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Lessons learnt on the management of short-lived fish from the Bay of Biscay anchovy case study: Satisfying fishery needs and sustainability under recruitment uncertainty

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ABSTRACT

This paper summarizes the lessons learnt for the management of small pelagic fish from the case study of managing the international fishery on the Bay of Biscay anchovy. A constant catch regime ended up with a fishery crash and closure (2005–2009) after a series of recruitment failures. Precautionary advices had been disregarded due to their inability to predict the size of the population during the first half of the year when the major fishery takes place. The crash triggered the EU to develop a long-term management plan in 2008. In the absence of a recruitment indicator, biological risk was minimized through a close coupling between assessment, advice and management, changing the management year to start just after the spring surveys on adults. A major improvement arrived in 2014 by the incorporation of an early recruitment indicator from an autumn acoustic survey on juveniles. This allowed additional exploitation of the resource at similar risk levels. Accordingly, TACs are nowadays set after the recruit survey on a management calendar basis. The interactive collaboration between fishers, scientists, and managers allowed inclusion of the stakeholders' preferences for a biomass-based catch bounded harvest strategy suitable for these valuable fisheries. This strategy allows catches between a minimum and maximum TAC level, to account for an economically viable minimum activity when approaching a minimum biomass threshold level, and for the limited market absorption capacity when exceeding an upper biomass threshold level, respectively. Such strategy was adopted by consensus and supposed a successful participatory process in fishery management.

1. Introduction

Managing fisheries on small pelagic fish (SPF) is challenging because these are highly variable resources due to their short life span and strong dependence on yearly recruitments [8,93,110]. Furthermore, SPF may show long cyclic trends in abundance as a result of environmental and oceanographic factors [1,69] which amplify the risks of overcapacity [40,41]. The fluctuations in abundance, coupled with the shoaling behavior of the species, makes them highly vulnerable to fishing, particularly at low stock sizes, increasing the risk of overfishing and depletion [37,77,93,96]. For these reasons, the history of management of these populations shows several examples of collapses [91,94,95], including among others the Peruvian anchoveta [6,87], the Pacific sardine [50,101], and the North Sea herring [32]. Management of SPF needs therefore to be adaptative to the fluctuations in productivity and abundance of these resources to minimize the risks of collapses [7,8, 110].

Adaptative management of SPF can be achieved by understanding

Abbreviations: HCR, Harvest Control Rule; SPF, Small Pelagic Fish.

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the causes of such variability and incorporating that information into the harvest control rules [49], as implemented for the Pacific sardine [99], however this is feasible in very few cases [72,121]. More commonly, adaptative management is achieved through a direct surveying of the adults and, whenever possible, of recruits (as main indicators of productivity and drivers of next coming abundance) [8,135]. According to the uncertainty of the direct estimates and to the speed in translating the estimates into management actions, the harvest strategy will have to be more or less conservative to cope with the uncertainties on the current and future biomasses: Timely use of the information can lead to empirical harvest rules (based on the output of the surveys) as it is the case of the management of anchovy and sardines in South Africa [26,27] which may respond to escapement policies, aiming at maximizing catches whenever the Spawning biomass at the end of the fishery remains above a threshold escapement limit (that warrants the normal productivity of the stock), as for the Barents sea capelin [46], or the Peruvian anchoveta [7,68]. However, if survey precision is poor, or if its use is lagged by 1 year, without a recruitment indicator to forecast the managed population, then the harvest strategy will have to be more conservative and precautionary [13,31,82,110]. For instance, management of Chilean sardine and anchovy [122] is precautionary by selecting a fishing mortality target corresponding to 60% spawning biomass per recruit; and for the management of the North Sea Sprat the fishing mortality corresponding to the escapement policy is capped by a maximum value to account for the unknown level of recruitment [102]. The adoption of the Ecosystem based approach for the management of fisheries usually leads to more conservative approaches for SPF, with lower fishing targets or higher minimum biomass threshold levels, to reconcile the fishery objectives with the preservation of SPF role as prey and energy transfer from low to high trophic levels in the ecosystem [24,93,112,124]. In addition, the inclusion of economic considerations in the management objectives favors usually more conservative approaches as well [47,48].

The management of fishery of the Bay of Biscay anchovy (*Engraulis encrasicolus*) exemplifies a continuous effort to optimize the direct monitoring system (on adults and recruits), the advice and the management framework to achieve and efficient and timely use of the survey estimates for an improved management. This process led to the formulation of a management plan incorporating both biological and economic considerations, with the active participation of stakeholders, when the fishery was challenged with a stock collapse between 2005 and 2009 [4,91,95].

This anchovy stock has been exploited by Spanish and French fishers for more than a century [67,70,92]. Catches peaked in the sixties (Fig. 1), but scientific monitoring of catches started in the seventies [131] and regular monitoring with surveys began in the late eighties [79,108]. Since the mid-nineties, the International Council for the Exploration of the Sea (ICES) assesses the stock annually. Given the inability to forecast the managed population in the absence of an early recruitment indicator, ICES started providing management advice based on the precautionary approach (PA) [38,127,128]. However, management was based on a constant total allowable catch (TAC) of 30,000 or 33,000 t, regardless of ICES advice. The TACs supposed no major conditioning of the fishery, with catches sometimes exceeding and others not reaching the TAC. Therefore, in practice, this was an open access fishery, with two national fleets competing for the same resource and market [30,74]. The collapse and closure of the fishery in 2005 triggered the European Commission (EC) to develop a long-term Management Plan (MP) [19].

Multiannual Management plans have become one of the main tools of the European Common Fisheries Policy (CFP) to achieve the objectives of biological sustainability of the resources and of economic and social sustainability of the fishing fleets [16,88]. They contain the management objectives and the specific instruments for achieving them, e.g., harvest control rules (HCR), fishing effort restrictions, control, and complementary enforcement measures. In contrast to the traditional management approach, based on undertaking annual tactical decisions, management plans are tested by simulation before their implementation to ensure that they fulfill the long-term objectives while being robust to the plausible range of uncertainties [12,99]. This testing is known as the management strategy evaluation (MSE) approach [71,113]. In general, the process of developing a MP is usually lengthy, but once in place it reduces political haggling [12,88]. Participation of the decision makers and stakeholders (particularly fishers) is required in all stages of the development of the plan to properly address the management and fishing needs of the concerned fishery [26,99]. The 2002 reform of the CFP [16] incorporated the creation of Advisory Councils (ACs) to facilitate the participation of the stakeholders and increase the transparency of the management process. In these ACs, fishers, non-governmental organizations, and other stakeholders meet to formulate their views on fishery matters for the EC.

The purpose of this paper is to summarize the lessons learnt from the Bay of Biscay anchovy case study (hereafter BoB anchovy) about the key elements contributing to a successful management of small pelagic fish, putting special emphasis on the different management strategies developed according to the degree of knowledge on the incoming recruitment. First, we introduce the case study and describe the fishery. Then, we describe chronologically the main management cycles of this

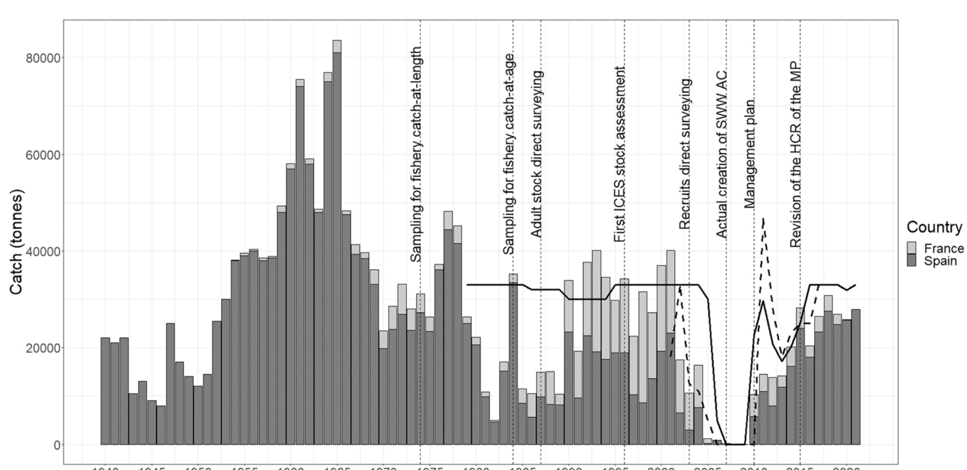

Fig. 1. Series of anchovy catches by country (bars) in the Bay of Biscay versus advice provided by ICES (dashed line) and TACs set up by managers (solid line), with notations on the main advances in the scientific monitoring and management. M.P. means Management Plan and SWWAC means South Western Waters Advisory Council.

stock: from the tactical annual advice and the first MP supported by a monitoring system on adults, to the latest HCR that incorporated a recruitment indicator. We end up with a discussion on the selected management strategies and on the benefits of having a participative process, when defining these strategies, as the best way to accommodate stakeholders' expectations in the context of long-term sustainability.

2. Bay of Biscay anchovy fishery

The BoB anchovy is a short-lived species rarely living more than three years [92,132] and becoming fully mature at age one [83]. On average, about 60% of the spawning stock biomass (SSB) (minimum 17% - maximum 95%) and of the total annual catch (25–87%) is sustained by the one-year-old recruits [67]. Catches at age 1 in weight account for about 52% and 76% in the first and second half of the year catches, respectively.

The development of this fishery during the first half of the twentieth century was linked to the opening of canning industries in the northern part of Spain and the modernization of the fleets [78]. Nowadays, a significant part of the production still goes for canning, but the majority goes for fresh consumption. Spain is the main importer of fresh anchovies in Europe [84]. As such, this is a valuable resource of rather high price per landed kg, about 2 €/kg [95], compared to other SPF around the world subject to reduction fisheries [81]. The decrease of catches between the sixties and the mid-eighties (with occasional sharp decreases, as in 1968–70, 1980–82 or 1984–86 (Fig. 1), the shrinkage of the anchovy distribution along the northern coast of Spain [70], and the shelf regulatory measures adopted in the fishery, halved the Spanish purse seine fleet [131], which was up to then the major component of the international fleet. During the eighties, the French fishery expanded with the introduction of pelagic trawlers, and during the nineties the two countries' catches became of similar magnitude, with an average combined landing of 30,200 t between 1990 and 2000. Even though Spain owns 90% of fishing rights, the increase in the French fishery was mainly achieved due to bilateral agreements between France and Spain [5,74]. At the beginning of this century, the population and the catches declined due to repeated failures of recruitment [57,58]. Subsequently the fishery crashed in 2005 and 2006, leading to a closure of the fishery until 2010.

Spanish and French fleets carry out seasonal fisheries on anchovy mainly in spring and summer-autumn respectively (Fig. 2). The Spanish fleet consists of purse seiners, while French boats are mostly pair trawlers, along a few French purse seiners. The anchovy fishery closure put in troubles to the national fleets [4,44,95,103,116,133]. Before the closure of the fishery, about 200 Spanish purse seiners operated in the anchovy fishery [134]; however, since the reopening in 2010, the boats with fishing licenses have been reduced to about 150–175 [65]. The number of French pelagic trawlers involved in the fishery was sharply reduced, passing from about 72 vessels in 2004 to around 20 (ten pairs of pelagic trawlers) in recent years, while the French purse seiner fleet remained basically unchanged at around 30 boats [65].

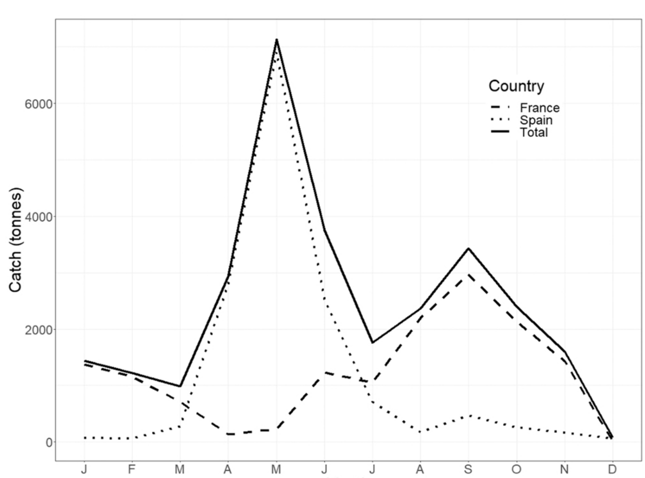

Fig. 2. Mean anchovy monthly catches (in tons) before the fishery closure (1992–2004). The sequential seasonal nature of the Spanish and French fisheries is evidenced.

3. Monitoring and advice prior to the collapse of the fishery: Short-term advice with unknown recruitment based on the precautionary approach

Before the fishery collapse, two spring surveys on adults were the only fishery-independent inputs for the assessment: an acoustic survey [34,79,80] and a Daily Egg Production Method (DEPM) survey [109, 114]. Both were carried out in May and provided indices of the adult biomass (ages 1 +) and the population age structure. The stock assessment was carried out yearly in September by ICES using the integrated catch at age analysis -ICA- model [86], which produced population estimates up to the interim year (Y), including the latest spring survey results of the year Y [58]. In the absence of any clear stock recruitment relationship, B_{lim}, the minimum spawning biomass below which recruitment could be impaired, was set at the historical minimum SSB estimate of 21,000 t and B_{pa}, a precautionary buffer level above B_{lim}, was set at 33,000 t, to guarantee that if the stock would be assessed at B_{pa} it would actually be above B_{lim} taking into account assessment uncertainty and natural variability [56].

In the nineties, as no indication of incoming recruitment was available, ICES did not provide any recommendation on catch levels. Certainly, an assessment including catches and the spring surveys of the age 1 + biomass until the interim year (Y), can only be able to inform the biomass of ages 2 + in the management year (Y+1) that account, on average, only 40% of the biomass and about 37% of catches (Fig. 3a). Alternatively, ICES suggested minimizing fishing mortality on juveniles by closing fishing areas with a high abundance of age-1 anchovies [54, 75]. Managers simply kept the traditional fixed TAC, around 30,000–33, 000 t.

Between 2000 and 2004, ICES proposed a two-stage advice on anchovy catches for the management year (Y+1) to implement the precautionary approach (PA). This implied an initial TAC advice to start the fishery, aimed at keeping the stock around B_{pa}, or above, under a poor recruitment scenario, and a revision in the middle of the year, after the spring surveys would have produced estimates of the population and realized recruitment at age 1 [55]. The TAC was estimated by a deterministic short-term forecast using the assessment outputs and hence risk of falling below B_{lim} was not directly assessed, but was deemed low by using B_{pa} as minimum spawning biomass target. This two-stage PA management attempted to minimise the loss of fishing opportunities associated with the cautionary assumption of recruitment while leading to a safer praxis than the constant TAC approach formerly applied. It implied, however, that most of the catches — those taken during the first half of the year (about 60%) — would be governed under the precautionary phase, which in practice implied a loss of catch opportunities to account for the unknown level of recruits. In addition, this two stage PA management affected the two countries differently: Spain, which obtains 87% of its catches in the first half of the year, would be governed by the conservative phase of the two-stage PA, while France, obtaining 67% of its catches during the second half of the year, would be mainly governed by the revised (more precise) TAC advice for the second half of the year (Fig. 2). As ICES' recommendation required the modification of ordinary European Union's (EU) management procedures based on annual TACs, and given the unbalanced implications for the national fleets, such approach was not implemented. Therefore, BoB anchovy continued to be managed with a fixed TAC around 33,000 t until the crash of the fishery in 2005. If the two-stage PA would have been applied, the stock would have been kept above B_{lim} in the period 2000–2004 (but not in 2005 as the recruitment was sharply reduced well

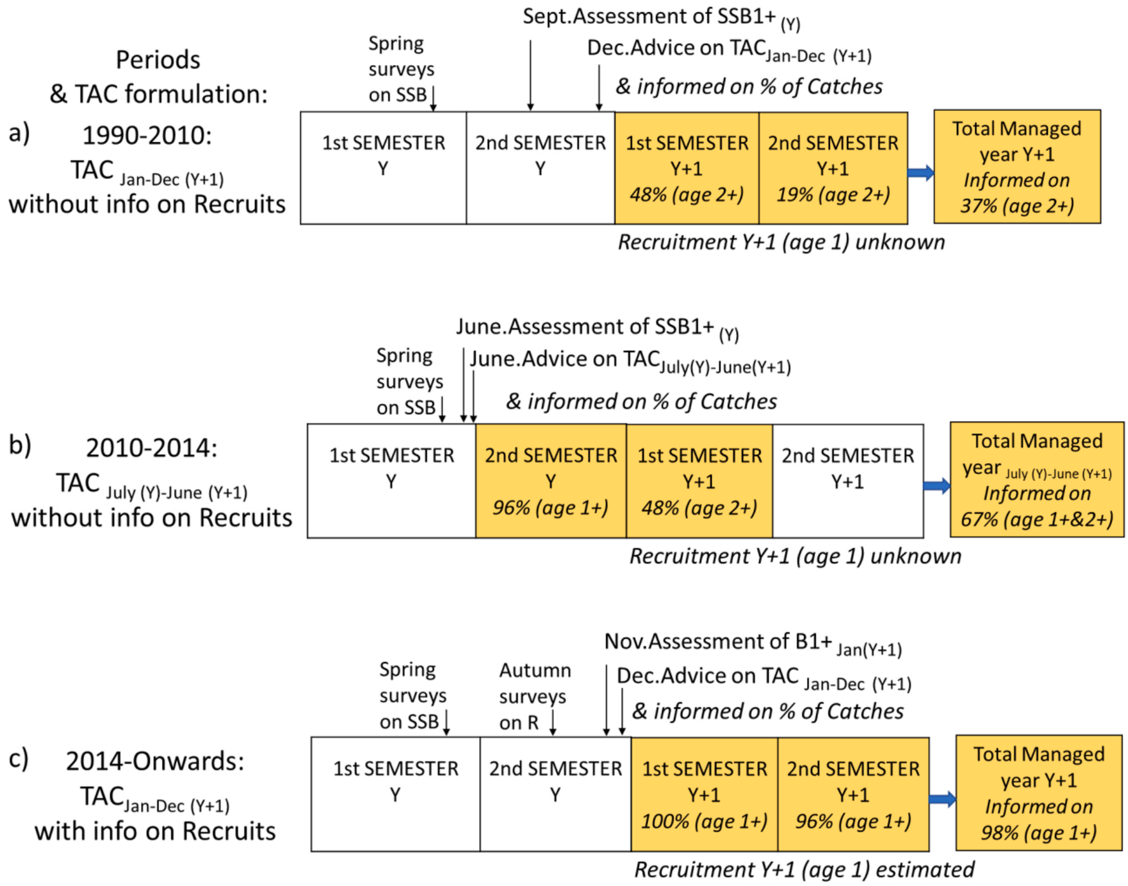

Fig. 3. Conceptual diagram of monitoring and assessment procedure by semesters (boxes in white) and management years (boxes in color) essayed in time for the Bay of Biscay anchovy fishery, 1990-2010 (a), 2010-2014 (b), and since 2014 (c), and implications in terms of the fraction (%) of the managed catch for which the advice was informed by surveys' observations (in cursive). We use the word semester to refer to half of the calendar year (i.e., by 1st semester we refer to January to June and by 2nd semester we refer to July to December).

below all previous assessed values), and it would have implied a reduction of fishing mortality because the reduction during the first half of the year (under the PA phase) would have not been compensated by a parallel increase during the second half of the year given the seasonality of the fleets.

4. Assessment and advice during the fishery closure

In 2005, after a series of consecutive recruitment failures, the anchovy fishery crashed. At that time, the assessment of anchovy changed to a Bayesian biomass-based model [52,58], which produced posterior distribution of the spawning biomass in the interim year (Y). This allowed probabilistic projections of the population to be made and the likelihood of falling below B_{lim} in the management year (Y+1) to be computed conditioned to an allowable level of catches and a recruitment scenario [52]. During the closure, a scenario of poor recruitment was selected as a mixture of posterior recruitment distributions since 2002, when repeated failures of recruitment had started [60]. During all this period, any fishery under such poor recruitment scenario led invariably to a probability above 10% of falling below B_{lim} in the management year (Y+1) and a recommendation of keeping the fishery closed was always passed to managers. This was also the case for the advice provided in 2009 for 2010. However, the fishery was reopened in 2010 with a provisional TAC of 7000 t upon a direct request of member states, because an autumn acoustic survey on juveniles (age 0), from a series which had started in 2003 [10], estimated the highest recruitment in its series (EU Council and Commission Statements 5032/10; [61]; Fig. 8). The use of such information was considered premature by part of the concerned scientific community, but managers opened the fishery disregarding ICES advice.

During the fishery closure, the population was assessed above B_{lim} in some years (Fig. 4). However, the condition for reopening (achieving

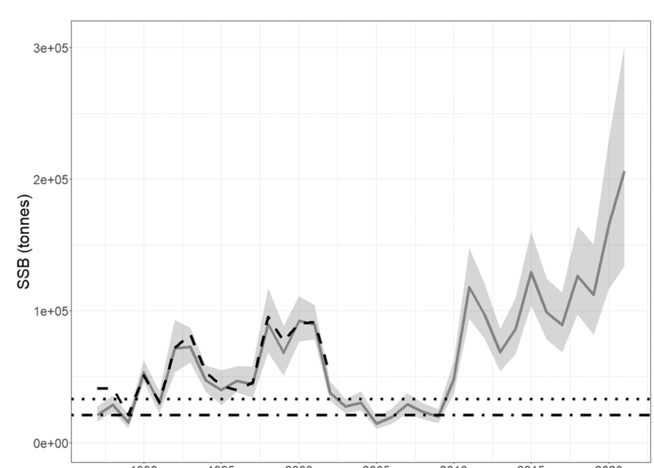

Fig. 4. Historical assessment of anchovy spawning biomass and biological reference points. The dashed line corresponds to the 2003 ICA assessment with B_{lim} (dashed and dotted line) and B_{pa} (dotted line) values superimposed (horizontal lines) ([56]b). The black line is the Bayesian biomass-based model estimates of historical series of anchovy SSB (shading covers the 90% posterior probability intervals) (as produced by ICES in 2021) [66].

more than 95% certainty of being above B_{lim} in the management year (Y+1) assuming a poor recruitment level) was not fulfilled. Therefore, the uncertain expectation on the stock status in the following year (with the assumption of poor recruitment) conditioned the realization of fishing in the interim year (Y). This was understandable for the critical situation of the stock in that period, but triggered the debate on the conditions for reopening the fishery [59]. From another perspective, the question was whether, given the lack of an early indication of recruitment, the advice should be given for the following year. A potential improvement could arise if information obtained from the spring surveys on adults were used as soon as available to give advice on the management of the fishery in the same interim year. If the assessment could be produced in June of the interim year, the management calendar could be set from July Y to June Y+ 1 to include the exploitation of the realized level of recruitment at age 1 in year Y (Fig. 3b). With the survey system on adults B1 + (biomass of ages 1 and older) in year Y, advice for year Y+1 is only informed in relation to survivors at age 2 + (B2 +), accounting for only about 37% of catches (median between 1990 and 2004), while if the advice is given for the management year from July Y to June Y+1, the advice is informed by the B1 + in the second half of year Y and by the survivors B2 + of the first half of year Y+1, comprising about 67% of the catches of such annual period. Hence, the unknown fraction (subject to assumptions) in the catch advice would be almost halved. An additional advantage of the new management calendar (July–June), in comparison with the two-stage PA, was that there was no need for a revision of the advice during the managed year, given that there would be no new information until the next spring surveys.

All this required a change to the fishery's management basis, which would affect both the calendar and the basis on which to provide advice, moving from the current short-term perspective (so much conditioned on assumptions about the incoming recruitment level) to a longer-term perspective including the entire recruitment dynamics [59].

5. First management plan: Long-term strategies under recruitment uncertainty

The repeated crash in 2005 and 2006 and the difficulties to recover the population above B_{pa} after the closure made evident to fishers and managers the risks of falling below some threshold biomass levels, both biologically (sensu B_{lim} and the risks of detrimental effects on future recruitments) and economically (as there seemed to be a threshold biomass below which the fishery crashed). This led to a consensus on the need to achieve a long-term MP for a sustainable fishery which should minimize the risks of low population levels. The formulation of MPs requires a process of definition of objectives, and formulation and evaluation of alternative management procedures, until adoption of the best procedure with the involvement of stakeholders, managers and scientists (Fig. 5). For the BoB anchovy, this process was officially launched by the EC in November 2007 [19]. The South Western Waters Advisory Council (SWWAC) was asked for its opinion on it, as they had been working on the long-term management of this fishery since 2006 [123].

In 2008, the EC asked the Scientific, Technical and Economic Committee for Fisheries (STECF) to analyze management strategies for this fishery, with the following management objectives: a) to ensure the exploitation of the stock at high yields consistent with maximum sustainable yield (MSY); and b) to guarantee the stability of the fishery, as far as possible, and with a low risk of stock collapse. These general objectives corresponded to the EU's adhesion to the Johannesburg Declaration of the World Summit on Sustainable Development, applied to fisheries through the MSY [17,129], and to minimize the risks of stock (and fishery) collapse, as recently experienced in the fishery.

A STECF subgroup, formed by scientists of different backgrounds, met twice in the first half of 2008 (Supplementary Material A) to test several TAC-based HCRs, through MSE. For the MSE, population model errors were included as uncertainties on the actual Stock Recruitment

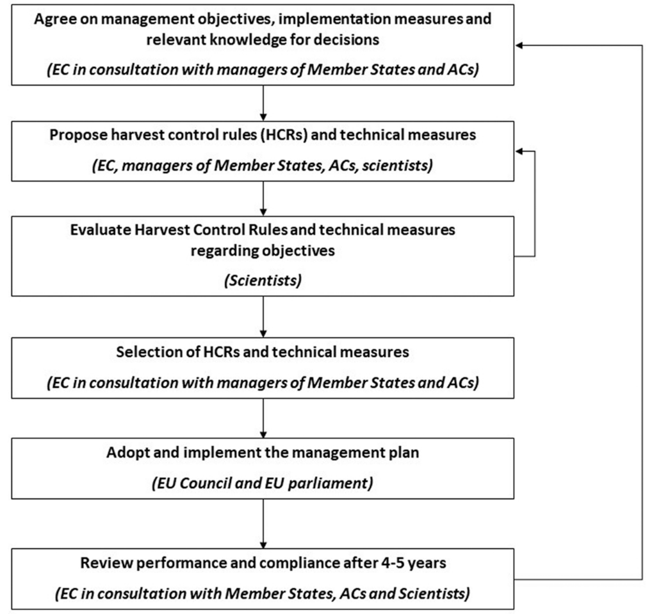

Fig. 5. General flow of the process of definition of management plans in the EU. EC means European Commission of the EU and AC means Advisory Councils.

relationship (SRR) (either Ricker or some others) and uncertainties on the population dynamics by age (either two-stage or full age structured model), in both cases as sensitivity analysis. Process errors came mainly as natural variability around the SRR. Survey and assessment errors were collapsed into a biomass observation errors (with a CV of 0.25) as resulting from an assessments emulator within the MSE (though a lower CV was also tested). Further details of the MSE work can be consulted in STECF reports [116,117] and in Sánchez et al. [107]. Results in terms of selected performance indicators, such as biological risk (i.e., risk of falling below B_{lim} in any of the 10 years of the projection period), risk of closures and economic indicators, were communicated to the EC and the stakeholders through the SWWAC, which had an active participatory role and formulated their preferences in respect of the evaluated HCRs [123].

The first proposal of the STECF subgroup was to manage the stock on a TAC year from July Y to June Y+1 to incorporate, as soon as possible, the most recent information on the level of stock in the interim year, so that fishing opportunities were maximized without compromising the future of the stock. This reduced the elapsed time between the monitoring system and the management procedure, so that past uncertainties in forecasting a year ahead (Y+1), arising from a lack of knowledge on the next recruitment, were reduced. The EC confirmed the feasibility of such an approach in the context of a long-term management plan for the fishery.

The HCRs were established in terms of harvest rates of the spawning stock biomass (SSB) in May, simply because this was the major input (estimates from surveys) and output of the assessment produced in June, and the reference for the evaluation of biological risks for the stock. In addition, this facilitated communication with managers and stakeholders and avoided the complications of using a fishing mortality-based rule for a population with only two main age groups with markedly different selectivity by fleets and by semesters.

Two main generic HCRs were devised (Fig. 6a and Table 1). The first rule (HCR A) allowed harvesting a fraction γ of the most recent spawning biomass estimate in excess of B_{lim}, corresponding to a proportional threshold harvesting [73]. The second was a biomass based rule (HCR B) [100] which allowed catching directly a fraction of the most recent biomass estimate, but reducing linearly the harvest rate for biomasses between B_{pa} and B_{lim}, to zero.

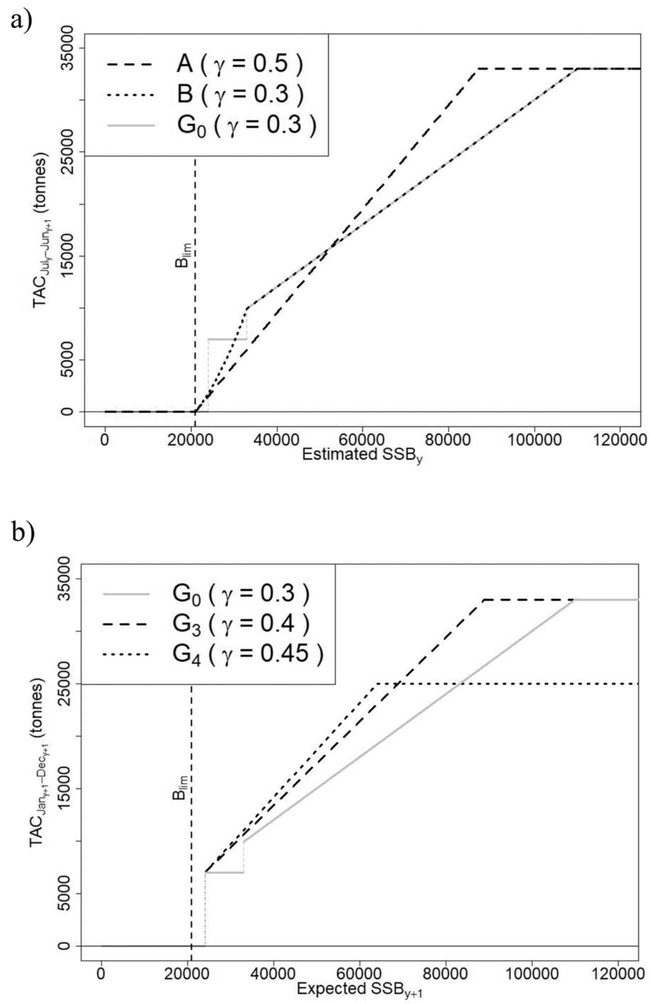

Fig. 6. Harvest control rules (HCRs) for Bay of Biscay anchovy defining TACs as a function of spawning biomass (SSB) (in tonnes). Upper panel (a): examples of final competing HCRs based on the SSB estimates in May of the interim year (Y), tested for the elaboration of the 2008 MP for a management year going from July Y to June Y+1: HCR A, B and G0 with slopes of 0.5 0.3 and 0.3 respectively, all bounded by a maximum TAC at 33,000 t. HCR G0 was almost identical to Rule B except for applying the minimum TAC at 7000 t as a constant step value for SSBs between 24,000 and 33,000 t. Bottom panel (b): selected HCRs which were tested for the elaboration of the 2013/2014 MP based on the expected SSB in the management year from January to December (Y+1). See rules' details in Tables 1 and 2.

The participation of stakeholders added variants to the former HCRs by asking to test the effects of bounding them with maximum TAC levels (TACmax), around 25,000 or 33,000 t, and with minimum TAC levels around 5000, 6000, or 7000 t, instead of allowing a continuous decline of TACs to 0 for decreasing SSB values (Fig. 6). The upper limits derived from the fact that international catches had been, on average, around 33,000 t since 1990, reaching a maximum of about 40,000 t in very few years (Fig. 1). The minimum allowable TAC levels were a demand of the fishers to guarantee a minimum economic viability of its activity accounting for the fishing costs. If the rule predicted catches below the minimum TAC level (TACmin), the fishery should be closed.

Analysis of the ex-vessel price showed net price dynamic inverse to production, revealing that the ex-vessel price of landings was like a parabola, with maximum values peaking around 32,000 t [107,115]. Detailed economic analysis [117] showed that the economic performance of the fleets was in fact maximized at lower levels of catches (well below 32,000 t). Furthermore, analysis of incomes and costs per fleet revealed that the minimum economically viable TAC would be around 7000 t [116,117]. These results endorsed the suggestions passed by stakeholders to optimize the economic performance of the fishery.

The rules which produced biological risks of falling below B_{lim} between 3% and 10% are shown in Fig. 6a and summarized in Table 2. For both HCRs (A and B) setting a maximum TAC allowed gaining stability of catches and diminished the risks of falling below B_{lim} at the expense of reducing average catches (Fig. 7). In addition, the economic performance of the fishery was improved with a TACmax of 33,000 t (Fig. 7d). Setting TACmin did not significantly affect the average level of catches but reduced the risk of the stock falling below B_{lim}, particularly when testing high harvest rates. However, it increased sharply the probability of closure [116].

Stakeholders initially selected HCR B with a TACmax of 33,000 t and a harvest rate of 0.4 [123]. However, this corresponded to a biological risk of almost 10%, which was considered too high by the EC (Table 2). Alternatively, lowering the harvest rate to 0.3 led to a biological risk around 6% that was considered acceptable by the EC. This harvest rate of 0.3 was below historical mean values (around 0.45).

Stakeholders additionally asked in July 2008 to consider a variant of rule B, with a TACmin applied over a range of low biomasses close to, but above B_{lim}, between 24,000 and 33,000 t (Table 1), to reduce the chance of closing the fishery at low biomass levels (Table 2). This demand arrived after the conclusion of the STECF work. However, an ad hoc work to assess this last suggestion [53] proved that the variant had a similar performance to the pre-selected HCR B [118].

Selection of the final HCR proposal for the anchovy management plan was undertaken by the EC in agreement with member states, adopting the variant of HCR B with a TACmax of 33,000 t and TACmin of 7000 t for biomasses between 24,000 and 33,000 t, with a harvest rate of 0.3 for SSB values above 33,000 t (named here after as HCR G0) (Fig. 6).

In 2009, the EC made a proposal to establish the first management plan for the BoB anchovy [20]. Despite the proposal never officially being adopted due to administrative reasons, the plan was implemented, given the strong support and commitment of stakeholders, through a direct agreement between Spain, France and the EC [88]. The HCR was applied to the fishery for the first time for the management period July 2010 to June 2011, after a provisional reopening of the fishery during the first half of 2010 (with a TAC of 7000 t) and having verified the actual recovery of the population above B_{pa}.

The ultimate reason for the fisher's preference of rules type B rather than type A, all producing the highest catches for the allowable level of biological risk, was basically related to the form of the HCR (Fig. 6a). The preferred rules allowed greater catches at low SSB levels, increasing the chances of an economically viable fishery even at those low stock levels and slightly reducing the risk of closures (particularly G0). The history of this fishery and the oscillating nature of the population may justify the selection of such HCR, which guarantees a rather regular and minimal viable fishery for the largest range of biomasses, including those just above B_{lim}, while being still precautionary.

Despite the G0 HCR being applied for the management of the fishery between 2010 and 2014, ICES still provided advice based on the PA until 2014 (i.e., using the probabilistic forecast of the management year, ICES advised on catches from July to June next year consistent with keeping spawning biomass above B_{lim}, with a certainty of 95% under an assumption of poor recruitment). It was only after verification that the rule was precautionary [64], in reply to a special request from the EC, that ICES adopted the G0 rule as basis of its advice.

6. Revision of the first management plan: Long-term strategies informed on incoming recruitment levels

A second version of the MP was defined in 2013/14 [119,120]. The original plan had a clause for re-evaluation after five years, but the revision was mainly triggered by changes in the assessment procedure and in the monitoring system. A benchmark in 2013 [62] changed the

Table 1
Summary of the alternative HCRs tested for the Bay of Biscay anchovy management plan definition and its revisions (with $B_{\text{lim}} = 21,000\text{t}$ *and* $B_{\text{pa}} = 33,000\text{t}$).

HCR name	Formula	Used for management ?	Ref.
HCR A	$TAC_{July_y-Jun_{y+1}} = \left\{ \begin{array}{ll} 0 & , \text{ if } \widehat{SSB}_y \le B_{\text{lim}} \\ \gamma \bullet \left(\widehat{SSB}_y - B_{\text{lim}}\right) & , \text{ if } \widehat{SSB}_y > B_{\text{lim}} \end{array} \right\}$ *With or without TACmin and TACmax*	No	STECF, [115–117]
HCR B	$TAC_{July_y-Jun_{y+1}} = \left\{ \begin{array}{ll} 0 & , \text{ if } \widehat{SSB}_y \le B_{\text{lim}} \\ \gamma \bullet \frac{\left(\widehat{SSB}_y - B_{\text{lim}}\right)}{\left(B_{pa} - B_{\text{lim}}\right)} \bullet \widehat{SSB}_y & , \text{ if } B_{\text{lim}} < \widehat{SSB}_y \le B_{pa} \\ \gamma \bullet \widehat{SSB}_y & , \text{ if } \widehat{SSB}_y > B_{pa} \end{array} \right\}$ *With or without TACminand TACmax*	No	STECF, [115–117]
HCR G0	$TAC_{July_y-Jun_{y+1}} = \left\{ \begin{array}{ll} 0 & , \text{ if } \widehat{SSB}_y \le 24,000 \\ 7,000 & , \text{ if } 24,000 < \widehat{SSB}_y \le 33,000 \\ \min\left(0.3 \bullet \widehat{SSB}_y, 33,000\right) & , \text{ if } \widehat{SSB}_y > 33,000 \end{array} \right\}$	2010–2014	[118]
HCR G4	$TAC_{y+1(Jan-Dec)} = \left\{ \begin{array}{ll} 0 & , \text{ if } \widehat{SSB}_{y+1} \le 24,000 \\ -3,800 + 0.45 \bullet \widehat{SSB}_{y+1} & , \text{ if } 24,000 < \widehat{SSB}_{y+1} \le 64,000 \\ 25,000 & , \text{ if } \widehat{SSB}_{y+1} > 64,000 \end{array} \right\}$	2015–2016	[119,120]
HCR G3	$TAC_{y+1(Jan-Dec)} = \left\{ \begin{array}{ll} 0 & , \text{ if } \widehat{SSB}_{y+1} \le 24,000 \\ -2,600 + 0.4 \bullet \widehat{SSB}_{y+1} & , \text{ if } 24,000 < \widehat{SSB}_{y+1} \le 89,000 \\ 33,000 & , \text{ if } \widehat{SSB}_{y+1} > 89,000 \end{array} \right\}$	2016-onwards	[119,120]

Table 2
Bay of Biscay anchovy. Summary statistics of harvest control rules resulting in risks of falling below B_{lim} between 0.03 and 0.1 in the STECF evaluations of 2008 and 2013/2014: HCR A (at slope -harvest rates- of 0.5 and 0.6) and rule B (at slope-harvest rates- of 0.3 and 0.4); the final adopted 2007 HCR (G0, originally known as rule E), which was a modification of rule B at a slope -harvest rate- of 0.3 with a minimum TAC of 7000 t (applicable over a range of SSB between 24 and 33 thousand tons); re-evaluation of G0 in 2013/2014 for two management calendar years; and the results for the two selected rules after the 2013/2014 STECF evaluation: G4 at a slope of 0.45 (applied in 2015 and preliminarily in 2016) and G3 at a slope of 0.4 (applied from 2016 onwards).

STECF Evaluation	2008	2008	2008	2008	2008	2013/2014	2013/2014	2013/2014	2013/2014
Management Calendar	July-June	July-June	July-June	July-June	July-June	July-June	Jan-Dec	Jan-Dec	Jan-Dec
Informed on Recruits?	No	No	No	No	No	No	Yes	Yes	Yes
Rule name (HCR)	Rule A	Rule A	Rule B	Rule B	G0 (Rule E)	G0 (Rule E)	G0	G4 (0.45)	G3 (0.4)
Intercept	-10,500	-12,600	0	0	0	0	0	-3800	-2600
Slope (Hr)	0.5	0.6	0.3	0.4	0.3	0.3	0.3	0.45	0.4
TACmax	33,000	33,000	33,000	33,000	33,000	33,000	33,000	25,000	33,000
TACmin	7000	7000	7000	7000	7000	7000	7000	7000	7000
P(SSB<Blim)	0.052	0.072	0.060	0.093	0.068	0.067	0.035	0.045	0.051
P(closure)	0.245	0.244	0.182	0.211	0.115	0.098	0.051	0.059	0.067
Average catch (t)	17,439	18,175	17,347	19,006	17,414	19,903	21,850	20,352	22,787
Average Sd. catch (t)	11,779	12,106	10,080	11,085	9452	9870	8779	6125	9083
Gross Income (€)	482,042	489,535	468,846	491,737					

stock assessment model [51], incorporating the modelling of catches at age and changes in natural mortality [62,130], and included a revision of the DEPM biomass series [109]. In addition, a major change came from the incorporation of the autumn acoustic survey on juveniles, capable of forecasting the strength of the next coming recruitment at age 1 in January [10] with sufficient reliability ($r2 = 0.899$) (Fig. 8). The new assessment was somewhat similar to its predecessor, producing probabilistic estimates of the past biomass and recruitments, and barely changed the past perception of the population (Fig. 4). For this reason, B_{lim} remained unchanged. For the revision of the MP, two STECF meetings took place, one in 2013 and another in 2014, with the participation of stakeholders and allowing for discussions with them before and after these meetings (supplementary material-A). The MSE was based on an age structured population model (ages 0–3 +) consistent with the assessment, with process error affecting mainly the stock recruitment relationship and biomass observation errors arising from an assessment emulator (with a CV of 0.25) [107,119,120].

The inclusion of the recruitment index into the assessment model, allowed advice to be produced for the following year (Y+1), informed by 98% of the managed catches and 100% of the spawning population upon which risk is assessed (Fig. 3c), certainly subject to the assessment uncertainties. To incorporate such forecasting capacity, the assessment and advice were moved to November, as soon as the estimates from the recruitment survey were available, and the management year was moved back to the calendar year (January-December of year (Y+1)).

The originally adopted HCR G0 was tested again for the original management calendar (July–June, uninformed on incoming recruitment) and for the new management calendar (January–December, informed on recruitment) (Fig. 6). In the latter case, TACs were set according to the expected spawning biomass in May of the management year, which is conditioned by the TAC itself. This required a recursive estimation of the TAC [120]. In addition, new HCRs were considered for the January–December management calendar, in which the TAC was set as a linear function of the expected SSB within the management year. All were continuous biomass-based HCRs allowing a constant harvest rate above a minimum biomass threshold level, wherein the minimum (starting) TAC level was 7000 t, for consistency with the 2008 formulation of the G0 HCR (Fig. 6, Table 1). Stakeholders asked again to test the performance of these HCRs constrained by TACmax values at 25,000 and 33,000 t STECF tested the performance of these rules under a revised MSE procedure, incorporating the changes in the population dynamics and in the observation and assessment model [107,119,120].

Comparison of the G0 HCR for the two management calendars (July–June and January–December, uninformed and informed on recruitment respectively) showed that the management procedure from January to December informed on recruitment almost halved the risk of

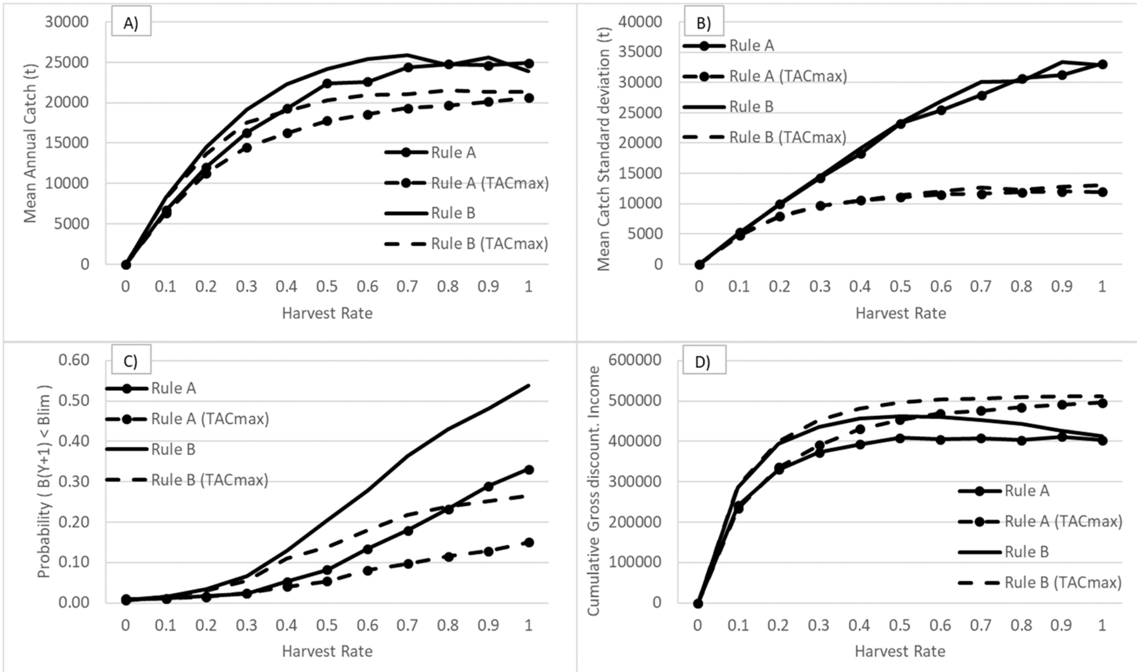

Fig. 7. Comparison of the performance of HCR A (harvest a constant fraction of the SSB in excess of Blim) and HCR B (allowing harvest a constant fraction of the SSB), including restriction or not by a maximum TAC level (TACmax) in terms of annual mean catch (panel A) and its standard deviation (panel B); annual probability of the SSB falling below Blim (panel C) and economic performance in terms of cumulative (over ten years) gross discounted income for the international fishery (panel D).
Adapted from [116].

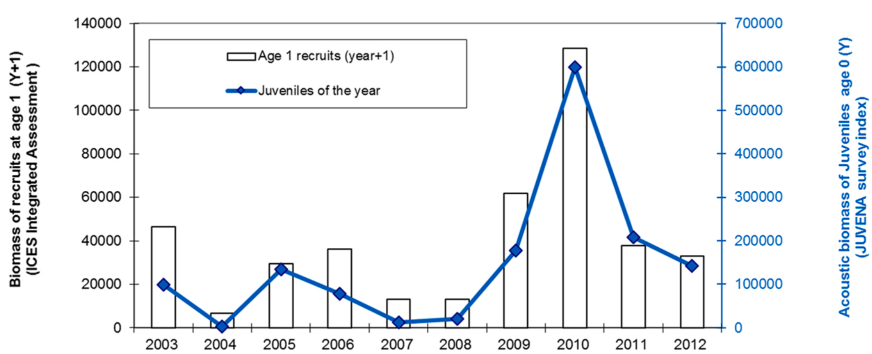

Fig. 8. Temporal series of anchovy juveniles (age 0) in year Y (blue line, from the autumn acoustic survey –JUVENA) versus estimates of biomass at age 1 in January Y+1 (white bars, from ICES integrated assessment, using adult surveys and catches only). Updated from Boyra et al. [10], including two additional years of independent estimates of both indicators of recruitment.

being below B_{lim} (to 3.5%) and reduced the probability of closures to 5%, while allowing higher mean annual catches (by about 2000 t) (Table 2). As the biological risk for the stock fell below 5%, there was room for improvement in the HCR to allow higher catches for the maximum allowable level of risk. Among the new tested HCRs, several showed a better performance in terms of catches and stability.

Fishers in 2014 preferred initially a rule bounded by a TACmax of 25,000 t with a harvest rate of 0.45, which was applied in 2015 and 2016 (HCR G4 in Table 2) [14]. However, in 2016, given the high daily catch rates and healthy status of the resource, fishers requested moving the TACmax back to 33,000 t (as before) with a harvest rate at 0.4 (HCR G3 in Table 1; Fig. 6b) [15]. Based on the good state of the stock [65], which would have allowed setting in 2015 and 2016 the respective maximum TAC values for the two rules (G4 and G3), and given that the proposed rule (G3) had also been assessed by STECF as precautionary (Table 2), the EC revised the 2016 TAC mid-year based on the newly adopted G3 rule.

The managers from the EC and member states (Spain and France) supported the preferred options of fishers and adopted G3(0.4) as the final rule. This rule has been applied to set the annual TACs since 2017. The inclusion of an early indicator of recruitment allowed selecting a HCR which resulted in about 15% higher catches than the original 2008 rule (Fig. 6b), for a slightly smaller level of risk (Table 2). This rule allowed a mean harvest rate of 0.34 for SSB between 24,000 and 80,000 t, below historical exploitation and of deterministic MSY harvest rates (supplementary material-B). ICES verified the precautionary performance of the new HCR [65] and nowadays uses the revised HCR as the basis of its advice to the EC.

7. Discussion

7.1. Precautionary short-term versus long-term strategies under recruitment uncertainty: towards a fast-reactive management after the surveys

Short-lived SPF require an adaptative management to account for their fluctuations in abundance [8,26,41,110]. A fixed TAC strategy does not accommodate the harvest to the stock fluctuations and it is known to imply a high risk of stock depletion and collapses at low abundance levels [31,93,105]. For the BoB anchovy such strategy supposed no effective management [30,131] and ended up with the collapse of the stock for about five years. The two-stage advice, where provisional annual fishing opportunities were updated in-year according to the strength of the incoming year class, once assessed, was developed in the early 2000 s as a precautionary (PA) short-term strategy in the absence of early information on recruitment. Such approach has been successfully applied to North Sea sandeel (since 2004) and North Sea sprat [18]. However, the two-stage PA advice entailed the administrative complexity of updating the TAC. In addition, for seasonal sequential national fleets, it could reduce the fishing opportunities of the fleet operating in the first half of the year (under the precautionary phase of the two-stage advise). As a result, the PA two-stage approach was never applied to the BoB anchovy and the constant TAC strategy continued until the crash of the fishery, despite the warnings passed to managers on the declining stock status [56,57].

In the absence of early recruitment indication, improved management can be obtained from HCRs making a close coupling between assessment, advice, and management. For the BoB anchovy this was obtained in the first management plan [116,117] by moving the advice to just after the spring surveys, for a management year going from July Y to June Y+1. Such approach reduced the uncertainties (assumptions) on the managed population, as the advice was informed by the major age classes contributing to the catches in the management period, just after being assessed. The risk of falling below B_{lim} for the SSB (Y+1) was still conditioned by the unknown level of recruits, but at least the harvest of the survivors contributing to the spawning of the management year was regulated effectively. This practice of moving the management calendar to just after the surveys to better manage the assessed in-year stock has been adopted for some other short-lived species, such as the North Sea sprat in 2013 [63], the Peruvian anchovy [6] and sardine and anchovy in South Africa [26].

Testing the performance of HCRs in a long-term perspective through MSE allowed managers and stakeholders to take informed decision about the “best” strategy without necessarily having to manage the stock under the most risk-averse assumption (that there will be low recruitment) of the PA advice, as the MSE incorporates the full recruitment dynamics, along with other uncertainties such as the observation and assessment errors, in a probabilistic framework. By “best” strategy, we refer to a sustainable long-term harvest strategy, for the available monitoring system and key uncertainties in the population assessment and dynamics, which complies with management objectives and offers to stakeholders acceptable trade-offs between the different management objectives.

7.2. Improving management through inclusion of recruitment indicators

Management of short-lived SPF is challenged by large recruitment variability [126], which accounts for the largest source of population interannual variability [110,111]. Therefore, early indication of recruitment [8,26,110] greatly benefits their management. Such information allows an early reaction to occasional recruitment failures, minimizing the risks of stock collapse/depletion, and alert on the opportunity of good catches when recruitment is strong. Sometimes the indicator might come from the relationship between recruitment success and environmental factors [49], as for the Pacific sardine [99], though this is rarely achieved [72,121]. For the BoB anchovy, many studies have attempted to relate oceanographic and environmental variables to recruitment [2,3,9,39,89,90,97,125], but without achieving a sufficient level of forecasting capability as to improve the management [28,29]. Nevertheless, approaches based on environmental indicators have been superseded by the preferred method of direct surveying of the early recruits [8,110]. Effectively, for this anchovy, inclusion of the autumn acoustic survey on juveniles [10,62] as indicator of recruitment in the assessment led to a reduction of biological risk for the same HCR and to an increase in catches for the same maximum allowable levels of biological risk, in the 2014 revision of the HCR [107]. Such benefits, expected for short-lived species so much dependent upon recruitment levels [23], had also been pointed out by a simulation of a survey-based management for this fishery [98]. However, the gain in mean catches (by about 15%, after inclusion of the recruitment indicator) may be considered modest. This can be partly due to the uncertainty of the acoustic survey estimates of recruitment, but it also reflects the good management performance already achieved with the HCRs of the first management plan (2008) based on the close coupling between surveys, advice and management. Bigger differences might have appeared if the harvest strategy would have been a constant escapement strategy but these are often discarded, due to the huge catch variability and risk of closures they imply [31,100], as happened in this case too [107].

7.3. The value of iterative and participatory development of MPs

Developing management plans with the participation of stakeholders is a practice suggested for the success of the process [99] which incentivizes fishers’ responsibility, allows for greater transparency for all stakeholders, and enhances the legitimacy and acceptance of management decisions [25,88,95,106]. For the BoB anchovy the elaboration of the initial plan and its review in 2014 took each time about two years till adoption of the final HCR for management (see Supplementary material-A). The process launched by the EC was designed to be open and participatory, formally consultative (*sensu* Leite and Pita [76]), allowing direct attending of stakeholders as observers in STECF meetings and asking them to formulate their views and positions. Such consultative iterative process was facilitated by the attitude of scientists presenting directly at the SWWAC meetings the progress achieved within STECF meetings and trying to incorporate their suggestions. The fact that for the original formulation of the MP and its review in 2014 two STECF meetings were required facilitated such participatory process. In the EU, the participatory and iterative development of MPs with stakeholders could be better assured by making mandatory for these processes to have a two round consultation loop with them on the definition, simulation and evaluation of the HCRs before their final adoption, as suggested as well by other authors [104,106].

Globally, the interaction with stakeholders shaped and enhanced the formulation of HCRs to better respond to their demand for a bounded exploitation of the resource so that a continuous (minimal and maximal) profitability of the fleet could be met, while minimizing catch variability and the risk of closures. Stakeholders’ opinions on the preferred HCRs were determinant for the final HCR selection for the MP, because managers were receptive and endorsed the final agreements of stakeholders as they complied with the initial objectives and the allowable levels of risk. Furthermore, the MP has been applied despite not being formally approved within the EU due to the strong agreement and support of all stakeholders (fishermen, NGOs and managers) from the two concerned countries [88]. This case study corroborates the benefit of stakeholder participation to reach an agreed management plan, enhancing their compliance with the MP [25,26,85,88,95,99,106]. This process exemplifies a success of the advisory role of ACs on management in the EU, when based upon agreement, achieving thus a relevant functional participatory process, *sensu* Leite and Pita [76], in the definition of the MP.

7.4. Catch bounded harvest strategies for a small fishery on high valuable short-lived species

The BoB anchovy is a highly valuable resource, most of its production going to the fresh market and the canning industry, both with a daily/weekly limited absorption capacity. If the supply is too high, exceeding the absorption capacity, the prices fall. This price dynamics, inverse to fish supply, explains the maximum economic value of a TAC around 32,000 t [117] and supports the stakeholders' preference for bounded harvest strategies, with TAC varying according to resource levels up to a maximum TAC. This contrasts with the typical escapement policy strategy applied in some industrial fisheries to small short-lived pelagic fishes, as in the Barents sea for capelin [45,46], or in Peru for the anchoveta [68], whereby the majority of the catches goes to fishmeal factories. Although these fisheries have some caps on processing capacity, they can process a huge amount of catches accounting for much of the biomass above the target biomass for escapement, which results in highly fluctuating catches [31,81]. Therefore, these escapement policies without upper limits seem unsuitable for highly valuable resources, as the BoB anchovy and in many Mediterranean areas, with limited market capacity, whereby optimal economic performance will be better achieved by harvest strategies bounded by maximum TAC levels.

The BoB anchovy HCR is a biomass-based catch bounded (BBCB) rule, rather similar as the one proposed by Froese et al. [43]. These rules mix and incorporate part of the benefits of the Conditional Constant Catch rule [22] and of the biomass-based harvest rate rules [31,100]. The rule, by setting a constant catch strategy above an upper biomass threshold reduces interannual catch variability as intended with constant or conditional constant catch strategies. By reducing progressively the catches below the upper biomass threshold avoids the frequent closures associated with pure threshold strategies [73] while still providing some biomass stability and minimizing risks of depletion, as expected from the biomass-based harvest rate rules [31,82] or with the proportional threshold harvesting strategies [35,73]. Assuming all fisheries on SPF will be necessarily variable this BBCB harvest strategy do partly reduce the inter-annual variability of catches certainly better than would result from an escapement or threshold strategies [73] and probably better than biomass based harvest rate rules [31,43]. Maximum TAC levels, have also been adopted for the management of other pelagic stocks, like the Pacific sardine [99] and the anchovy in Benguela [26], also linked to the market capacity. Nevertheless, this is probably one of the few cases were explicit acknowledgment of the relevance of these boundaries was made since the beginning and was supported by an economic analysis on the performance of the fishery [107,117].

The value of the minimum TAC level is obvious to assure the fishery has a minimum economic viability whenever open and has also been included in the management of the South African anchovy [26] and proposed for the northern anchovy [124]. The HCR variant approved for the first formulation of the management plan set this minimum TAC over a range of low biomass values (Fig. 6a). The approach was good to give stability to a minimally economically viable fishery in situations of poor stock status, while minimizing the biological risk for the stock. In the latest revision of the plan, the TACmin was just the lowest end of the allowable range of catches set by the HCR. Definition of TACmin values may be of interest for the management of other pelagic fisheries on highly valuable resources.

In order to be precautionary, the selected rule implied fishing well below the deterministic MSY levels (Supplementary material-B), something aligned with the recommendations for the management of these short lived species particularly in the context of ecosystem based fishery management [43,93,110,112]. In addition, setting maximum TAC makes a larger fraction of the surplus production of this typical prey available, during years of high abundance, to top predators [43], as advocated for northern anchovy as well [124]. As such, the role of this small short-lived species as a forage species in the ecosystem is preserved as much as possible, although in periods of resource shortage conflicts between the predators and the fisheries can occur.

7.5. Concluding remarks and prospects

The management of this fishery confirms that optimal management of short-lived species is achieved by the inclusion of a recruitment indicator, which allows anticipating management to the ups and downs of these resources. But it also shows that much can be gained when the monitoring system consists of adult surveys only, by implementing a fast reactive management of the in-year population by setting the TACs just after the surveys.

Management of SPF should be customized to the features of the fishery and the resource [110] by a tailored tuning of the HCR parameters. This was achieved thanks to the interactive participatory process between scientists, stakeholders and managers that allowed inclusion of stakeholders' preferences for a biomass-based catch bounded harvest strategy. Such strategy accommodated the fishery needs of an optimal exploitation close to the maximum economic yield at high stock levels (with TACmax), as defined by the market absorption capacity, while allowing for a minimum economically viable fishery at poor abundance levels (with TACmin), constraining thus interannual variability. In addition, the upper bound catch level can preserve much of the role of SPFs as forage species in the ecosystem [42]. For these reasons we consider that biomass-based catch bounded harvest strategies may attract more attention for the design of harvest control rules for SPF resources.

Since the recovery of the stock and the implementation of the management plan, in 2010, this fishery exploits anchovy at harvest rates about half the historical levels, or less, while the resource stays around maximum historical levels [66]. The high levels of recruitments in recent years may be related partly to the lower harvest rate implemented but also to favorable environment occurring in recent years [11,21,36,125]. Besides this, the closure might have partly altered the dynamics of price formation, because prices after recovery were lower than expected [95] This can result partly from the increase in imports during the closure, confirming the influence of the global market on these fisheries [81,84], but also from a reduction of the mean size of landed anchovy, either due to density dependence growth dynamics or to environmental changes in productivity [21,33]. How much these changes affect the performance of the HCRs remains to be studied further in the next revision of the MP.

CRediT authorship contribution statement

Andrés Uriarte: Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Leire Ibaibarriaga:** Methodology, Writing – review & editing, Visualization. **Sonia Sánchez-Maroño:** Methodology, Writing – review & editing, Visualization. **Pablo Abaunza:** Writing – review & editing. **Marga Andrés:** Validation, Formal analysis, Writing – review & editing. **Erwan Duhamel:** Writing – review & editing. **Ernesto Jardim:** Conceptualization, Supervision, Writing – review & editing. **Lionel Pawlowski:** Writing – review & editing. **Raúl Prellezo:** Validation, Formal analysis, Writing – review & editing. **Beatriz A. Roel:** Conceptualization, Supervision, Writing – review & editing.

Data Availability

No data was used for the research described in the article.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2023.105512.

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