There are evidences that larger horse mackerel becomes much less targeted by predators and from observed diet composition it is obvious a progression in the mean trophic level from the younger planktophagic to the older ichthyophagic individuals (e.g. Cabral and Murta, 2002). From these considerations and following several approaches to derive general equations for M based on relationships between M and other aspects of the life history, such as growth rate and observed mean lifespan (e.g. Gislason *et al.*, 2010), the natural mortality adopted in horse mackerel assessment is dependent on age, being higher for younger ages. The adopted values are based in the estimates for other similar pelagic species, observed diet composition of fish predators in the area and taking into account the observed mean life span and growth rate in southern horse mackerel.

The adopted values are presented in the text table below (5+: age 5 and older fish).

Age	**0**	**1**	**2**	**3**	**4**	**5+**
M	0.9	0.6	0.4	0.3	0.2	0.15

B.2. Commercial catch

Discards

Discards are estimated by both countries (Portugal since 2014, Spain since 2003) from national at-sea sampling (DCF) on board commercial vessels operating in ICES Division 9a. Vessel selection for trip sampling is quasi-random from within a set of cooperative vessels. Annual discard estimates, although mainly for bottom trawl fleet (Jardim and Fernandes, 2013; Prista and Fernandes, 2014; ICES, 2016a) are made available to the assessment working group (WGHANSA) and are shown to be very low and not frequent and usually considered negligible.

Sampling for catch-at-length

At-market sampling is carried out within DCF to obtain the length composition of horse mackerel landed at auctions by Portuguese and Spanish vessels operating in each Subdivision of ICES Division 9a (Spain – 9.a.n; Portugal – 9.a.c.n, 9.a.c.s, 9.a.s). The sampling frame consists of a list of "ports x auction day" for each fleet segment and stratification (by Subdivision and quarter) is used to improve sampling coverage through the year and along the coast. Data is archived in national Data Basis and quality assurance procedures are performed routinely. The sampling scheme is believed to achieve a good coverage of the fishery (above 95% of the total catch). An alternative approach to estimate the catch length composition of horse mackerel based on modelled commercial size categories has been applied to Portuguese catches of horse mackerel (Azevedo *et al.*, 2016), presented and discussed during ICES (2017a). The new approach, requiring lower at-market sampling effort, can increase the precision of the estimates and is less subject to random errors than the current sampled trip raising approach. Although no revisions of the past length and catch-at-age composition are required, the size-category approach will be adopted to estimate the Portuguese annual catches in the future (ICES, 2017a).

Catch in numbers-at-age

Catch-at-age data have been obtained by applying a semester ALK (Portuguese data) and a semester ALK (Spanish data) to each of the catch length distribution estimated by fleet segment (bottom trawl, purse-seine and artisanal) and country from the samples of each Subdivision. The catch in numbers-at-age used in the assessment is the total international catch-at-age for the range of 0-11+, starting in 1992. Catch-at-age data is uploaded every year in ICES InterCatch (https://intercatch.ices.dk/).

Mean length-at-age and mean weight-at-age

Both mean length-at-age and mean weight-at-age values are calculated by applying the mean, weighted by the catch, over the mean weights or mean lengths-at-age obtained from the length-weight samples of each national biological sampling programme. Taking in consideration that the spawning season is very long, from September to June, that the whole length range of the species has commercial interest in the Iberian Peninsula and that discards are negligible, there is no special reason to consider that the mean weight in the catch is significantly different from the mean weight in the stock.

B.3. Surveys

The survey datasets currently available for the assessment of southern horse mackerel are those from the bottom-trawl surveys carried out in the 4th quarter (October) by Portugal (Pt-GFS-WIBTS-Q4) and Spain (Sp-GFS-WIBTS-Q4) in ICES Division 9a. Both surveys covers the bulk of the geographical distribution of the southern horse mackerel stock at the same time but do not cover the southernmost part of the stock distribution area, corresponding to the Spanish part of the Gulf of Cadiz. In that area another bottom-trawl survey is carried out (Sp-GFS-caut-WIBTS-Q4), usually in November, but is shorter in time (since 1998) and the raw data were unavailable in time for ICES (2017a) to investigate the effect of merging it with the data sets from the other areas.

The Spanish survey from Subdivision 9.a.n and the Portuguese survey are treated as a single survey, although they are carried out with different vessels and slightly different bottom-trawls gears. The catchability of R/V "Cornide de Saavedra" and R/V "Noruega" were compared for different fish species during project SESITS (EU Study Contract 96-029) and no significant differences were found for horse mackerel (ICES, 2011). Inter-calibrations between fishing gears of the Portuguese R/V´s ("Noruega" and "Capricórnio") and more recently between Spanish R/V´s ("Miguel Oliver" and "Cornide de Saavedra") also showed similar catchability and proportion of bentho-demersal species. Thus, the raw data of the two datasets are merged and treated as a single dataset (Mendes *et al.*, 2017).

From each haul the total number of individuals is estimated and survey abundance data is standardized to number per hour (including zeros). From each haul, a length frequency distribution is estimated for the total catch. These length distributions are then transformed into age composition, using the age–length keys obtained from otoliths reading of the fish sampled in each area (Portuguese and Spanish) during the 4th quarter of the year. The frequency of age class a in a given haul is then given by $n_a = \sum_l n_l \times p_{a|l}$, where n_l is the frequency of length class l in that haul and $p_{a|l}$ is the proportion of fish in age class a within length class l.

Different ways of obtaining an abundance index by age and year were explored in the past and during ICES (2017a). In summary, the results of the abundance and presence/absence analysis indicates that horse mackerel abundance shows a patchiness in the distribution across the entire time-series (1983–2015) with occasional high values that seem to be consistent across all the stock Subdivisions. The bulk of the horse mackerel surveyed individuals are from the younger ages (ages 0 to 3) and mostly distributed in the larger northwest and southwest areas, below 100 m with some abundance in the intermediate depth layer (100–200 m). Horse mackerel shows a strong stratification of younger individuals onshore that gradually go offshore as they grow and all age groups are found within the stock boundaries with no apparent inward migration from neighboring populations. Horse mackerel is considered to be a pelagic species, but its behaviour is closer to that of a demersal species than the rest of typical pelagic species. The IBTS data provides a good sampling of this species with valuable information on horse mackerel distribution, abundance, age/length distributions, also providing a good signal of cohort dynamics showed by the IC values (Mendes *et al.*, 2017).

An acceptable modelling/smoothing method was not achieved to deal with the noisy survey data, especially the strong variability of age 0. The survey abundance index for tuning the assessment is then based on a stratified mean abundance-at-age, $\bar{y}_{st}$, by taking the mean catch (excluding age 0) per strata, including a combination of three depth strata (from 20 to 500 m) and 13 sectors (from Cape Finisterra to Guadiana River) over the total strata in the surveyed area, following the methodology presented by Cochran (1960):

$$\bar{y}_{st} = \sum_{h=1}^{L} N_h \bar{y}_h \Big/ N$$

Where, N is the total number of units in all strata, N_h is the total number of units in stratum h and $\bar{y}_h$ is the age sample mean of abundance in number in stratum h

Horse mackerel estimations from spring acoustic surveys were also analysed to investigate the spatial distribution of horse mackerel juveniles and as a possible indicator of the recruitment strength for this species, which could prove to be useful for short-term forecasts. Not in all years it was possible to produce acoustic estimates of horse mackerel. Point estimates from 2009, 2013 and 2016 revealed a positive relationship between fish length and bottom depth. Recruitment acoustic estimates were compared with the current assessment but no conclusion was obtained with the available estimates. The current acoustic survey design prioritizes fishing for sardine (ICES, 2017a). Further work should be carried out in the future to increase the amount of fishing hauls for identification of horse mackerel shoals and provide acoustic estimates of juveniles.

An historic overview of the Egg Production survey developments was presented at the ICES (2017a). The major change since the beginning of the series was undertaken in 2007, when the DEPM methodology started to be adopted, in place of the AEPM. Since then improvements were reached in several aspects, including issues related to surveying (plankton surveying grid and gear), laboratorial analysis (egg identification, egg development rates and histological spawning markers) and data analyses (spawning time and synchronicity, fecundity pattern, and statistical analysis for parameter estimations). Egg production, female mean weight and fecundity were estimated for the more recent surveys, following the DEPM procedures, but spawning fraction estimates are still to be verified and therefore SSB estimation is not yet available. SSB estimates for 2013 and 2016 will be discussed at ICES WGMEGS as well as egg production for as many surveys as possible using the whole data series (including some AEPM and surveys directed at sardine for which the horse-mackerel eggs were processed) which may be used as external auxiliary information.

C. Assessment: data and method

Model/Program language: AMISH (**A**ssessment **M**ethod for the **I**bero-Atlantic **S**outhern **H**orse mackerel) / ADMB

Model type: AMISH is an age-based model similar to Stock Synthesis, flexible with regards to the type of data that may be include, the functional forms that can be used for biological processes (e.g. S–R relationship) and fishery (e.g. selectivity) and the number of parameters that may be estimated. The catch-at-age is not assumed to be known exactly and the model allows the inclusion of annual estimates of sampling variability (for both catch-at-age composition and survey index precision). The model begins in the first year of available data with an estimate of the population abundance-at-age. Recruitments are estimated for each year. In subsequent ages and years the abundance-at-age is reduced by the total mortality rate. This projection continues until the terminal year specified. Symbol definitions used in model equations are given in Table I. Variables and equations are given in Table II.

Data used: time-series of total international catch, international catch-at-age (ages 0-11+), biomass index of IBTS survey, abundance-at-age from IBTS survey (ages 1–11+) and mean weight-at-age in the catch and stock. Natural mortality-at-age and maturity-at-age are time invariant. The proportion of F and M before spawning is set fixed at 0.04 which corresponds to mid January when is assumed that main spawning takes place.

Model assumptions: Initial recruitment (age 0) is governed by the Beverton and Holt S–R relationship, assuming a steepness of h=0.8. The fishing mortality is assumed to be separable into an age component (called selectivity) and a year component (called the F multiplier). One selectivity block for the survey abundance index, three selectivity blocks for the catch-at-age (1992–1997, 1998–2011, 2012 onwards). Selectivity-at-age (constant for ages 7+) is allowed to change gradually over time. Landings data by year is fitted assuming a CV of 5%, and the survey index data is fitted assuming a CV of 30%. For the fishery proportions-at-age it is assumed an “effective sample size” of 100 and for the survey estimates of age composition an “effective sample size” of ten. Priors (lognormal) are included for some parameters.

Estimated parameters: The number of estimated parameters is 104. Since in the current model code SSB is computed with the input of the stock mean weight-at-age of the last year of the assessment and assuming that the input maturity-at-age represents only females, SSB at spawning time is computed with an R routine using the estimated time-series of population size-at-age and the inputs on the mean weight-at-age in the stock, the proportion mature-at-age and the proportion of F and M before spawning.

Objective function: The overall log-likelihood is the weighted sum of a combination of several components: catch biomass (Lognormal), abundance indices (Lognormal), proportion-at-age in the catch and survey (Multinomial), selectivity-at-age in the catch and in the survey (Lognormal), and penalty components regarding smoothness for selectivities, fishing mortality regularity and recruitment regularity and curvature, the latter having negligible effect on parameter estimation (Table III).

Minimization: It occurs in phases, in which groups of parameters are estimated simultaneously, while the remaining parameters are maintained at their initially assigned values. Minimization is implemented using standard ADMB process. The best set of all parameters are those that minimize the value of the objective function.

Outputs: The R (R Core Team, 2015) package "PBSmodelling" (version 2.67.266) is used to process and view model outputs.

References: AMAK (2011), Lowe *et al*. (2012).

D. Short-term projection

Model used: Determinist short-term projections.

Software/code: Performed with R using the Fisheries Library in R (FLR) "FLAssess" and "Flash". The R code to run the short-term projections is available upon request and in ICES WGHANSA SharePoint.

Initial stock size: Input to the short-term projections is the stock number-at-age 1–11+ estimated at the 1st of January in the final year of the assessment. For last assessment data year in 2015, the assessment provides the surviving stock numbers at 1st January of 2016 for ages 1–11+. Recruitments (age 0) at 1st January estimated in the final year of the assessment is replaced by the geometric mean recruitment of the time-series. The stock number-at-age 1 in the intermediate year (final year of the assessment +1) are the survivors of the geometric mean recruitment assumed in year-1.

Natural mortality: values used in the assessment.

Proportion of F and M before spawning: the value used in the assessment (0.04) which corresponds to mid January when is assumed that main spawning takes place.

Maturity ogive: values of the final year of the assessment.

Weight at age in the catch and in the stock: values of the final year of the assessment.

Exploitation pattern: Selectivity in the final year of the assessment.

Intermediate year assumptions: F *status quo* equal to the F-at-age in the final year of the assessment unless there is a management plan.

A management plan for Southern horse mackerel was developed by initiative of the Pelagic Advisory Council (PELAC), which may adopt another approach for the intermediate year assumption. In this case, F *status quo* will be equal to the F-at-age with a catch constraint in the intermediate year.

E. Biological reference points

Biological Reference Points were estimated in the 2016 Assessment Working Group (WGHANSA, ICES 2016a), approved by ICES and adopted for the development of the management plan for this stock in PELAC. The methodology to estimate Biological Reference Points (BRP) for southern horse mackerel stock followed the framework proposed in ICES (2017b) guidelines for fisheries management reference point for category 1 stocks. Recent state-of-the-art workshops recommended that MSY BRP´s should be evaluated with stochasticity in a number of biological parameters and typically, a recent period should be chosen that reflects the current productivity and fishery regimes (ICES, 2016b). The BRPs were estimated in ICES (2016a) and revaluated during ICES (2017a) using the assessment adopted at the benchmark. The stock information was converted to FLStock object using the "FLCore" package (version 2.6.0.20170130). Simulations analyses were conducted with package "msy" using the Eqsim routines (version downloaded 09/02/2017), a stochastic equilibrium reference point software that provides MSY reference points based on the equilibrium distribution of stochastic projections. The method is described in more detail in ICES (2013) and the software short manual can be found at the following link: https://github.com/einarhjorleifsson/msy/tree/master/inst/doc.

The southern horse mackerel shows no obvious S–R relationship. SSB shows a stable and narrow dynamic range and erratic recruitments with occasional strong year classes. There is no evidence of reduced reproductive capacity at any of the observed SSB levels. It was decided that given the high biomass condition of the stock associated with low fishing mortality, below the current F_{MSY} proxy, there was support to fit a segmented regression with a forced breakpoint at 182kt as the mean lower bound of the 90% CI of the observed SSB. The 90% CI encompasses the true B_{MSY} and the 5th percentile of the observed SSB was proposed as a candidate for $B_{trigger}$ (Azevedo *et al*., 2016). In order to analyze an F_{MSY} candidate in relation to precautionary limits, i.e. prob(SSB< B_{lim}), a proxy for B_{lim} was derived as $B_{lim} = B_{pa} * \exp(-1.645\ \sigma) = 102$, where B_{pa} is the segmented regression breakpoint with $\sigma = 0.32$ as the standard deviation of SSB in the final year of the assessment.

Reference points were estimated based on the proposed segmented regression and historical variation in population, productivity parameters and assessment error and autocorrelation were used in the stochastic simulations. F_{lim} was estimated at 0.19 and the median F_{MSY} was estimated at 0.15. Based on the ICES general guidelines for determining F_{MSY}, it was also tested whether fishing at F_{MSY} is precautionary in the sense that the probability of SSB falling below B_{lim} in a year in long term simulations with fixed F is ≤ 5% ($F_{p.05}$; redefined as F_{pa} since 2021). The $F_{p.05}$, F_{pa} was estimated at 0.15 and therefore the F_{MSY} (0.15) is not restricted because of this precautionary limit. A full description of the methodology and biological/productivity parameters is available in Azevedo *et al*. (2016). The Biological Reference points for southern horse mackerel stocks are show in Table 1.

Table 1. Summary table of Biological Reference Points (weights in thousand tonnes).

BRP	VALUE	TECHNICAL BASIS
B_{lim}	103	$B_{lim} = B_{pa} * \exp(-1.645\ \sigma)$ $\sigma = 0.32$ (0.34)
B_{pa}	181	$B_{pa} = B_{trigger}$
$B_{trigger}$	181	Lower bound (average) of 90%CI of $SSB_{1992–2015}$
F_{lim}	0.19	Stochastic long-term simulations (50% probability SSB > B_{lim})
F_{pa}	0.15	F that leads to SSB ≥ B_{lim} with 95% probability (update May 2021).
F_{MSY}	0.15	Stochastic long-term simulations

F. References

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Table I. Symbols definition used for model equations.

General Definitions	**Symbol/Value**	**Use in Catch-at-Age Model**
Year index: $i = \{1992, 1993, \ldots\}$	i	
Age index: $j = \{0, 1, 2, \ldots, 11^{+}\}$	j	
Mean weight in year i by age j	$W_{i,j}$	
Maximum age beyond which selectivity is constant (*)	*Maxage*	Selectivity parameterization
Instantaneous Natural Mortality	M_j	Fixed in time
Proportion females mature at age j	p_j	Definition of spawning biomass
Sample size for proportion in year i	T_i	Scales multinomial assumption about estimates of proportion at age
Survey catchability coefficient	q^s	Prior distribution: *lognormal*(μ_q^S , σ_q^2)
Stock–recruitment parameters	R_0 h σ_R^2	Unfished equilibrium recruitment, steepness, variance
Virginal biomass	φ	Spawning biomass per recruit when there is not fishing

(*) refer to Section C for the number of selectivity parameters estimated.

Table II. Variables and equations describing implementation of the Southern horse mackerel assessment model (AMISH).

Eq Description	Symbol/Constraints	Key Equation(s)
Survey (s) biomass index by year (ẟ represents the fraction of the year when the survey occurs)	I_i	$I_i = q\sum_{j=0}^{11} N_{ij}\ W_{ij}\ S_j e^{-\delta Z_{ij}}$
Catch biomass by year	C_i	$\hat{C}_i = \sum_{j=0}^{11} N_{ij}\,W_{ij}\,\frac{F_{ij}}{Z_{ij}}\left(1 - e^{-Z_{ij}}\right)$
Proportion-at-age j, in year i	$P_{ij},\ \sum_{j=0}^{11} P_{ij} = 1.0$	$P_{ij} = \frac{C_{ij}}{\sum_j C_{ij}}$
Number-at-age in first year and age	$j = 0$, i=1st year (1992)	$N_{ij} = e^{\mu} R^{\varepsilon_i}$
Number-at-age in first year	$0 < j < 10$, i=1st year (1992)	$N_{ij} = e^{\mu} R^{\varepsilon_{1992-j}} \prod j\, e^{-M_j}$
Number-at-age in first year in age plus-group	$j = 11+$, i=1st year (1992)	$N_{ij} = N_{i,j-1}/\left(1 - e^{-M_{j-1}}\right)$
Numbers-at-age 0 in remaining years	$j = 0,\ \sum_i \varepsilon_i = 0$	$N_{ij} = e^{\mu} R^{+\varepsilon_i}$
Numbers-at-age in remaining years	$0 < j < 11$	$N_{ij} = N_{i-1,j-1} e^{Z_{i-1,j-1}}$
Numbers-at-age group plus in remaining years	$j = 11+$	$N_{ij} = N_{i-1,j-1} e^{Z_{i-1,j-1}} + N_{i-1,j} e^{-Z_{i-1,j}}$
Catchability of abundance index	μ^s	$q_i^s = e^{\mu s}$
Instantaneous fishing mortality		$F_{ij} = e^{\mu + \eta_j + \phi_i}$
Mean fishing effect	μ	
Annual effect of fishing mortality in year i	$\phi_i\ ,\sum_i \phi_i = 0$	
Age effect of fishing (regularized) in years with time variation allowed	$\eta_{ij},\ \sum_i \eta_{ij} = 0$	$S_{ij} = e^{\eta_j}$
Age effect of fishing (regularized) in years where selectivity is constant over time	$\eta_{ij} = \eta_{i-1,j}$	
Natural Mortality vector	M_j	
Total mortality	Z_{ij}	$Z_{ij} = F_{ij} + M_j$
Spawning biomass (spawning takes place at mid of January)	B_i	$B_i = \sum_j N_{ij}\, e^{-(0.5/12) Z_{ij}} W_{ij} p_j$
Recruitment-at-age 0 (Beverton–Holt function)	$\ddot{R}_i$	$\ddot{R}_i = \frac{\alpha B_i}{\beta + B_i};\ \alpha = \frac{4hR_0}{5h-1},\quad \beta = \frac{B_0(1-h)}{5h-1}$, β_0 is virgin biomass, R_0 is recruitment at virgin biomass and h is steepness

Table III. Specification of objective function that is minimized (i.e. the penalized negative of the log-likelihood).

Likelihood /penalty component		Description / notes
Catch biomass likelihood	$L_1 = \lambda_1 \sum_i \ln\left(\frac{C_i}{\hat{C}_i}\right)^2$	Fit to catch biomass in each year
Abundance indices	$L_2 = \sum_s \lambda_2^s \sum_i \ln\left(\frac{I_i^s}{\hat{I}_i^s}\right)^2$	Survey abundances
Proportion-at-age	$L_3 = \sum_{l,i,j} \tau_i^l \, P_{ij}^l \ln \ddot{P}_{ij}^l$	$l = \{s, f\}$ for survey and fishery age composition observations
Penalty on smoothness for selectivities	$L_4 = \sum_l \lambda_4^l \sum_i \left(\eta_{j+2}^l + \eta_j^l - 2\eta_{j+1}^l\right)^2$	$l = \{s, f\}$ for survey and fishery selectivity
Fishing mortality regularity	$L_5 = \lambda_5 \sum_{i=1992} \phi_i^2$	
Penalty on recruitment regularity	$L_6 = \lambda_6 \sum_i \varepsilon_i^2$	Influences estimates where data are lacking (e.g. if no signal of recruitment strength is available, then the recruitment estimate will converge to median value).
Penalty on recruitment curve	$L_7 = \lambda_7 \sum_i \ln\left(\frac{N_{i,0}}{\tilde{R}_i}\right)^2$	Conditioning on stock–recruitment curve (but reduced to have negligible effect on estimation).
Priors	$L_8 = \left[\lambda_8 \frac{\ln(M/\hat{M})}{2\sigma_M^2} + \lambda_9 \frac{\ln(q/\hat{q})^2}{2\sigma_q^2}\right]$	Prior on natural mortality, and survey catchability
Overall objective function to be minimized	$\dot{L} = \sum_k L_k$	