Advance View
https://doi.org/10.3354/meps12602

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Available online:
July 17, 2018

Contribution to the Theme Section 'Drivers of dynamics of small pelagic fish resources: biology, management and human factors'

Challenges of management strategy evaluation for small pelagic fish: the Bay of Biscay anchovy case study

Sonia Sánchez[1,*], Leire Ibaibarriaga[2], Andrés Uriarte[1], Raul Prellezo[2], Marga Andrés[2], Pablo Abaunza[3], Ernesto Jardim[4], Sigrid Lehuta[5], Lionel Pawlowski[6], Beatriz Roel[7]

[1]AZTI, 20110 Pasaia, Gipuzkoa, Spain
[2]AZTI, 48395 Sukarrieta, Bizkaia, Spain
[3]Instituto Español de Oceanografía (IEO), 28002 Madrid, Spain
[4]European Commission, Joint Research Centre (JRC), 21027 Ispra (VA), Italy
[5]Institut Français de Recherche et d'Exploitation de la Mer (IFREMER), 44311 Nantes, France
[6]Institut Français de Recherche et d'Exploitation de la Mer (IFREMER), 56100 Lorient, France
[7]A & B Word, Layshla, Chester Road, Kelsall, Cheshire CW6 0SE, UK

ABSTRACT: Modeling major uncertainties in population and fishery dynamics is fundamental for reliable management strategy evaluation. Here we describe the bio-economic impact assessment of alternative harvest control rules (HCRs) in developing a management plan for Bay of Biscay anchovy, using R software and the FLBEIA software package. Further, we show how the modeling work was adapted as new biological information and data sources became available. The underlying general HCR consists of exploiting a proportion of the estimated spawning stock biomass (SSB), and is operative for 2 alternative management calendars: July–June or January–December. The final shape of the rule is determined by the harvest rate, the biomass trigger points, and the total allowable catch (TAC) thresholds. The performance of the HCRs was evaluated according to the biological and economic risks, probability of fishery closure, expected average catches, and their standard deviation. Robustness of these rules, given alternative recruitment models and quota shares among fleets, was also tested. The inclusion of a recruitment index allowed moving the management calendar from July–June to January–December, and led to higher (~15%) and more stable average catches, while reducing biological risks and the probability of fishery closure (by ~25%). The presence of minimum and maximum TAC levels allowed improved fishery performance. Recruitment was the uncertainty of major relevance in determining the relative performance of the rules, while there was little effect on biological risk of different quota shares among countries. The simulation results were the cornerstone for the selection of the adopted HCRs by stakeholders and managers.

KEY WORDS: Bay of Biscay · Anchovy · *Engraulis encrasicolus* · Management strategy evaluation · Management plan · FLBEIA

INTRODUCTION

The Bay of Biscay anchovy fishery constitutes an example of how the crash and closure of a fishery led to the development of a management plan, which became operative after stock recovery in 2010. Since then, the fishery has been operating in a sustainable (ICES 2016b) and profitable manner. Two main aspects may be of interest to other case studies: (1) the process of developing and implementing a management plan that has undergone the full cycle (set objectives; propose, formalize, and test management measures; implement management plan; and review performance) and has involved the collaboration of scientists, managers, and stakeholders as suggested for the process (Punt et al. 2016); (2) the quantitative

*Corresponding author: ssanchez@azti.es

assessment of alternative harvest control rules (HCRs) following the management strategy evaluation (Tonkin et al. 2008) or management procedure approach (IWC 1999, Aranda & Motos 2006) that usually forms the basis of a management plan before implementation. The former is discussed by A. Uriarte et al. (unpubl.), while the latter is addressed in this article.

Since its creation by the International Whaling Commission (IWC 1999), management strategy evaluation (MSE) has been used worldwide for the development of management plans (Goodman et al. 2002, De Oliveira & Butterworth 2004, Bastardie et al. 2010, STECF 2015). MSE allows us to compare alternative management strategies and identify those that fulfill the management objectives while being robust to the uncertainties in the system (Butterworth et al. 2010, Punt et al. 2016). Therefore, establishing all elements necessary for MSE requires modeling the stock and fishery dynamics and identifying the major potential sources of uncertainty. In other words, MSE needs to be individually adapted to the stock and fisheries characteristics of each case (Punt et al. 2016). Furthermore, within the same case study, MSE should be able to conform to any new information and evolve by incorporating new elements and eliminating irrelevant ones.

Small pelagic species, like anchovies, are a challenge for fishery management due to their life history characteristics, and often because of management decisions unrelated to the monitoring (Barange et al. 2009). They are considered to be short-lived species with high and variable natural mortality. Consequently, population levels are highly dependent on the magnitude of incoming recruitment, which is highly variable and influenced by environmental factors (Petitgas et al. 2013). Improved understanding of recruitment processes and their potential relationship with environmental conditions would contribute to more efficient management, but this has rarely been achieved successfully (Subbey et al. 2014, Punt et al. 2016). Besides boom and bust recruitment dynamics, multi-decadal regimes have also been observed for some small pelagic species (Lluch-Belda et al. 1989, 1992) and might also need to be considered in the design of management procedures (De Oliveira 2006).

The aggregative behavior of small pelagic fish makes the catch per unit effort unreliable as a proxy of abundance (Csirke 1988, Fréon & Misund 1999) and therefore, fisheries-independent surveys are required. Surveys for eggs and larvae, as well as acoustic surveys are often used for close monitoring of the stock (Gunderson 1993), either to fit the population models, including their estimates as abundance indices, or to directly implement management decisions. Therefore, any bias or lack of precision in the surveys will have immediate consequences on the stock. For these cases, the estimation of constant harvest strategies, such as F_{msy} (i.e. the fishing mortality rate which, if applied constantly, would result in maximum sustainable yield), can be difficult, and usually risk-averse decisions are suggested, for example short-term escapement strategies (Gjøsæter et al. 2015).

The objective of this work was to describe the underlying MSE process for the Bay of Biscay anchovy, focusing on how small pelagic fish characteristics were considered and how the modeling work was adapted as new biological information and data sources became available. To do so, firstly, the fishery and the management framework are described. Secondly, the set of explored HCRs are presented. Next, changes made during the modeling process, motivated by changes in the assessment methodology and the participation of stakeholders, are described. The results allowed us to identify the most relevant sources of uncertainties for the management of the Bay of Biscay anchovy, which could be applicable to other short-lived pelagic species.

MATERIALS AND METHODS

Case study

The Bay of Biscay anchovy *Engraulis encrasicolus* is a small pelagic fish that is a prey species for piscivorous fish, mammals, and birds in the region (Preciado et al. 2008, Lassalle et al. 2011). It spawns during spring off the Spanish and French Atlantic coasts, and early juveniles are found during summer and autumn in the southeastern part of the Bay of Biscay (Uriarte et al. 1996, Irigoien et al. 2007, Petitgas et al. 2010b).

Two countries (Spain and France) exploit the Bay of Biscay anchovy, each operating in different periods and areas. The Spanish fishery is carried out with purse seiners, and about 90–95% of the catches occur during the first half of the year. The French fleet instead uses mainly pelagic trawlers, but also some opportunistic purse seiners, and between 70 and 100% of the catches are fished during the second semester. The number of vessels involved in both fisheries has decreased since the year 2000 (Andrés & Prellezo 2012, STECF 2014). According to the relative stability principle, Spain owns 90 % of the quota and France the remaining 10 %. However, various bilateral agreements for quota transfers between these countries since 1991 have led to a more balanced share of the total allowable catch (TAC) (Aranda & Motos 2006), around 50 % for both countries.

The population is monitored by 3 fishery-independent annual surveys. Two spring surveys estimate the adult population at age and the spawning stock biomass: a daily egg production method survey (BIOMAN) and an acoustic survey (PELGAS). These surveys have been carried out regularly since 1987 and 1989, respectively, (Massé et al. in press, Santos et al. in press). In addition, since 2003, an acoustic survey (JUVENA) is carried out in autumn to estimate the juvenile abundance that will form the next year's recruitment at age 1 (Boyra et al. 2013). The abundance of juveniles in autumn constitutes a reliable indicator of the strength of recruitment to the adult stock in the following year (Boyra et al. 2013, Boyra 2017, in press). As a consequence, since 2014, the estimates from JUVENA were also included in the assessment as an index of recruitment (ICES 2014a), improving the knowledge base for making management decisions.

From 1979 to 2005, the fishery was managed using a fixed TAC between 30 000 and 33 000 t, set independently to the stock status. The fishery collapsed in 2005, due to successive poor recruitments, and was closed for 5 yr (ICES 2006, Andrés & Prellezo 2012). Since 2010, the fishery has been managed according to a long-term management plan (COM[2009] 399 final, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52009PC0399&rid=5), which was revised in 2014 (STECF 2014). The development and agreement of the HCRs associated with these plans have been supported by extensive and thorough simulation testing work (STECF 2008a,b, 2009, 2013, 2014) within the MSE framework (Smith et al. 1999, Sainsbury et al. 2000). The work was carried out in 2 phases: (1) in 2008, for the initial management plan to be used once the stock had achieved recovered status (STECF 2008a,b); and (2) in 2014, for the revision of the management plan after being in force for several years, and due to important changes in the assessment methodology, such as the incorporation of a recruitment index from the autumn acoustic survey JUVENA (STECF 2013, 2014).

Definition of a management plan in 2008

The general management objectives for the anchovy fishery, as defined by the European Commission, were: to ensure the exploitation of the stock at high yields consistent with the maximum sustainable yield, guaranteeing stability (as far as possible) with a low risk of stock collapse (Non-paper of the EC on long-term management for anchovy, November 2007 unpubl.)

Usually management runs from January to December. In the absence of any valid indicator of recruitment at age 1 in the management year (y+1), management of the population in y+1 was very uncertain,

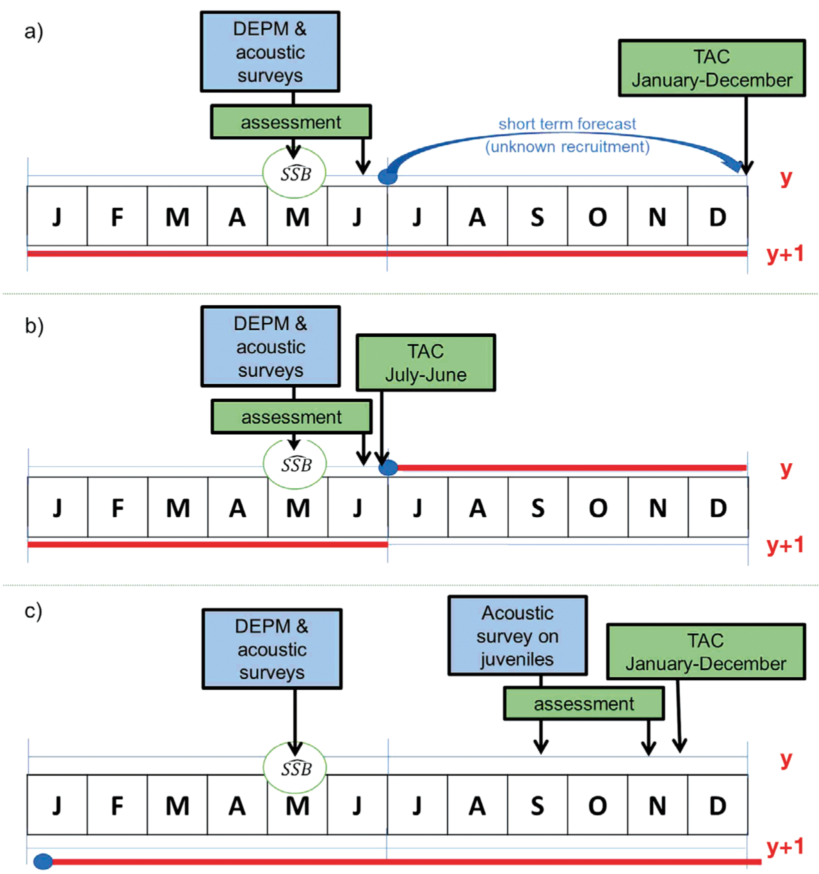

Fig. 1. Conceptual diagram of management calendars employed for the anchovy fishery in the Bay of Biscay. DEPM: daily egg production method; TAC: total allowable catch; SSB: spawning stock biomass

because most of the catches and population would depend upon the unknown new recruits (by about 60%; Fig. 1a). For this reason, it was decided to manage the population in the year of the assessment (as observed by the spring surveys in May), while minimizing the risks for the population in the following year. To achieve this, the management calendar was moved from January (y+1)–December (y+1) to July (y)–June (y+1). The basis for these decisions was the recent in-year spawning stock estimates from the assessment based on spring surveys of adults (in May of year y) (Fig. 1b). In this way, catches, as defined by the HCR, would regulate much of the exploitation of the recently assessed stock and hence its contribution to spawning in the next year (y+1), making the most of the newly acquired information on stock abundance from the surveys. Furthermore, with this approach, there is no need to make predictions on the unknown incoming recruits which form the bulk of the population and the catch in year y+1. This simplifies the procedure of defining the HCRs.

On this basis, the HCRs considered (Rules A, B, C, D, and E in Table 1) determined the annual TAC (in t) from the period from July of year y to June of year y+1 (denoted by $\mathrm{TAC}_{Jul_y-Jun_{y+1}}$) according to the spawning stock biomass (SSB) estimate $\widehat{SSB}_y$ (corresponding to the stock biomass on 15 May). For all HCRs, the effects of having maximum and minimum TACs were also tested at the request of the stakeholders. The maximum TAC at 33 000 t aimed at providing stability to the TACs at high levels of the resource and was based on the evolution of the fleet's capacity and the anchovy market. The minimum TAC of 7000 t represented the threshold below which fishing was considered economically not viable (by the fishermen) leading to a TAC of 0. Therefore, for each HCR, 4 cases were considered: (1) no maximum or minimum TAC; (2) 33 000 t maximum TAC, no minimum TAC; (3) no maximum TAC, 7000 t minimum TAC; and (4) 33 000 t maximum and 7000 t minimum TAC. An additional Rule E allowed the minimum TAC to be taken over a range of low values (between 24 000 and 33 000 t).

In order to test the proposed HCRs, the MSE framework was used to simulate the anchovy fishery (Table 2, Fig. 2; also see Supplement 1 at www.int-res.com/articles/suppl/m12602_supp.pdf). The MSE framework was implemented in R software (https://www.r-project.org/). The simulation model is divided into the operating model (OM) and the management procedure (MP). The OM represents the 'real world,' which consists of the fish stocks and the fleets, whereas the MP represents the 'perceived world,' comprising the perceived system and the management actions taken. Stochasticity was introduced using Monte Carlo simulation (Refsgaard et al. 2007). A detailed description of the simulation model can be found in Supplement 1.

Within the OM, 3 seasons were considered within the year (1 July to 31 December, 1 January to 15 May 15, 16 May to 30 June). Population dynamics are simulated given a 2-stage biomass population model. Catches are assumed to be taken instantaneously at the middle of the defined periods. The management procedure was run annually. Since the currently used assessment model is a Bayesian model which is very time-demanding, it was not possible to incorporate the assessment model into the simulation, and a short-cut approach was used. Observation and assessment uncertainty were considered jointly in the observation error model (OEM) based on the simulation testing results of the assessment model (Ibaibarriaga et al. 2011). Management advice is generated by means of an HCR that sets the TAC from July of year y to June of year y+1, based on an estimate of the real population simulated in the OM (subject to error). Implementation error was not considered, and seasonal catches were determined based on assigning a fixed proportion of the TAC each season, based on historical catches. Catches at age are estimated based on a flat selectivity pattern. The initial SSB (in 2007) was assumed to follow a log-normal distribution with mean equal to the median SSB from the most recent assessment (ICES 2007, Ibaibarriaga et al. 2008), and a coefficient of variation (CV) of 25% to account for the uncertainty in the initial conditions. No errors were considered for the age-1 proportion of the population. For initialization, a fishery closure from 15 May 2007 up to July 2008 was simulated. Subsequently, the simulation period started and the HCRs were applied.

An independent algorithm was developed to evaluate the socio-economic impact of the different HCRs (Fig. 2; Supplement 1). In this case, both Spanish and French fleets were included as independent fleets to infer the economic results for each of them separately. Given the annual catches (median value) simulated in the MSE, these were disaggregated by country and season based on historical catches. The effort devoted by fleet and season was then estimated given a Schaefer-type production function (Schaefer 1954), with effort and biomass elasticities equal to 1. The SSB value was taken from the abundances (median values) simulated in the OM of the MSE. Prices for anchovy were modeled by country and season as a linear function of the total landings of the stock by semester (on a log scale), conditioned to

Table 1. Summary of the alternative harvest control rules (HCRs) tested for the Bay of Biscay anchovy management plan definition and revision. TAC: total allowable catch; γ: harvest rate; B_{lim}: biomass limit below which a stock is considered to have a reduced reproductive capacity; B_{pa}: biomass above which the stock is considered to have a full reproductive capacity; B_{trig}: biomass trigger point; SSB: spawning stock biomass; SWW AC: South West Waters advisory council

Rationale	Formula	Gamma	Trigger points[a]	TAC_{min} (kt)	TAC_{max} (kt)	Calendar	HCR name	Reference
Fraction above B_{lim}	$\text{TAC}_{July_y-Jun_{y+1}} = \begin{cases} 0 & , \text{ if } \widehat{SSB}_y \le B_{\text{lim}} \\ \gamma \cdot (\widehat{SSB}_y - B_{\text{lim}}) & , \text{ if } \widehat{SSB}_y > B_{\text{lim}} \end{cases}$	0, 0.1,…, 1	B_{lim}	None/7	None/33	Jul–Jun	Rule A	STECF (2008a,b)
Fraction of SSB	$\text{TAC}_{July_y-Jun_{y+1}} = \begin{cases} 0 & , \text{ if } \widehat{SSB}_y \le B_{\text{lim}} \\ \gamma \cdot \frac{(\widehat{SSB}_y - B_{\text{lim}})}{(B_{\text{pa}} - B_{\text{lim}})} \cdot \widehat{SSB}_{y-1} & , \text{ if } B_{\text{lim}} < \widehat{SSB}_y \le B_{\text{pa}} \\ \gamma \cdot \widehat{SSB}_y & , \text{ if } \widehat{SSB}_y > B_{\text{pa}} \end{cases}$	0, 0.1,…, 1	B_{lim}, B_{pa}	None/7	None/33	Jul–Jun	Rule B	STECF (2008a,b)
Constant risk	$\text{TAC}_{July_y-Jun_{y+1}} = \begin{cases} 0 & , \text{ if } \widehat{SSB}_y \le 26{,}500 \\ 0.766 \cdot (\widehat{SSB}_y - 26{,}500) & , \text{ if } \widehat{SSB}_y > 26{,}500 \end{cases}$	0.766	26.5 kt			Jul–Jun	Rule C	STECF (2008a,b)
Fixed TAC	$\text{TAC}_{July_y-Jun_{y+1}} = \begin{cases} 0 & , \text{ if } \widehat{SSB}_y \le 24{,}000 \\ 7{,}000 & , \text{ if } 24{,}000 < \widehat{SSB}_y \le 33{,}000 \\ 33{,}000 & , \text{ if } \widehat{SSB}_y > 33{,}000 \end{cases}$	–	24 kt, B_{pa}	7	33	Jul–Jun	Rule D	SWW AC (pers. comm.)
Fraction of SSB	$\text{TAC}_{July_y-Jun_{y+1}} = \begin{cases} 0 & , \text{ if } \widehat{SSB}_y \le 24{,}000 \\ 7{,}000 & , \text{ if } 24{,}000 < \widehat{SSB}_y \le 33{,}000 \\ \gamma \cdot \widehat{SSB}_y & , \text{ if } \widehat{SSB}_y > 33{,}000 \end{cases}$	0, 0.1,…, 1	24 kt, B_{pa}	7	33	Jul–Jun	Rule E	STECF (2009)
Fraction of SSB[b]	$\text{TAC}_y = \begin{cases} 0 & , \text{ if } \widehat{SSB}_y \le B_{trig1} \\ \text{TAC}_{min} & , \text{ if } B_{trig1} < \widehat{SSB}_y \le B_{trig2} \\ \alpha + \gamma \cdot \widehat{SSB} & , \text{ if } B_{trig2} < \widehat{SSB}_y \le B_{trig3} \\ \text{TAC}_{max} & , \text{ if } \widehat{SSB}_y > B_{trig3} \end{cases}$	0, 0.1,…, 1	$B_{\text{trig1}} = 24$ kt $B_{\text{trig2}} = 24/33$ kt B_{trig3} for TAC_{max}[c]	7	33/25	Jul–Jun/ Jan–Dec	Rules G1: $B_{\text{trig2}} = 33$, $\text{TAC}_{\text{max}} = 33$ G2: $B_{\text{trig2}} = 33$, $\text{TAC}_{\text{max}} = 25$ G3: $B_{\text{trig2}} = 24$, $\text{TAC}_{\text{max}} = 33$ G4: $B_{\text{trig2}} = 24$, $\text{TAC}_{\text{max}} = 25$	STECF (2013, 2014)

[a] $B_{\text{lim}} = 21$ kt, $B_{\text{pa}} = 33$ kt

[b] For management year y from July to June: $\text{TAC}_y = \text{TAC}_{July_y-Jun_{y+1}}$ and $\widehat{SSB}$ is the estimate of SSB in year y, $\widehat{SSB}_y$; and for January to December: $\text{TAC}_y = \text{TAC}_{Jan_y-Dec_y}$ and $\widehat{SSB}$ is the expected SSB during the management period, $\widehat{SSB}_y$

[c] $B_{\text{trig3}} = B_{\text{trig2}} + \dfrac{\text{TAC}_{\text{max}} - \text{TAC}_{\text{min}}}{\gamma}$

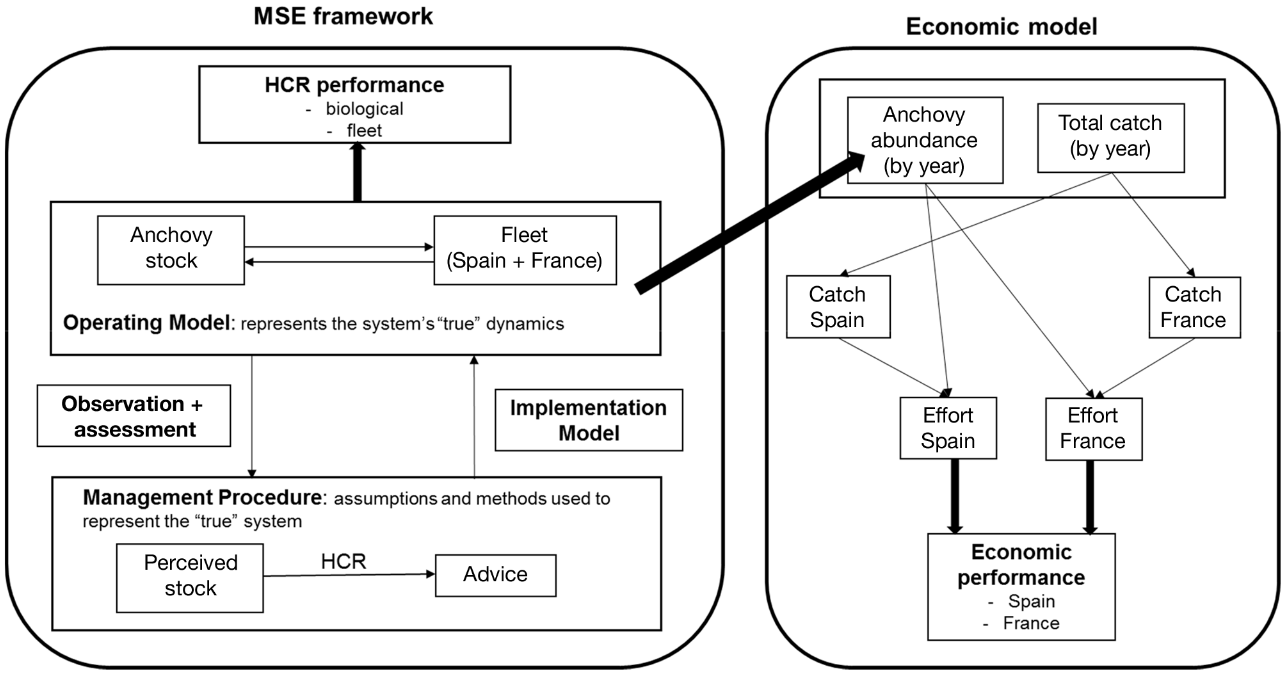

Fig. 2. Conceptual diagram of the modeling approach. MSE: management strategy evaluation; HCR: harvest control rule

Table 2. Details of the management strategy evaluation (MSE) framework and its conditioning for the base case (see details in Supplements 1 & 2 at www.int-res.com/articles/suppl/m12602_supp.pdf). OM: operating model; MP: management procedure; HCR: harvest control rule; (C)BBM: biomass-based model (including catches); SR: stock recruitment model; SSB: spawning stock biomass; B_{lim}: biomass limit below which a stock is considered to have reduced reproductive capacity

	MP definition in 2008	MP revision in 2013
Software	R (https://www.r-project.org) Ad hoc created code	R (https://www.r-project.org) FLBEIA framework[a]
OM		
Biological	Two-stage model in biomass (ages 1, 2⁺) based on half-year BBM assessment[b]	Age-structured model in numbers (ages 0–3⁺) based on half-year CBBM assessment[c]
Recruitment	Ricker SR	Ricker SR
Observation model	Observation + assessment error (CV 25%)	Observation + assessment error (CV 25%)
MP		
HCRs	Discontinuous HCRs Rules A, B, C, D, and E (see Table 1)	Continuous HCRs Rules G1, G2, G3, and G4 (see Table 1)
Implementation model	$TAC_y = TAC_{Jul_y-Jun_{y+1}}$ No implementation error	$TAC_{Jul_y-Jun_{y+1}}$ and $TAC_{Jan_y-Dec_y}$ No implementation error
Conditioning: initial population	Half-year BBM assessment results in 2008[b,d]	CBBM assessment results with 1987–2013 data[c,e]
Simulations	10 yr 500 iterations	20 yr 1000 iterations
Performance statistics (see formulation in Supplement 3)	Biological risks, i.e. p(SSB < B_{lim}) in any year; Probability of fishery closure; Yield: average catch, standard deviation of the catch; Economic risk (probability of having negative cash flow by country); and Discounted present value of the landings by country	Biological risks, i.e. p(SSB < B_{lim}) in any year; Probability of fishery closure; Yield: average catch, standard deviation of the catch, interannual variation (IAV) and p(IAV < 5000 t); Economic risk (probability of having negative cash flow by country); Discounted present value of the landings by country

[a]García et al. (2017); [b]Ibaibarriaga et al. (2008); [c]Ibaibarriaga et al. (2011); [d]ICES (2007); [e]ICES (2013a)

information from the period 2000–2006, and showing a negative effect for the volume of landings in the price and that anchovies landed in the first half of the year would reach higher prices.

Simulations were carried out considering a range of sources of uncertainty (Table 3). Firstly, alternatively to the Ricker stock-recruitment (SR) model, Beverton-Holt, segmented regression, and quadratic hockey stick models were also examined. Additionally, even though no significant autocorrelation was found in the recruitments, a major concern in the recruitment modeling was to account for a potential permanent regime shift in recruitment levels (as observed from 2002 to 2009), either due to the biomass level of the stock itself or to an environmental regime shift. To explore the implications of a potential regime shift, a scenario of low recruitment was also considered according to a normal distribution with mean and standard deviation equal to 19000 and 9200 t, respectively (ICES 2007), truncated to be positive. Secondly, motivated by the lack of complete knowledge of the real biological dynamics, alternatively to the 2-stage model an age-structured model was used in the OM for contrast (a complete description of the model and its conditioning can be found in STECF 2008a). Finally, regarding the catch allocation in seasons, an alternative variable quota allocation scenario was defined. This would result from a new potential TAC share agreement, where a part of the Spanish quota, proportional to the TAC, would be transferred to France on an annual basis (STECF 2008a). This alternative TAC sharing would ultimately imply a different seasonal international catch allocation every year. Catches by countries and semesters were deduced for any potential TAC given the following assumption on catch allocation by countries in semesters to apply in the future to their quotas (Q): $Q_{\text{Spain,sem1}} = 0.87 \times Q_{\text{Spain}}$ and $Q_{\text{France,sem1}} = 0.24 \times Q_{\text{France}}$ (STECF 2008a).

The dynamics were simulated for 10 yr and run for 1000 iterations. All simulated scenarios are listed in Table 3. The performance of HCRs in relation to the management objectives (such as the sustainability of the stock and the profitability of the fleet) was evaluated given the performance statistics described in Supplement 3.

Management plan revision in 2013

In 2013, after some years of application of the selected HCR (COM[2009[399 FINAL), the European Commission requested the revision of the agreed management plan. This revision was trig-

Table 3. Summary of the sensitivity analysis carried out during the management strategy evaluation process. OM: operating model; MP: management procedure; HCR: harvest control rule; TAC: total allowable catch; SR: stock recruitment

	MP definition in 2008	MP revision in 2013	Source of uncertainty[a]
OM			
Biological	Two-stage model in biomass (ages 1, 2^+)[b]		Model structure error
	Age-structured model in numbers (ages 0–3^+)		
Recruitment	Ricker SR model[b]	Ricker SR model[b]	Process error
	Persistent low recruitment	Sensitivity to 3 successive years of poor recruitment	
	Other: Beverton-Holt, segmented regression, quadratic hockey stick SR models, and historical variability	Other: Beverton-Holt	
MP			
Observation + assessment error	CV = 25%[b]	CV = 25%[b]	Observation error
	CV = 15% (as assessment predicts)	CV = 15% (as assessment predicts)	
HCRs	Rules A, B, C, D, and E (see Table 1)	Rules G1, G2, G3, and G4 (see Table 1)	–
TAC calendar	$\text{TAC}_{Jul_y-Jun_{y+1}}$	$\text{TAC}_{Jul_y-Jun_{y+1}}$ and $\text{TAC}_{Jan_y-Dec_y}$	–
Implementation model			
Catches 1st semester		60% (as historical; i.e. TAC share = 50%)[b]	Implementation error
		75% (TAC share: 80% Spain and 20% France)	

[a]Base case; [b]From the classification of Francis & Shotton (1997)

gered by changes in the assessment methodology and new data on recruitment from the autumn acoustic survey JUVENA (Boyra et al. 2013). The possibility to test alternative HCRs was also open.

The inclusion of an index of juveniles from the JUVENA survey provided reliable information on recruitment at age 1 in year y+1 into the base knowledge for management. This opened the possibility of managing the population and the catches of year y+1 based on an assessment carried out at the end of the previous year (Fig. 1c). Certainly, information on survivors (ages 2^+, coming from the spring surveys in year y) and of the new recruits (age 1, coming from the autumn acoustic survey on juveniles) would allow a forecast for year y+1. On this basis, HCRs to manage the population from January to December y+1 were also devised. The final shape of the HCRs was defined by some parameters such as the harvest rate, the biomass trigger points, and the TAC maximum and minimum thresholds (Table 1). HCRs that were discontinuous ($\alpha = 0$) and continuous at trigger points were tested. The performance of each HCR was tested in the July–June and January–December management calendars for γ values between 0 and 1. Present HCRs cover the alternatives of having or not having: (1) a maximum TAC of 25 000 or 33 000 t; and (2) a minimum TAC of 7000 t (Table 1).

The MSE approach was updated to the new situation. In this case, the FLBEIA framework was used to test the performance of different management strategies by means of simulations. FLBEIA is a flexible toolbox with which to perform bio-economic impact assessment of fisheries management strategies under the MSE approach (García et al. 2013, 2017, Prellezo et al. 2016). It is presented as an R (R CoreTeam 2015) library, which makes use of the FLR tools (Kell et al. 2007). All of these packages and their source codes are freely available at GitHub (http://github.com/flr). A detailed description of the main differences of the simulation model relative to the 2-stage model can be found in Supplement 2.

In this new approach, the biological OM was age-structured (ages 0 to 3^+) and the population dynamics were simulated in numbers at age by semesters. Regarding the fleets, a unique fleet operating in each semester was considered. As the Spanish and French fisheries largely dominate catches in the first and second half of the year, respectively, such simplification was considered good enough to reflect the major changes in fishing selectivity throughout the year. Selectivity patterns for these 2 sequential fisheries were estimated conditioned to the assessment results for age 1, and fixed at the values estimated by Uriarte (2005) for the rest of the age classes. Management advice was generated based on HCRs that establish the annual TAC (in t): (1) as a constant proportion of the latest estimate of SSB, for the July–June management calendar; or (2) of the expected SSB during the management period, for the January–December calendar. For the January–December calendar, when estimating the expected SSB: (1) the selectivity at age for the first semester was fixed at the median values of the last assessment; and (2) the proportion of catches in the first semester was assumed as historical. In the OEM, a short-cut approach was taken, assuming that the joint observation and assessment uncertainty was the same, independently of when the assessment was expected to occur (either in June or December). Given the TAC, total catches by semester were disaggregated by age using the different selectivity patterns.

The parameters of the OM were based on the most recent available results of a Bayesian biomass-based model including catches (CBBM) (Ibaibarriaga et al. 2011, ICES 2014b), and Markov chain Monte Carlo (MCMC) draws were used to account for all uncertainty in the true population and fishery states arising from the assessment.

Regarding the economic model, the anchovy price was estimated differently for the first and second semester. In the first semester, the expected price was estimated as a linear function of the total landings of the stock in this season (on a log scale), conditioned to the 2010–2013 data, deducing a negative effect for the volume of landings in the price. For the second semester, anchovy prices were fixed at the average price between 2010 and 2013, as no model could be fitted to the data. Economic results were computed for each of the simulations, whereas in defining the management plan in 2008, only the median values were considered.

Simulations were carried out considering previously evaluated sources of uncertainty, as well as several new ones (Table 3). First, with the introduction of the January–December management calendar, there was a need to make some inference to estimate the expected SSB for applying the HCR. To infer the abundance in spring, given the stock status at the beginning of the year, assumptions on growth, mortality, and the distribution of catches among semesters are required. Within the MP, the percentage of catches assumed for the first semester was 60% (i.e. the historical value). Thus, alternative quota allocations different from the historical ones would lead to a mismatch between the catch percentage by semesters in the OM and the one assumed in the MP, for the HCRs in the calendar year. Therefore, we tested how a change in the quota allocations would affect the performance of the HCRs given this assumption. An alternative quota allocation based on an expected TAC share by countries of 80% (Spain) and 20% (France) was also tested, implying a share of the TAC equal to 75% for the first semester. Secondly, given the fact that anchovy recruitment is highly variable and uncertain, alternatives to the Ricker recruitment were tested. This time, the persistent low recruitment regime was not considered valid any more as the stock seemed to have entered a high production period. However, in order to test some repeated recruitment failures, 3 successive years with low recruitment were forced (sampled randomly from the ⅓ lowest recruitments of the time series, those of the years 1988, 1990, 2001–2002, and 2004–2008). The 3 repeated recruitment failures were forced to happen in the 10th year of projection (2023–2025) over a 20 yr projection period (still leaving 8 yr to allow for population recovery), being thus able to test if the HCR allows for posterior stock recovery. Additionally, an SR model that does not assume overcompensation, such as Beverton-Holt, was also tested.

The dynamics were simulated for 20 yr and run for 500 iterations. In comparison to the 2008 MSE, the projection period was extended further, up to 20 yr, to allow the population to recover in the scenarios where a recruitment failure was forced. All simulated scenarios are listed in Table 3.

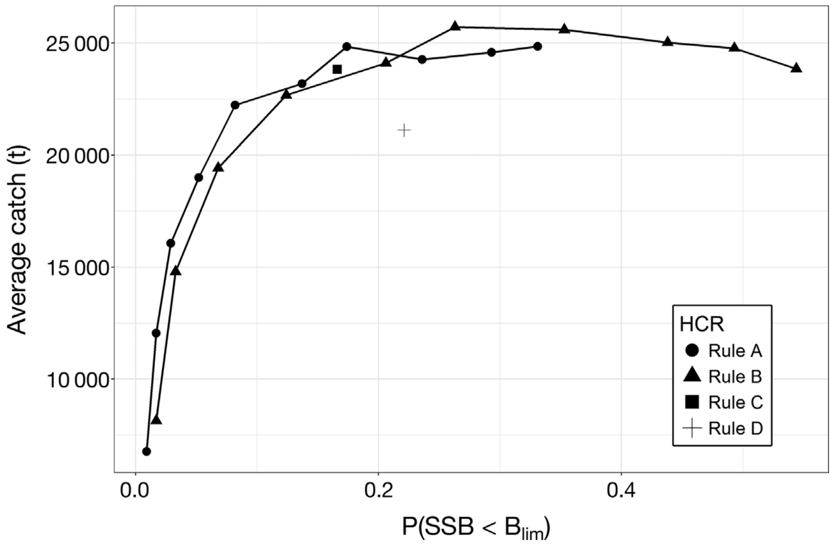

Fig. 3. Catch (in t) vs. risk. Comparison of Rules A, B, C (without maximum or minimum total allowable catch [TAC]), and Rule D (see Table 1). Different data points for Rules A and B correspond to the different harvest rates (i.e. γ parameter in Table 1). From bottom left corner to the upper right corner, points correspond to increasing harvest rates from 0.1 to 1. SSB: spawning stock biomass; B_{lim}: biomass limit below which a stock is considered to have reduced reproductive capacity (in the case of a 2-stage operating model, Ricker stock recruitment, constant allocation); HCR: harvest control rule

RESULTS

Definition of a management plan in 2008

For the base case 2-stage model (Ricker SR model and constant catch allocation between countries and semesters), the Rules A, B, and C (with no TAC_{min} or TAC_{max} restrictions) resulted in a similar level of catches for the same level of risks (Fig. 3). Rule C, which is based on a short-term risk of 15% (under a low recruitment scenario), resulted in long-term risks of 16%. These levels are similar for Rules A and B, with harvest rates in the range 0.6–0.7 and 0.4–0.5, respectively. Rule D, which has only 2 possible TAC options (TAC_{max} and TAC_{min}), gave average catches 3500 t lower than the rest of the HCRs for similar levels of biological risk (above 0.2).

The enforcement of an upper TAC limit reduced the mean catches and consequently the risk for all HCRs. In addition, it stabilized the catches and reduced the probability of fishery closure compared to the case with no upper limit for the TAC level (Fig. 4). Rule E yielded a result very similar to Rule B with a TAC_{max} at 33 000 t in terms of both risks and catches (Fig. 4). Comparing Rule B (with a maximum of 33 000 t and a minimum threshold TAC of 7000 t) to Rule E (which has the same TAC_{max} and a minimum economically viable TAC at 7000 t for SSBs between 24 000 and 33 000 t), both HCRs again showed a very similar performance in terms of risks and catches, but Rule E gave a lower probability of fishery closure (Fig. 4).

There was a high sensitivity to a persistently low recruitment scenario, with catches of on average less than 10 000 t than for the Ricker scenario. The risk of falling below the biomass limit below which a stock is considered to have reduced reproductive capacity (B_{lim}) was always above 10% in any year of the simulations for any of the harvest strategies investigated (Fig. 5). When SR models alternative to Ricker were tested (Beverton-Holt, segmented regression, and

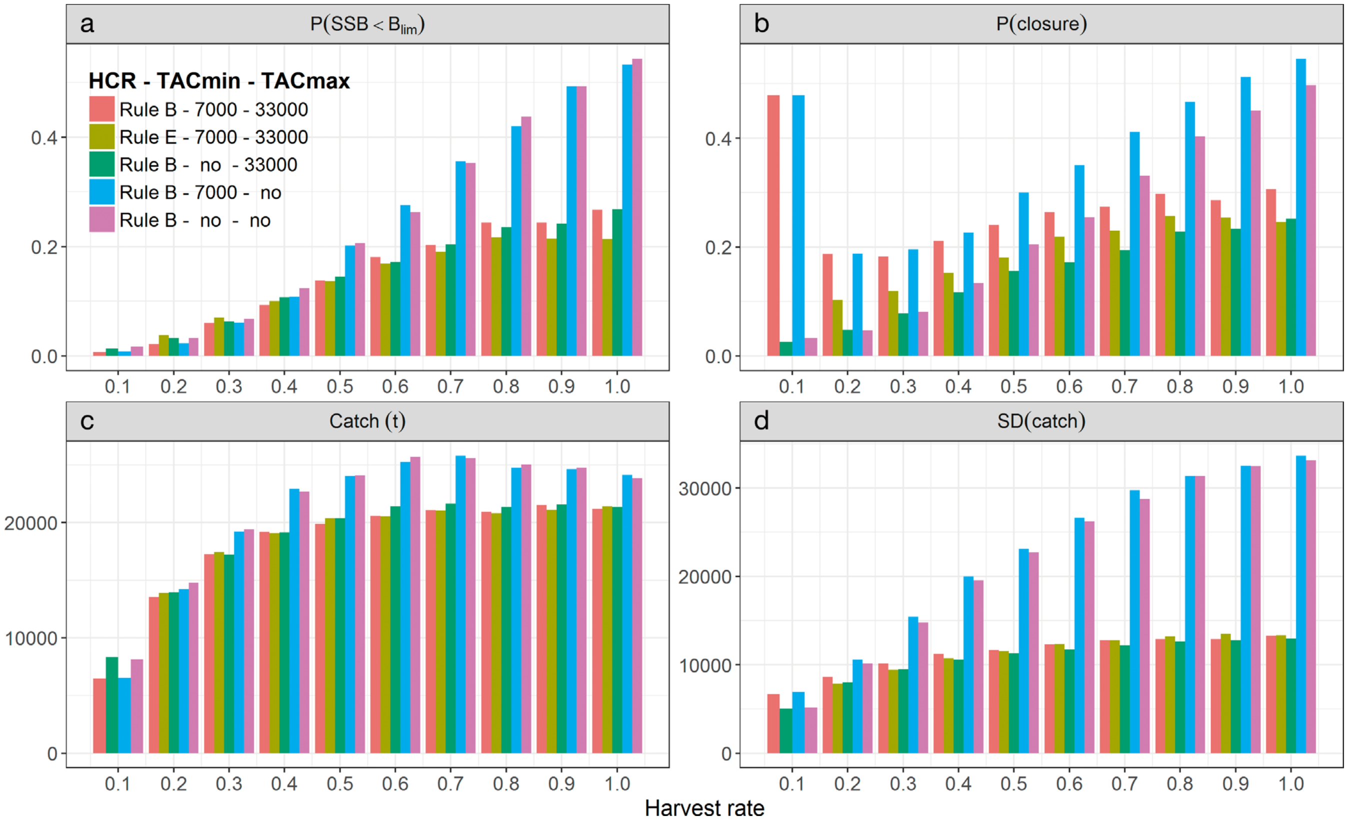

Fig. 4. Summary statistics for Rule B (see Table 1) with and without a minimum and maximum total allowable catch (TAC_{min} and TAC_{max}) and for Rule E with TAC_{min} and TAC_{max}. (a) Probability of spawning stock biomass (SSB) being below the biomass limit below which a stock is considered to have reduced reproductive capacity (B_{lim}), (b) probability of fishery closure, (c) average catch (in t), and (d) standard deviation of the catch as a function of the harvest rate (in the case of a 2-stage operating model, Ricker stock recruitment, constant allocation). HCR: harvest control rule

quadratic hockey stick), they did not result in any major contrasting results for the MSE.

Regarding the economic analysis, the minimum value of catches necessary to yield positive cash flow (that is, to cover the fixed costs) was estimated between 7000 and 11 000 t, depending on the scenario. Maximum value of the TAC was obtained at a TAC level of 32 000 t for the selected price model (Model 1). The highest overall discounted cash flow decreases with the harvest rate. Nevertheless, this decrease is flatter when setting a TAC_{max} of 33 000 t. Moreover, the economic risk is much lower in this case, and also limits the catch variability and biological risks. Finally, it was confirmed that international economic results do not depend on TAC share by country, although the results by country obviously changed.

The selected HCR for the Bay of Biscay anchovy management plan (COM[2009] 399 FINAL) was Rule E, which was the rule allowing higher catches at lower biomass levels at the expense of a reduction in the fishing possibilities at higher biomass levels. A harvest rate of 0.3 was determined as producing a biological risk around the maximum allowable risk set at 5%. Expected trajectories of stock development under this HCR can be found in Supplement 4 (Fig. S2).

Although the models used to assess the initial stock status and to carry out the simulations changed, the selected Rule E still remained within the same risk limits at the selected harvest rate (0.3), and was considered precautionary (Fig. 6). Moreover, this new evaluation forecasted higher catches (around 15%), less variability, and lower probabilities of fishery closure compared to the evaluation of the rule in terms of biomass.

Management plan revision in 2013

The inclusion of an available recruitment index allowed moving the management calendar from July–June to January–December. Comparing the management calendar for the tested HCR at the

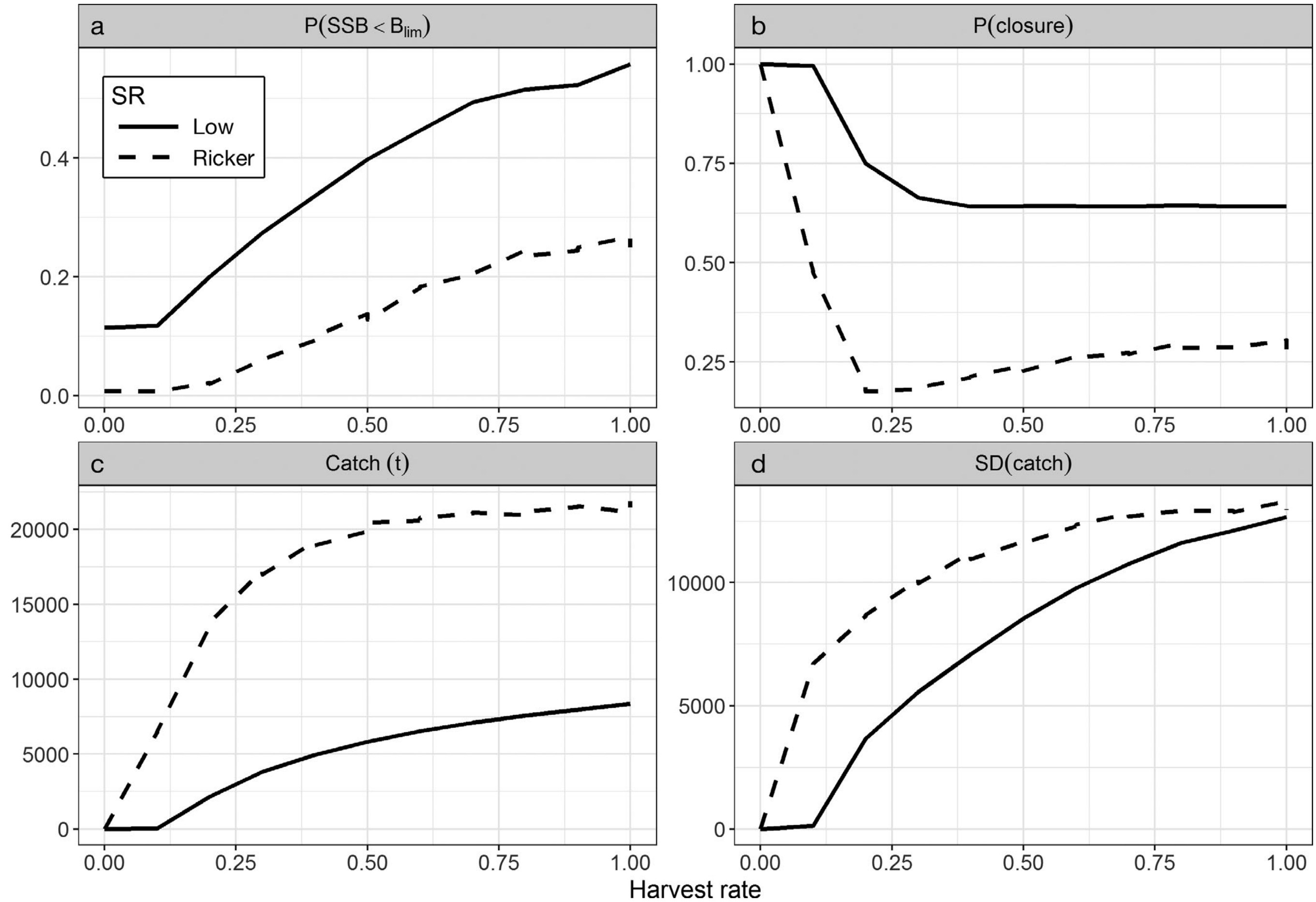

Fig. 5. Sensitivity of the performance of Rule B (see Table 1) to the stock recruitment (SR) model, for Rule B with minimum and maximum total allowable catch (TAC_{min} and TAC_{max}) of 7000 and 33 000 t. Summary statistics for Rule B under different SR models (Ricker SR model and continuous low recruitment levels) and biological operating models (2-stage or age-structured model) selected for the analysis. (a) Probability of spawning stock biomass (SSB) being below the biomass limit below which a stock is considered to have reduced reproductive capacity (B_{lim}), (b) probability of fishery closure, (c) average catch (in t), and (d) standard deviation of the catch as a function of the harvest rate

same harvest rates, this January–December calendar led to higher (~5%) and more stable average catches, while reducing biological risks and the probability of fishery closure (by ~40%; Fig. 7), for the same harvest rates. For the same level of allowable risks, the average catch increase was around 15% combined with a reduction of 25% in the probability of fishery closure. Furthermore, the sensitivity of this result to changes in the expected percentage of catches by semesters as a result of, for instance, different TAC share between countries was minimal. For example, if the share by countries changed to the expected situation given the actual country shares and the agreement in place (leading to 75% of the catches expected in the first semester, instead of what was assumed, i.e. 60%), for Rule G1 in the January–December management calendar, the risk shows variations smaller than 1%, while catches would not differ by more than 400 t, showing similar stability in catches.

When comparing Rules G1, G2, G3, and G4 in the January–December management calendar, Rules G1 and G2 (i.e. the HCRs with a biomass range in which TAC_{min} is applied) implied lower risks and probability of closure (Fig. 8). Rules G1 and G3 (i.e. the HCRs with TAC_{max} = 33 000 t) allowed higher catches, but they were less stable (Fig. 8). Interannual catch variability increased when increasing the harvest rate (Fig. 8). Finally, more stable catches were achieved for Rules G4 and G2 (i.e. those with TAC_{max} = 25 000 t) (Fig. 8) but at the expense of reducing mean catches. Overall, imposing a biomass range in which TAC_{min} is applied implies lower risks and probability of closure, whereas setting a lower TAC_{max} gives more stability in the catches at the expense of a reduction of

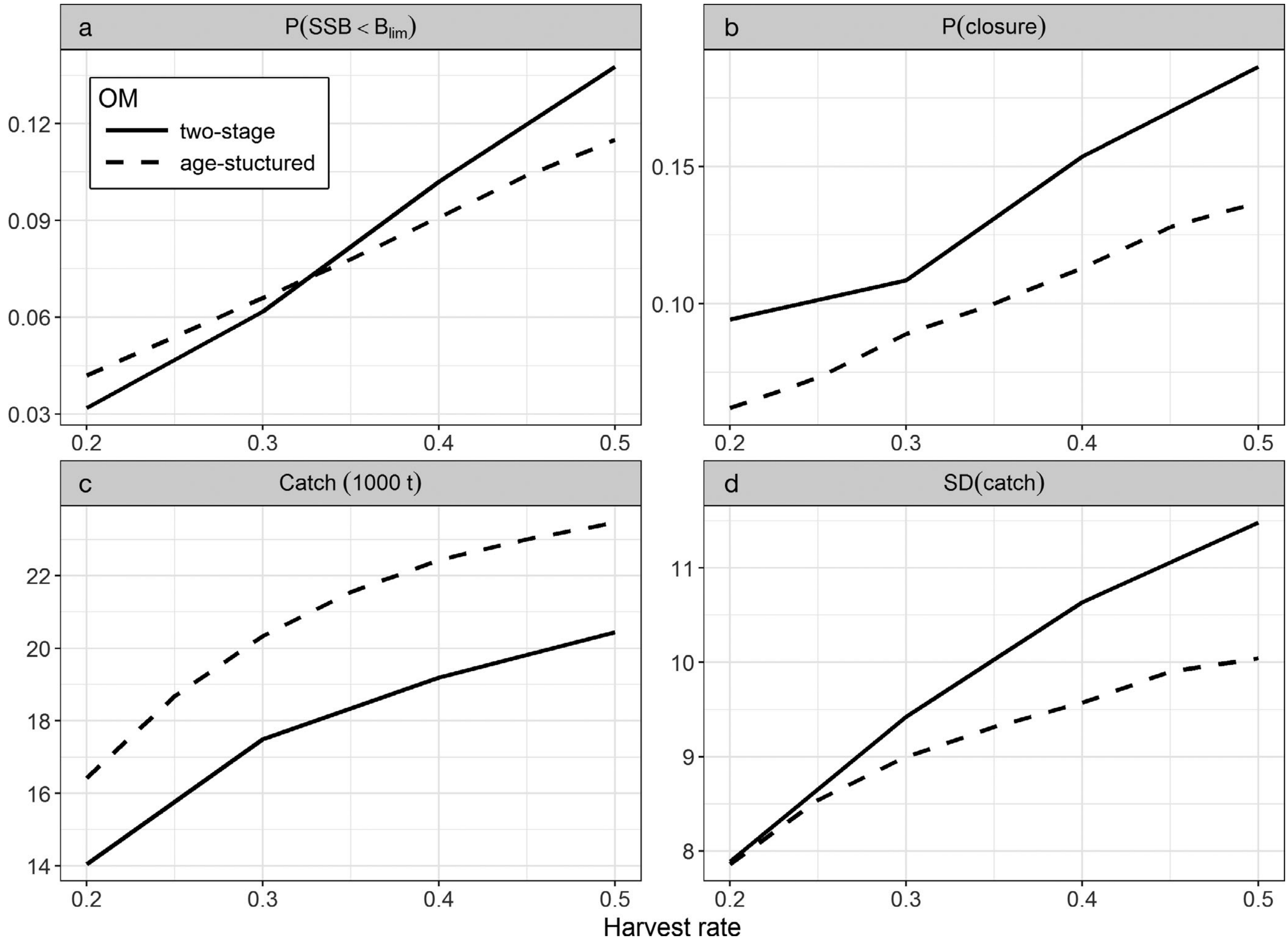

Fig. 6. Comparison of the performance statistics for the re-evaluation of the management plan harvest control rule (HCR; age-structured model) and for the previous evaluation (2-stage model). (a) Probability of spawning stock biomass (SSB) being below the biomass limit below which a stock is considered to have reduced reproductive capacity (B_{lim}), (b) probability of fishery closure, (c) average catch (in 1000 t), and (d) standard deviation of the catch as a function of the harvest rate. OM: operating model

the mean expected catches. The higher average catches resulting in admissible risks of falling below B_{lim} (i.e. lower than 0.05) were achieved for G1 (γ < 0.7) and G3 ($\gamma \leq 0.4$) (Fig. 8), whereas for G4, catches were more stable but with an expected mean around 3000 t lower than the HCR providing the highest catches, namely Rule G3 (Fig. 8).

Given the simulated results presented, the management calendar was moved to the calendar year. Managers, motivated by the stakeholders' proposal, finally selected Rule G4 with a harvest rate of 0.45 to be applied in 2015. Afterwards, the fishermen requested a change to Rule G3 with a harvest rate of 0.4, which implied similar risks (~5%) and expected catches 2500 t higher. Therefore, the selected HCR applied since 2016 onwards is Rule G3 at $\gamma = 0.4$.

Both selected HCRs could recover the SSB after recruitment failure in less than 2 yr (i.e. ~1.5 yr). However, in the case of recruitment failure, the risks are doubled (10%) and the catches are between 2600 and 2700 t lower and less stable than for the Ricker recruitment model. Expected trajectories of stock development under these 2 HCRs can be found in Supplement 4 (Figs. S3 & S4).

DISCUSSION AND CONCLUSIONS

Recruitment forecasting remains one of the main challenges in fish stock assessment and management, especially for small pelagic fish with highly variable and environmentally driven recruitment. Subbey et

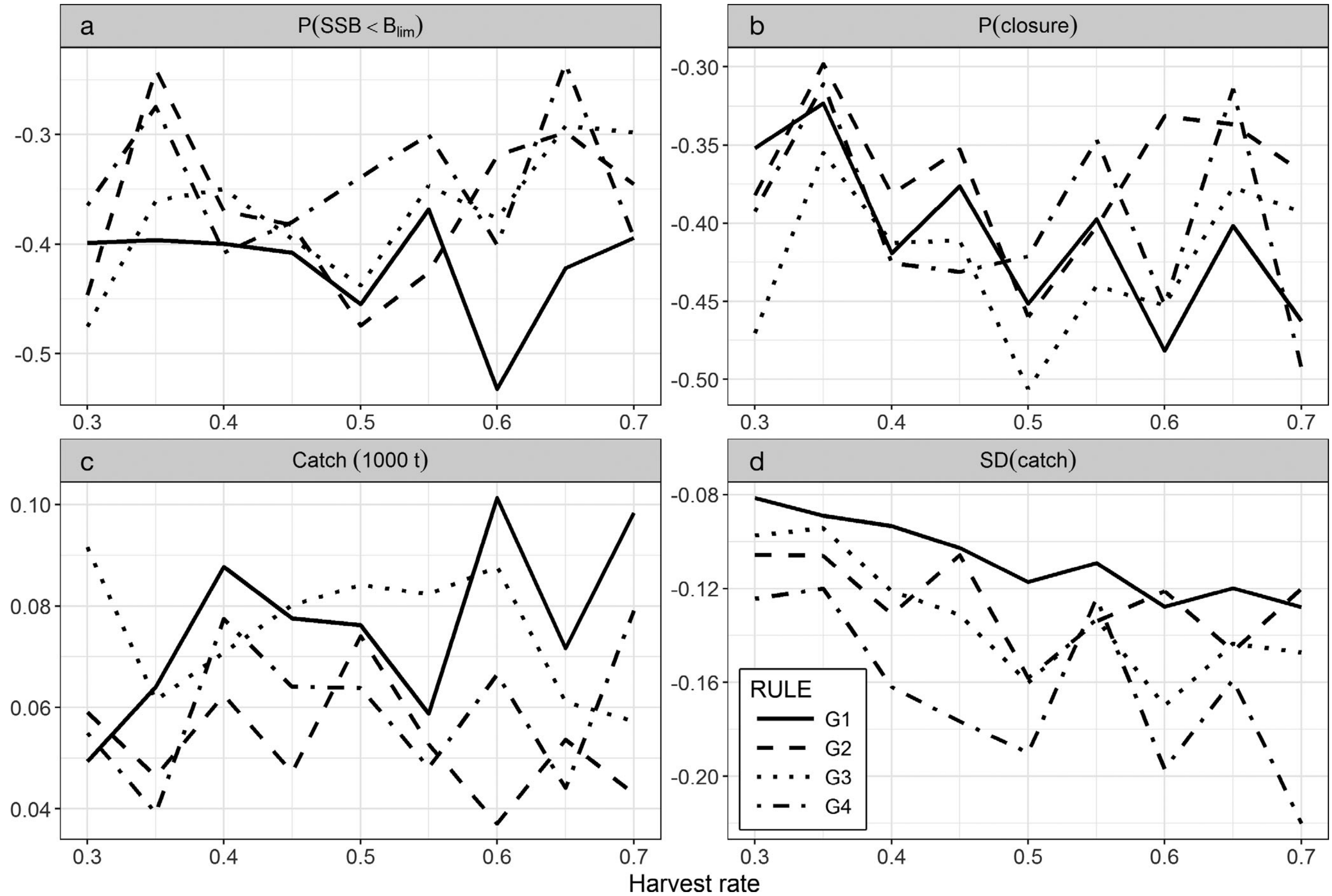

Fig. 7. Summary statistics for Rules G1, G2, G3, and G4 (see Table 1), expressed as the relative change of the indicator when changing from the July–June management calendar to the January–December one (i.e. ratios above 0 indicate that performance statistics are higher for the January–December than for the July–June calendar). (a) Probability of spawning stock biomass (SSB) being below the biomass limit below which a stock is considered to have reduced reproductive capacity (B_{lim}), (b) probability of fishery closure, (c) average catch (in 1000 t), and (d) standard deviation of the catch as a function of the harvest rate

al. (2014) asserted that substantial changes are still required to allow stock-recruitment relationship modeling and forecasting relevant for management. The inclusion of environmental indices has been devised as an alternative to improve management (Tommasi et al. 2017); nevertheless, a minimum capacity prediction is required to allow a significant improvement (De Oliveira & Butterworth 2005, De Oliveira et al. 2005). Our work showed the importance of real-time monitoring and the use of the most up-to-date information for fast-reactive management. Without any information on next year's recruitment, moving the management focus from the following year population to the in-year estimated one, allowed us to maximize the exploitation of the in-year population, while keeping the risk of SSB falling below B_{lim} in the following year at acceptable levels (STECF 2008a, Penas 2016).

The availability of a reliable recruitment index from a new fishery research survey allowed us to reduce biological risks and the probability of fishery closure for a January–December management year. Catches could be increased by 15% for the same level of allowable risks. Furthermore, the expected economic value of this new survey was positively evaluated by Prellezo (2017). Still, the benefit was not as great as expected from earlier simulation studies on the management of year *y*+1 (Pomarede et al. 2010). This was probably due to the improved management achieved by changing the management calendar in the absence of a recruitment indicator, as it allowed exploiting the in-year estimated population as much as possible by avoiding the use of any explicit short-term forecast. Another alternative, when there is no information on incoming recruitment at the time of the analysis, is setting a provisional TAC until information on incoming recruitment strength is made available. This information can be provided by (1) a survey, as is the

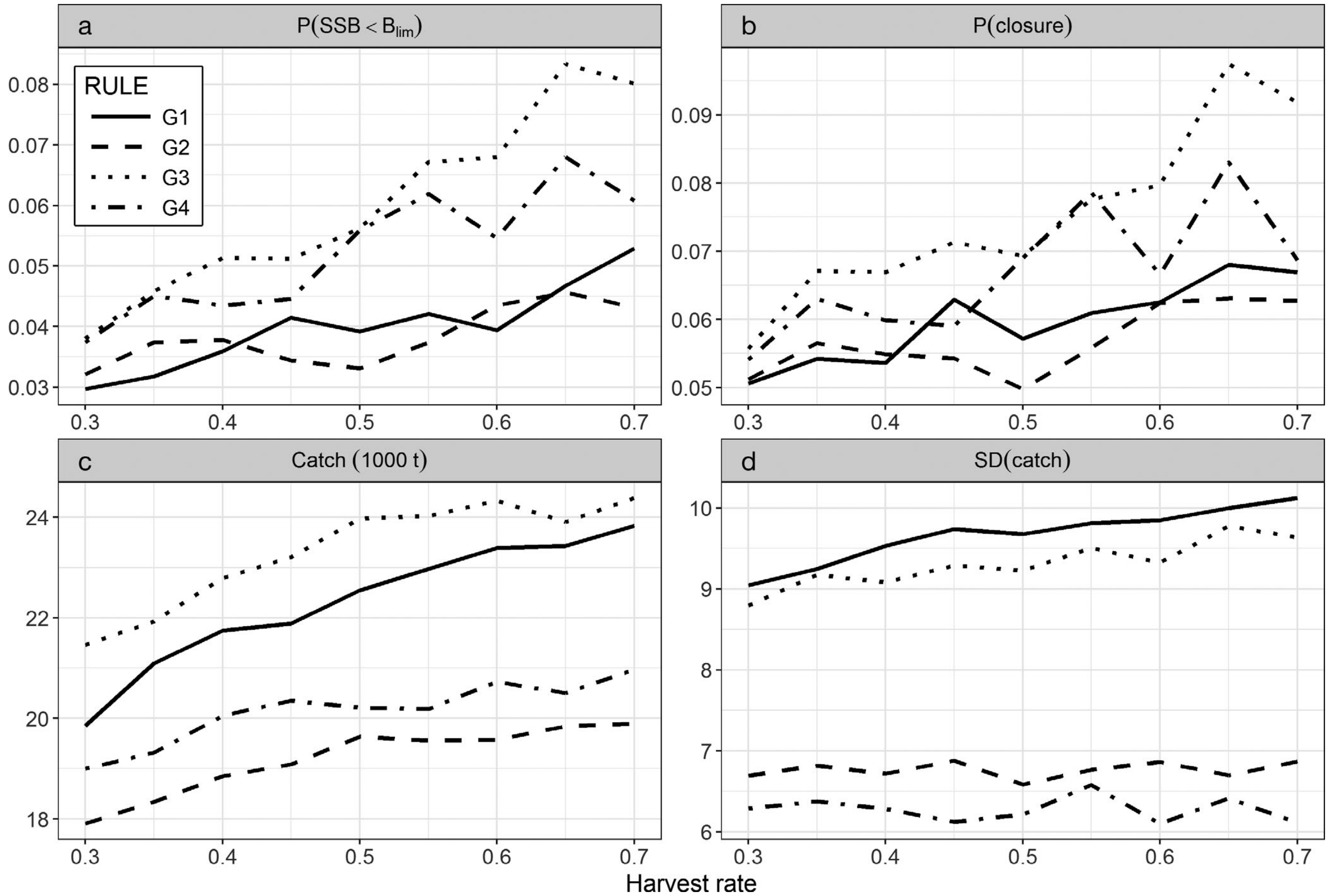

Fig. 8. Summary statistics for Rules G1, G2, G3, and G4 (see Table 1) in the January–December management calendar. (a) Probability of spawning stock biomass (SSB) being below the biomass limit below which a stock is considered to have reduced reproductive capacity (B_{lim}), (b) probability of fishery closure, (c) average catch (in 1000 t), and (d) interannual catch variation (%) as a function of the harvest rate

case for the South African anchovy (Plagányi et al. 2007) or (2) commercial fisheries, as occurs with the North Sea sandeel (Penas 2016). This possibility was also initially considered for the Bay of Biscay anchovy, but was not tested because of the lack of support from stakeholders, either politically, as it was considered too legally complex to be implemented, or by the industry, which assumed it could create inequalities among country fleets due to their marked seasonality.

The simulation results showed that, independently of the selected HCR, the mean catches determined the risk, as found in other similar cases (De Oliveira & Butterworth 2005). So for a given set of HCRs allowing similar catches/risks, the final selection of the HCRs seemed to come from the following facts: (1) the shape of the harvest (catches) across the range of potential SSBs (and the level of SSB for which maximum TAC is reached); (2) the stability of catches (although they are all highly variable); and (3) the economic performance of the HCR (which was invariantly maximized for the HCRs having a TAC_{max}). Therefore, the selection of a specific HCR depends on how to distribute the yield given the stock status. Tested HCRs have focused on exploiting a proportion of the estimated available biomass or the expected biomass (depending on the management calendar). However, a commonly used management strategy for short-lived species is what is known as the escapement strategy (ICES 2013b, Gjøsæter et al. 2015), which allows catches that would lead to a reduction of the SSB up to a certain level. When biomass is estimated to be below this escapement threshold, fishing is not allowed. The escapement threshold is often set to the biomass above which the stock is considered to have full reproductive capacity (B_{pa}) (e.g. North Sea sandeel and Norway pout) to allow a high probability of SSB being above $B_{\lim}$ (ICES 2013a). This type of rule was not tested for the Bay of Biscay anchovy, because it was considered to be infeasible for the operating fleets. This fishery appears to have limitations in market demand, and has shown a negative relation between prices and catches (STECF 2008b). Alternatively, HCRs that allowed exploiting just a fraction above a certain biomass threshold were tested (Rules A and C), but they were ultimately discarded, as other HCRs showed better performance in relation to management objectives. Fixed TAC strategies have been demonstrated to be inappropriate for managing short-lived species (Ruiz et al. 2017).

TAC constraints to limit the catches below a specific threshold (Cochrane et al. 1998, Punt et al. 2016) are usually associated with changes in the allowable catches in the previous years. For example, within ICES, a TAC variation limit of a certain percentage (usually between 15 and 25%) is applied to many stocks (Penas 2016). Moreover, the management strategy for the southern and eastern scalefish and shark fishery, in addition to a maximum TAC change of 50% (up or down), requires not changing the previous year's TAC if the expected change is <10% (Punt et al. 2016). The example in De Moor et al. (2011) includes (1) maximum and minimum TACs, but including exceptional measures when the population falls below a specified threshold, and (2) a maximum decrease from year to year, following a 2-tier system to adjust these changes during boom and bust periods, and a mid-season increase in TACs. The main aim of this constraint is to allow the fleets sustainability and permit their gradual adaptation. However, given the high variability of short-lived species, this is not justified or even sought by these fisheries. Interannual variability will invariantly happen, but setting upper catch levels will provide more stability at high levels of the resource, while accommodating market absorption capacity. In this case study, these catch constraints arise due to the capacity limitations of the fleet, supported by the fact that catches have not attained allocated quotas in several recent years (ICES 2016a), and since the fishery reopened in 2010, catches have been lower than 30 000 t. Industrial fisheries, such as the South African purse seine fishery, may be more interested in strategies that allow taking advantage of the occasional booms while not increasing the risk of falling below a $B_{\lim}$ threshold (Butterworth 2007, De Moor et al. 2011) at the expense of higher TAC variability.

One of the main findings regarding economic analysis was the confirmation of the value of the catch thresholds proposed by the stakeholders. This analysis pointed to a minimum TAC of 7000 t for a sustainable fishery and a maximum TAC of 32 000 t, which gives consistency between the simulation results and the perceptions of the fishermen. The maximum TAC is also in agreement with the catches in the period 1980–2005, before the fishery closure, when TACs were set between 30 000 and 33 000 t independently of the scientific advice. The economic analysis additionally allowed assessing the impacts by country. However, there was no feedback between biological and economic models. That is, total annual catches were estimated independently to the fleets' capacity and profitability. Therefore, more suitable methodologies should be adopted, but these require high-resolution data which are not readily available (Nielsen et al. 2018). The FLBEIA framework has implemented the functions required to incorporate the necessary improvements, but the economic information (e.g. effort, landings and price to analyse the behaviour of the fleet, effort allocation and revenues of the fleets) was not provided on time. Consequently, it was not possible to include the fleet dynamics in the OM, which would provide additional indications about the economic performance of each of the fleets involved in this fishery for the different harvesting strategies. Additionally, it would allow simulations and testing for undershooting of the TAC, which has been observed in recent years (ICES 2016a). This is of major importance for the fleets, which can be limited by their capacity and/or by the market's absorption capacity. Moreover, French and Spanish fleets should be modeled separately, including the different métiers (pelagic trawlers and purse seiners); this would allow analysis of the economic impact of the different management strategies at a lower level. TAC borrowing or banking from one year to the next (according to Article 4[2] of Regulation [EC] No 847/96) could also be analyzed in future studies. After the fishery closure, average prices seem to have suffered a structural change (Garza-Gil et al. 2011). One of the reasons for this change may be the fact that when the fishery was closed for 5 yr, it left a market niche, which may have been filled by anchovies from other places. However, this analysis has not been done, and the real causes of the price change have not been established. In any case, the economic effect of the fishery closure was not only visible during the closure, but will also continue to have effects in the medium term.

The change in the tool for conducting MSE and the adoption of FLBEIA was considered important because this tool has the potential to incorporate bio-economic feedback and at the same time admitted seasonal steps within the year. Moreover, it is presented as an R package which provides a stable framework that has been tested for different case studies (García et al. 2013, 2017, Prellezo et al. 2016, 2017, Sampedro et al. 2016). FLBEIA was modeled using half-yearly steps to study the calendar changes to set the TACs and to simulate the different fishing patterns of the fisheries by semesters.

Small pelagic species are subject to periods of low or high recruitment and productivity (Lluch-Belda et al. 1989, MacCall 1996). This forces a consideration of the possible changes in the recruitment regimes for an effective management of the stock. In the present study, low frequency variability (long periods of high or poor productivity) was properly tested, as done in De Oliveira (2006), but low recruitment regimes were modeled in 2 different ways. Initially, given its high variability and following a period of persistently low recruitments since 2002, in the work carried out for the definition of a management plan in 2008 a scenario of persistent low recruitment levels during the whole projection period was evaluated. Simulations showed that for such a low recruitment regime, biological risks would increase to levels well above 10% for harvest rates >0.2. However, in the revision phase of the management plan in 2014 after the recent recovery of recruitment levels and of the population, a short regime shift to low recruitment was considered more appropriate to test the recovery capacity for the different HCRs. For this, a short period (3 yr) of repeated recruitment failures were tested and compared among the rules. It was found that all tested HCRs could recover in <2 yr. As a reference, other small pelagic stocks which collapsed in the past required around 15–20 yr to recover (Barange et al. 2009, Petitgas et al. 2010a). However, risks for the SSB of falling below B_{lim} rose from precautionary levels (5%) up to 10%. Therefore, poor recruitment regimes could lead to an invalidation of the inferred results from the MSE testing, since recruitment was demonstrated to be the uncertainty of major relevance in determining the relative performance of the HCRs.

Besides recruitment, sensitivity to other factors was also tested. There was little sensitivity to quota sharing and therefore to the percentage of catches by semester. Other factors such as the consideration of lower CVs for the SSB estimate were not influential at all. Sensitivity to higher CVs was not considered, as a CV of 25% was considered enough to account for all of the uncertainty surrounding the stock assessment model. Due to time constraints to provide advice on the performance of the different HCRs on time, only the uncertainty sources that were considered critical were selected, disregarding others that potentially could also impact the HCRs' performance (e.g. natural mortality, maturity, growth, etc.). Therefore, future analyses should include these broader considerations, and in addition to testing them relative to the base case, the effect of their combination should also be assessed. This would be achievable in any potential future revision of the management plan (as we currently have a tested, functioning framework, which allows this wide range of analysis to be carried out), since the development of the framework is more time demanding than the running of alternative simulations. No assessment was simulated within the MP, and observation and assessment uncertainty were considered jointly by adding random noise to the values simulated in the OM. The use of this short-cut approach was motivated by the considerable time required by the Bayesian assessment model to yield an output. This, however, limited the analysis by not accounting for estimation uncertainty. Different authors have warned against the use of the short-cut approach (Butterworth 2007, ICES 2013b), but it could be considered appropriate if the approximation proposed is demonstrated to give results consistent with the assessment, as was the case here, since the assessment model has proved to provide unbiased estimates (Ibaibarriaga et al. 2011). As soon as a maximum likelihood version of the assessment model is parameterized, providing results comparable to its Bayesian counterpart, a model-based MP would be possible. In addition, the increased computational power provided by the grid and cluster computing available now will allow us to test a wider range of uncertainties and to increase the number of iterations in future analyses.

Acknowledgements. This work was carried out with the financial support of the Basque Government (Agriculture and Fisheries Department), the European Commission under projects 'Comparative Evaluations of Innovative Solutions in European fisheries management' (CEVIS, contract no. 022686) and 'Understanding the mechanisms of stock recovery' (UNCOVER, contract no. 022717) and under a request for services for the Bay of Biscay anchovy (commitment no. SI2.676322) and the European Fisheries Fund under Denafit and Kudea projects (grant agreement nos. 351BI20100057 and 04201200395, respectively). This publication does not necessarily reflect the views of the funding parties and in no way anticipates the Commission's future policy in this area. The manuscript was greatly improved following input from various anonymous reviewers. This is publication number 862 from the Marine Research Division of AZTI.

LITERATURE CITED

Andrés M, Prellezo R (2012) Measuring the adaptability of fleet segments to a fishing ban: the case of the Bay of Biscay anchovy fishery. Aquat Living Resour 25: 205–214

Aranda M, Motos L (2006) Management strategy evaluation (MSE) and management procedure (MP) implementations in practice: a review of constraints, roles and solutions. Dev Aquacult Fish Sci 36:409–421

Barange MA, Bernal M, Cergole MC, Cubillos LA and others (2009) Current trend in the assessment and management of stocks. In: Checkley D, Roy C, Alheit J, Oozeki Y (eds) Climate change and small pelagic fish. Cambridge University Press, Cambridge, p 191–255

Bastardie F, Vinther M, Nielsen JR, Ulrich C, Paulsen MS (2010) Stock-based vs. fleet-based evaluation of the multi-annual management plan for the cod stocks in the Baltic Sea. Fish Res 101:188–202

Boyra G (2017) Acoustic abundance of juvenile anchovy for predicting recruitment. PhD dissertation, Universidad del País Vasco / Euskal Herriko Unibertsitatea, San Sebastian

Boyra G (in press) Anchovy juvenile acoustic surveys JUVENA 2003-2012. In: Massé J, Uriarte A, Angelico MM, Carrera P (eds) ICES Cooperative Research Report (CRR), Book 332. ICES, Copenhagen

Boyra G, Martinez U, Cotano U, Santos M, Irigoien X, Uriarte A (2013) Acoustic surveys for juvenile anchovy in the Bay of Biscay: abundance estimate as an indicator of the next year's recruitment and spatial distribution patterns. ICES J Mar Sci 70:1354–1368

Butterworth DS (2007) Why a management procedure approach? Some positives and negatives. ICES J Mar Sci 64:613–617

Butterworth DS, Bentley N, De Oliveira JAA, Donovan GP and others (2010) Purported flaws in management strategy evaluation: basic problems or misinterpretations? ICES J Mar Sci 67:567–574

Cochrane KL, Butterworth DS, De Oliveira JAA, Roel B (1998) Management procedures in a fishery based on highly variable stocks and with conflicting objectives: experiences in the South African pelagic fishery. Rev Fish Biol Fish 8:177–214

Csirke J (1988) Small shoaling pelagic fish stocks. In: Gulland JA (ed) Fish population dynamics. John Wiley & Sons, New York, NY, p 271–302

De Moor CL, Butterworth DS, De Oliveira JAA (2011) Is the management procedure approach equipped to handle short-lived pelagic species with their boom and bust dynamics? The case of the South African fishery for sardine and anchovy. ICES J Mar Sci 68:2075–2085

De Oliveira JAA (2006) Long-term harvest strategies for small pelagic fisheries under regime shifts: the South African pilchard-anchovy fishery. In: Hannesson R, Barange M, Herrick SFJ (eds) Climate change and economics of the world's fisheries: examples of small pelagic fish stocks. Edward Elgar publishing, Cheltenham, p 151–204

De Oliveira JAA, Butterworth DS (2004) Developing and refining a joint management procedure for the multispecies South African pelagic fishery. ICES J Mar Sci 61: 1432–1442

De Oliveira JAA, Butterworth DS (2005) Limits to the use of environmental indices to reduce risk and/or increase yield in the South African anchovy fishery. Afr J Mar Sci 27:191–203

De Oliveira JAA, Uriarte A, Roel BA (2005) Potential improvements in the management of Bay of Biscay anchovy by incorporating environmental indices as recruitment predictors. Fish Res 75:2–14

Francis RICC, Shotton R (1997) 'Risk' in fisheries management: a review. Can J Fish Aquat Sci 54:1699–1715

Fréon P, Misund OA (1999) Dynamics of pelagic fish distribution and behaviour: effects of fisheries and stock assessment. Fishing News Books, Oxford

García D, Urtizberea A, Diez G, Gil J, Marchal P (2013) Bioeconomic management strategy evaluation of deepwater stocks using the FLBEIA model. Aquat Living Resour 26: 365–379

García D, Sánchez S, Prellezo R, Urtizberea A, Andrés M (2017) FLBEIA: a simulation model to conduct bio-economic evaluation of fisheries management strategies. SoftwareX 6:141–147

Garza-Gil MD, Varela-Lafuente MM, Caballero-Miguez G, Álvarez-Díaz M (2011) Analysing the profitability of the Spanish fleet after the anchovy moratorium using bootstrap techniques. Ecol Model 70:1154–1161

Gjøsæter H, Bogstad B, Tjelmeland S, Subbey S (2015) A retrospective evaluation of the Barents Sea capelin management advice. Mar Biol Res 11:135–143

Goodman D, Mangel M, Parkes G, Quinn T, Restrepo V, Smith T, Stokes K (2002) Scientific review of the harvest strategy currently used in the BSAI and GOA groundfish fishery management plans. North Pacific Fishery Management Council, Anchorage, AK

Gunderson DR (1993) Surveys of fisheries resources. John Wiley & Sons, New York, NY

Ibaibarriaga L, Fernandez C, Uriarte A, Roel BA (2008) A two-stage biomass dynamic model for Bay of Biscay anchovy: a Bayesian approach. ICES J Mar Sci 65: 191–205

Ibaibarriaga L, Fernandez C, Uriarte A (2011) Gaining information from commercial catch for a Bayesian two-stage biomass dynamic model: application to Bay of Biscay anchovy. ICES J Mar Sci 68:1435–1446

ICES (International Council for the Exploration of the Sea) (2006) Report of the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy (WGMHSA). Galway, Ireland. ICES CM 2006/ACFM:36. ICES, Copenhagen

ICES (2007) Report of the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy (WGMHSA). ICES Headquarters. ICES CM 2007/ACFM:31. ICES, Copenhagen

ICES (2013a) Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES, Bilbao, Spain. ICES CM 2013/ACOM:16. ICES, Copenhagen

ICES (2013b) Report of the Workshop on Guidelines for Management Strategy Evaluations (WKGMSE). ICES HQ, Copenhagen, Denmark. ICES CM 2013/ACOM:39. ICES, Copenhagen

ICES (2014a) Report of the Benchmark Workshop on Pelagic Stocks (WKPELA). ICES, Copenhagen, Denmark. ICES CM 2014/ACOM:43. ICES, Copenhagen

ICES (2014b) Report of the Working Group on Southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES, Bilbao, Spain. ICES CM 2013/ACOM:16. ICES, Copenhagen

ICES (2016a) Anchovy (*Engraulis encrasicolus*) in Subarea 8 (Bay of Biscay). ICES advice on fishing opportunities, catch, and effort. Bay of Biscay and the Iberian Coast and the Oceanic Northeast Atlantic ecoregions, Book 7. ICES, Copenhagen

ICES (2016b) Report of the Working Group on southern Horse Mackerel, Anchovy and Sardine (WGHANSA). ICES, Lorient, France. ICES CM 2016/ACOM:17. ICES, Copenhagen

Irigoien X, Fiksen Ø, Cotano U, Uriarte A and others (2007) Could Biscay Bay anchovy recruit through a spatial loophole? Prog Oceanogr 74:132–148

IWC (International Whaling Commission) (1999) Report of the Scientific Committee, Annex N. The revised management procedure (RMP) for baleen whales. J Cetacean Res Manag 1(Suppl):251–258

Kell LT, Mosqueira I, Grosjean P, Fromentin JM and others (2007) FLR: an open-source framework for the evaluation and development of management strategies. ICES J Mar Sci 64:640–646

Lassalle G, Lobry J, Le Loc'h F, Bustamante P and others (2011) Lower trophic levels and detrital biomass control the Bay of Biscay continental shelf food web: implications for ecosystem management. Prog Oceanogr 91: 561–575

Lluch-Belda D, Crawford RJM, Kawasaki T, MacCall AD, Parrish RH, Schwartzlose RA, Smith PE (1989) Worldwide fluctuations of sardine and anchovy stocks: the regime problem. S Afr J Mar Sci 8:195–205

Lluch-Belda D, Schwartzlose RA, Serra R, Parrish R, Kawasaki T, Hedgecock D, Crawford RJM (1992) Sardine and anchovy regime fluctuations of abundance in four regions of the world oceans: a workshop report. Fish Oceanogr 1:339–347

MacCall AD (1996) Patterns of low-frequency variability in fish populations of the California current. Calif Coop Ocean Fish Invest Rep 37:100–110

Massé J, Duhamel E, Petitgas P, Doray M, Huret M (in press) Spring acoustic surveys: Pelgas survey. In: Massé J, Uriarte A, Angelico MM, Carrera P (eds) ICES Cooperative Research Report (CRR), Book 332. ICES, Copenhagen

Nielsen JR, Thunberg E, Holland DS, Schmidt JO and others (2018) Integrated ecological-economic fisheries models — evaluation, review and challenges for implementation. Fish Fish 19:1–29

Penas E (2016) The conservation policy. In: Penas E (ed) The common fisheries policy: the quest for sustainability. Wiley Blackwell, Chichester, p 49–98

Petitgas P, Secor DH, McQuinn I, Huse G, Lo N (2010a) Stock collapses and their recovery: mechanisms that establish and maintain life-cycle closure in space and time. ICES J Mar Sci 67:1841–1848

Petitgas P, Uriarte A, Nogueira E, Massé J, Cotano U (2010b) Bay of Biscay anchovy. In: Petitgas P (ed) Life cycle spatial patterns of small pelagic fish in the Northeast Atlantic. ICES Cooperative Research Report (CRR), Book 306. ICES, Copenhagen, p 40–44

Petitgas P, Rijnsdorp AD, Dickey-Collas M, Engelhard GH and others (2013) Impacts of climate change on the complex life cycles of fish. Fish Oceanogr 22:121–139

Plagányi ÉE, Rademeyer RA, Butterworth DS, Cunningham CL, Johnston SJ (2007) Making management procedures operational—innovations implemented in South Africa. ICES J Mar Sci 64:626–632

Pomarede M, Hillary R, Ibaibarriaga L, Bogaards J, Apostolaki P (2010) Evaluating the performance of survey-based operational management procedures. Aquat Living Resour 23:77–94

Preciado I, Velasco F, Olaso I (2008) The role of pelagic fish as forage for the demersal fish community in the southern Bay of Biscay. J Mar Syst 72:407–417

Prellezo R (2017) Expected economic value of the information provided by fishery research surveys. Fish Res 190: 95–102

Prellezo R, Carmona I, García D (2016) The bad, the good and the very good of the landing obligation implementation in the Bay of Biscay: a case study of Basque trawlers. Fish Res 181:172–185

Prellezo R, Carmona I, García D, Arregi L, Ruiz J, Onandia I (2017) Bioeconomic assessment of a change in fishing gear selectivity: the case of a single-species fleet affected by the landing obligation. Sci Mar 81:371–380

Punt AE, Butterworth DS, de Moor CL, De Oliveira JAA, Haddon M (2016) Management strategy evaluation: best practices. Fish Fish 17:303–334

RCoreTeam (2015) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Refsgaard JC, van der Sluijs JP, Højberg AL, Vanrolleghem PA (2007) Uncertainty in the environmental modelling process — a framework and guidance. Environ Model Softw 22:1543–1556

Ruiz J, Rincón MM, Castilla D, Ramos F, del Hoyo JJG (2017) Biological and economic vulnerabilities of fixed TACs in small pelagics: an analysis of the European anchovy (*Engraulis encrasicolus*) in the Gulf of Cádiz. Mar Policy 78:171–180

Sainsbury KJ, Punt AE, Smith ADM (2000) Design of operational management strategies for achieving fishery ecosystem objectives. ICES J Mar Sci 57:731–741

Sampedro P, Prellezo R, García D, Da-Rocha JM and others (2016) To shape or to be shaped: engaging stakeholders in fishery management advice. ICES J Mar Sci 74: 487–498

Santos M, Uriarte A, Boyra G, Ibaibarriaga L (in press) Anchovy DEPM surveys 2003–2012 in the Bay of Biscay (subarea VIII) BIOMAN. In: Massé J, Uriarte A, Angelico MM, Carrera P (eds) ICES Cooperative Research Report (CRR), Book 332. ICES, Copenhagen

Schaefer MB (1954) Some aspects of the dynamics of populations important to the management of commercial marine fisheries. Inter-Am Trop Tuna Comm Bull 1:27–56

Smith ADM, Sainsbury KJ, Stevens RA (1999) Implementing effective fisheries-management systems — management strategy evaluation and the Australian partnership approach. ICES J Mar Sci 56:967–979

STECF (Scientific, Technical and Economic Committee for Fisheries) (2008a) Report of the meeting to inform the Commission on a long-term management plan for the stock of anchovy in the Bay of Biscay (ICES Sub-area VIII). Hamburg, April 14–18, 2008. STECF-SGRST, Hamburg

STECF (2008b) Working Group Report on the long term management of Bay of Biscay anchovy. San Sebastian, June 2-6, 2008. STECF-SGBRE, Brussels

STECF (2009) 30th plenary meeting report of the Scientific, Technical and Economic Committee for Fisheries (PLEN-09-01). European Communities, Luxembourg

STECF (2013) Advice on the Harvest Control Rule and Evaluation of the Anchovy Plan COM(2009) 399 Final

(STECF-13-24). EUR 26326 EN, JRC 86109. Publications Office of the European Union, Luxembourg

STECF (2014) Evaluation/scoping of management plans – data analysis for support of the impact assessment for the management plan of Bay of Biscay anchovy (COM(2009)399 final). (STECF-14-05). EUR 26611 EN, JRC 89792. Publications Office of the European Union, Luxembourg

STECF (2015) Multiannual management plans SWW and NWW (STECF-15-04 & 09). EUR 27406 EN, JRC 96964. Publications Office of the European Union, Luxembourg

Subbey S, Devine JA, Schaarschmidt U, Nash RDM (2014) Modelling and forecasting stock-recruitment: current and future perspectives. ICES J Mar Sci 71:2307–2322

Tommasi D, Stock CA, Pegion K, Vecchi GA, Methot RD, Alexander MA, Checkley DM Jr (2017) Improved management of small pelagic fisheries through seasonal climate prediction. Ecol Appl 27:378–388

Tonkin ZD, Ramsey DSL, King AJ (2008) Larval and juvenile Australian smelt *Retropinna semoni* somatic and otolith growth parameters — implications for growth interpretation of wild fish. Ecol Freshw Fish 17:489–494

Uriarte A (2005) Assessment of the Bay of Biscay anchovy by means of a seasonal separable VPA. ICES CM 2005/ACFM:08 (WD for the ICES WGMHSA 2005). ICES, Copenhagen

Uriarte A, Prouzet P, Villamor B (1996) Bay of Biscay and Ibero Atlantic anchovy populations and their fisheries. Sci Mar 60(Suppl 2):237–255

Editorial responsibility: David G. Reid (Guest Editor), Galway, Ireland

Submitted: September 18, 2017; Accepted: April 17, 2018
Proofs received from author(s): June 15, 2018