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Defining sustainable and precautionary harvest rates for data-limited short-lived stocks: a case study of sprat (*Sprattus sprattus*) in the English Channel

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Empirical harvest control rules set catch advice based on observed indicators and are increasingly being used worldwide to manage fish stocks that lack formal assessments of stock and exploitation status. Within the International Council for the Exploration of the Sea, trend-based rules that adjust advice according to recent survey observations have been adopted; however, there is increasing evidence that such rules do not work well for short-lived pelagic species that can exhibit large inter-annual fluctuations in stock size. Constant harvest rates, removing a fixed proportion of observed biomass index, have been proposed as a suitable strategy for managing short-lived species. Unknown survey catchability has, however, remained a barrier to reliance on their application on these stocks in the past. We apply simulation testing to define a robust, sustainable constant harvest rate for a data-limited short-lived stock, using the English Channel sprat as a case study. By conditioning a management strategy evaluation framework based on existing and borrowed life-history parameters and precautionary considerations, we test and show that a constant harvest rate outperforms trend-based catch rules, maximizing yields while reducing risks of stock overexploitation, and conclude an 8.6% constant harvest rate provides sufficiently precautionary catch advice for this stock.

Keywords: data-limited, fisheries advice, management strategy evaluation, short-lived fish.

Introduction

Most fish stocks worldwide are data-limited and lack quantitative assessments of stock and exploitation status (Rosenberg *et al.*, 2014, 2018); nevertheless, requirements for scientific advice on sustainable and precautionary management for all exploited stocks continue to grow (Berkson *et al.*, 2011; Newman *et al.*, 2015; Flood *et al.*, 2016). This has led to a proliferation of work to develop and test assessment methods for data-limited stocks (e.g. Gedamke and Hoenig, 2006; MacCall, 2009; Rosenberg *et al.*, 2014; Hordyk *et al.*, 2015a, 2015b); however, such methods may not work well when applied to species with life histories that violate model assumptions (Carruthers *et al.*, 2014; Chong *et al.*, 2020; ICES, 2020a).

Empirical harvest control rules (HCRs) set catch advice based on observable indicators and offer a readily applicable tool for managing data-limited stocks that have survey or other standardized indices representative of trends in stock metrics. Without a status assessment, many operate by adjusting advised catches according to trends in an index, with the aim of maintaining current stock levels (e.g. Geromont and Butterworth, 2015). Within the International Council for the Exploration of the Sea (ICES), such an approach has been implemented as a "2-over-3" trend-based catch rule (ICES, 2021a). In this case, an index of annual abundance or biomass (the average of the last two values divided by the average of the previous three) in combination with a 20% uncertainty cap, which limits the change in advice to no more than ±20%, and a precautionary buffer, which reduces the advice by 20% every 3 years if stock status is considered either poor or highly uncertain. However, ICES is currently transitioning to alternative catch rules that better align with maximum sustainable yield (MSY) objectives, including the *rfb*-rule (Fischer *et al.*, 2020; ICES, 2022):

$$A_{y+1} = A_y \, r f b. \tag{1}$$

This variant of a trend-based catch rule sets the next catch advice (A_{y+1}) based on the last advised catch (A_y; or the last observed catch) multiplied by (i) the trend in the biomass index ("r"), which is calculated as the ratio of the average of the last "x" index values divided by the average of the previous "z" index values ($x = 2$ and $z = 3$ give the default "2-over-3" rule); (ii) an exploitation proxy f calculated by comparing the mean length in the catch to a length-based proxy for the MSY fishing mortality (F_{MSY}; Jardim *et al.*, 2015); and (iii) a biomass safeguard b that reduces the advised fishing opportunities when the index falls below a threshold level (generally defined relative to the lowest observed index value(s), with the reduction proportional to the latest index value relative to the threshold value). Simulation testing of the *rfb*-rule for a range of differing life-history types has shown it to perform reasonably well for stocks with a growth rate coefficient $k \leq 0.32$ year^{-1} but very poorly for stocks with rapid growth and

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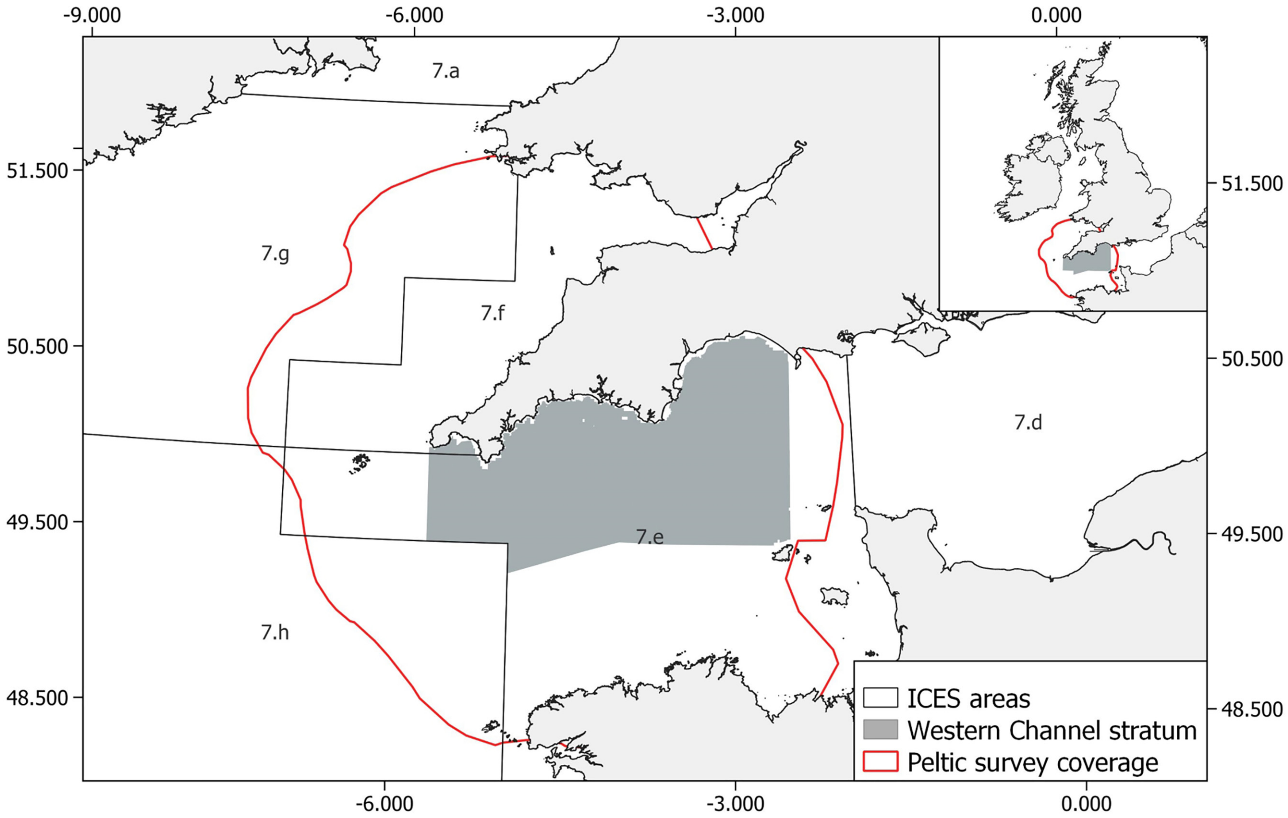

Figure 1. Channel sprat stock spatial definition (ICES divisions 7.d and 7.e), PELTIC survey coverage (red line), and the north-western channel stratum core survey area used to provide advice on fishing opportunities (shaded grey).

limited maximum age typical of small pelagic fishes, even when the separate components of the rule are optimized (Fischer *et al*., 2020, 2021).

Two life-history characteristics that contribute to poor performance of the 2-over-3 rule for short-lived pelagic fishes are (i) high interannual variability in recruitment and consequent variable population dynamics; and (ii) high natural mortality and a short lifespan (ICES, 2018a). Furthermore, owing to their short lifespan and delays between the survey and implementation of associated management, a large part of the observed population will have died by the time management is implemented, leaving high uncertainties about the status of the stock when the fishery happens. Over the last 3 years, methods of stock assessment and catch advice for data-limited stocks of short-lived species have been further developed (ICES, 2019a, 2020b). Simulation testing elements of the *rfb*-rule in combination with alternative advice change limits and schedules have led to the recommendation of a modified trend-based rule for data-limited short-lived stocks: a 1-over-2 rule (the average of the last index value divided by the average of the previous two) coupled with an 80% uncertainty cap, limiting the change in advice to no more than ±80%, and a biomass safeguard, while shortening as far as possible the lag between survey observation and management (ICES, 2020a). The 1-over-2 implementation of the *r* component and wider uncertainty cap increases reactivity to the large fluctuations in stock dynamics exhibited by short-lived pelagic species, while the *b* component protects stocks at low perceived stock size. The *f* component is omitted because the "boom and bust" dynamics typical of short-lived pelagic species violate the assumption of a stable length distribution (ICES, 2018b). While the optimized trend rule reduces risks to small pelagic stocks, the parameterization of the trend component *r* carries the undesirable property of reducing fishing opportunities over time ($x < z$; Sánchez-Maroño *et al*., 2021), which is further exacerbated by restricting changes in advice to ±80%. For example, an 80% reduction of the catches in one year would have to be matched by a 500% increase in catches the following year to return to the same level, taking a minimum of 3 years to achieve when increases are constrained to 80%. Because of this, it has been recommended to apply the rule provisionally until a better assessment and management system is set up (ICES, 2020b; Sánchez-Maroño *et al*., 2021).

The sprat (*Sprattus Sprattus*) in the English Channel (the stock being classified as in ICES divisions 7.d and 7.e; Figure 1), hereafter referred to as Channel sprat, is an example of a short-lived pelagic stock where fishing opportunities have gradually reduced since trend-based rules, coupled with further 20% precautionary buffer reductions in advice every third year, were implemented. The stock is characterized by fast growth, early maturity, and high interannual variability in recruitment. It is also prey for many larger piscivores, which results in a relatively high natural mortality. Consequently, only around 8% survive beyond age 3 and ages 1–3 dominate the fishery (ICES, 2021b). The fishery on this stock is small, with three vessels actively targeting sprat in Lyme Bay (in ICES Division 7.e) and accounting for 96% of the landings (average since 2003; ICES, 2020c). Data available for Channel sprat include landings tonnages and estimates of biomass (including some information on age and length) from an acoustic survey (PELTIC—Pelagic Ecosystem Survey of the Celtic Sea and Western Channel; Figure 1) that has been carried out in

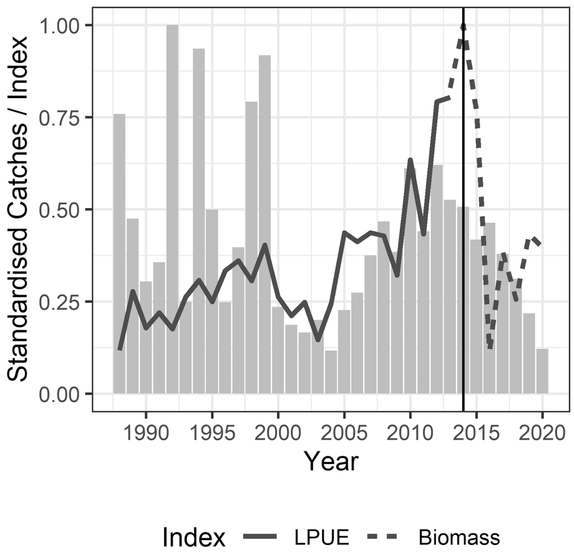

Figure 2. Standardized catches (bars) and biomass indices based on LPUE (solid line) and the PELTIC survey (dashed line). The solid vertical line represents the first implementation of a trend-based catch rule (2013 advice implemented in 2014).

the area every October since 2013 (ICES, 2015a; Doray *et al.*, 2021). Attempts to apply a data-limited assessment have been hindered by both the life-history characteristics of a short-lived species and the relatively short length of the survey time series (ICES, 2019a); hence, the advice for this stock has been based on biomass indicators (Figure 2). The catch advice for 2014–2016 was based on a 2-over-3 rule applied to commercial landings per unit effort (LPUE; kg/h; ICES, 2015b) with interannual changes in advice restricted to 20%. From 2016, the commercial LPUE was replaced by the PELTIC survey biomass index (tonnes), and advice basis varied from 1-over-2 (for implementation in 2017 and 2021) to 1-over-3 (2018) and 2-over-3 (2019, 2020), all with changes in advice restricted to 20% and with further 20% precautionary reductions in advice for 2018 and 2021 (ICES, 2021b).

The catch advice for Channel sprat has reduced in recent years, largely driven by repeated low biomass index observations between 2016 and 2019 that were below 50% of the index values obtained in 2013–2015 (Figure 2). In addition, the selected trend rules included the high 2014 and 2015 values in the denominators of the index ratio (r) for the provision of advice through to 2020, such that the advice for this short-lived stock was based on indicators reflecting up to the last 6 years of history, where most of the current stock did not exist. The reductions in trends were mitigated by the 20% uncertainty cap but were accelerated by the application of precautionary buffer reductions in 2017 and 2020. Because the Channel sprat fishery is small, the progressive quota reductions (2016–2021) drove down fishing opportunities to the brink of profitability. This is despite a lack of evidence that catches were driving the population trends, and improvements being observed in the survey index in the following years (Figure 2). Interactions with fishermen and fishery representatives intensified in 2016, which included discussions on the best approach to follow, identifying data needs and fishery objectives.

Constant harvest rates (CHRs), where the advised catch corresponds to a fixed proportion of the observed survey biomass index, are an alternative empirical HCR. It has been suggested that they may perform better for small pelagic stocks (Fischer *et al.*, 2021; Sánchez-Maroño *et al.*, 2021) and avoid the undesirable reduction properties of trend-based catch rules coupled with advice change limits and precautionary buffer reductions. However, determination of an appropriate harvest rate level remains a major hurdle to be overcome for implementation in management. This is due to the unknown relationship between survey observations and the true underlying population, termed the "catchability" of the survey, when data are limited. Here, we use simulation testing to derive a precautionary and sustainable CHR for the stock of sprat in the English Channel. We condition a generic management strategy evaluation (MSE) framework based on existing and borrowed life-history parameters where available, and precautionary considerations coupled with expert knowledge where data do not exist or are extremely uncertain, to define a CHR that is robust to key uncertainties and errors (Punt *et al.*, 2016). To our knowledge, our initial study is the first to employ simulation testing when defining a CHR applicable on a survey biomass index for sustainable management of a data-limited stock.

Methods

We condition a generic MSE framework (Fischer *et al.*, 2020) to derive a CHR level for Channel sprat that maximizes yield whilst keeping low biological risks and compare its performance to variants of trend-based catch rules relevant to the recent management of this stock. The MSE simulation framework consists of (1) an operating model (OM) that represents the population dynamics and fisheries of the true stock of Channel sprat; and (2) a management procedure (MP) that represents the analyst's perception of the stock and an HCR to be tested. The two components are linked *via* a feedback loop such that a simulated survey draws observations from the OM to inform the analysists perception of the stock in the MP, and the HCR in the MP results in a catch that is removed from the OM (Punt *et al.*, 2016). The simulations proceed in annual time steps following a seasonal management schedule that runs from 1st July to 30th June, and has been implemented for the Channel sprat stock since July 2022 (European Commission, 2022; Supplementary Section S1).

Operating models

Population dynamics and fisheries

An age structured reference stock was created from life-history parameters using Fisheries Library for R (Kell *et al.*, 2007), FLife, and FLBRP packages (see Fischer *et al.*, 2020). Growth was modelled with the von Bertalanffy equation fitted to observations of length-at-age of sprat in the English Channel obtained from the PELTIC survey (Supplementary Section S2). The maximum age was set as 6, which constitutes a plus group (a summation of all fish at age 6 and older), where the stock reaches 95% of its asymptotic length, L_∞. Stock weights were modelled *via* an allometric relationship fitted to weight-at-length observations from the PELTIC survey (Supplementary Section S2) and subsequently converted to age *via* the fitted von Bertalanffy equation.

There are no data available on spawning stock biomass (SSB) and recruitment; hence, recruitment was modelled by a segmented regression stock recruit function parameterized from steepness and virgin SSB. Steepness was taken as the

Table 1. Life-history parameter values used to create the reference stock of sprat and alternative values used to explore OM uncertainty.

Parameter	Reference case	Alternative values (explored in Supplementary Section S3)
Asymptotic length (cm)	14.9	13, 16
Growth rate (1/yr)	0.454	0.4, 0.6
Age at length = 0 (yr)	−1.452	−0.8
Length-weight multiplier	4.8×10^{-6}	8×10^{-6}
Length-weight exponent	3.19	2.96
Steepness	0.65	0.5
Virgin spawning biomass (units)	1000	–
Standard deviation of recruitment deviations	0.78	0.5

median value for sprat in a meta-analysis (equal to 0.65; Myers *et al.*, 1999). This is lower than the 0.75 typically assumed in MSE studies (e.g. Fischer *et al.*, 2020; Mildenberger *et al.*, 2021) and applicable to clupeids (Thorson, 2020) and can be considered precautionary for this fast-growing species. Recruitment variability was implemented through a log-normal error term with a relatively high standard deviation of 0.78, as occurs in the neighbouring North Sea sprat stock (ICES, 2020c) and is consistent for clupeoids (Thorson *et al.*, 2014). Autocorrelation in recruitment was not modelled because no autocorrelation is observed for North Sea sprat (ICES, 2019b). Spawning was assumed to occur in March following Milligan (1986) and Bréchon et al. (2013), by accounting for the mortality that occurs in the first three quarters of the model year when calculating SSB. Given that life-history parameter values are derived from stock-specific data and precautionary considerations, we proceed with a reference stock to obtain the main results, while alternative plausible life-histories have been explored in Supplementary Section S3 (Table 1).

Maturity was modelled with a sigmoid function centred on the age at 50% maturity, which was estimated by the FLife package to occur in the 0-age class. Given SSB is calculated 9 months into the model year, this gave maturity values close to those of the neighbouring North Sea sprat stock (ICES, 2020c). Fisheries selectivity was modelled with a double normal function, which was parameterized with a high standard deviation above modal age classes to simulate an asymptotic selection pattern, consistent with information from pelagic trawlers targeting sprat in Lyme Bay (ICES, 2019b). Natural mortality was modelled as a length-based process based on the fitted von Bertalanffy parameters (Gislason *et al.*, 2010) and subsequently converted to age. Derived life-history relationships are shown in Figure 3. Further details on how age structured stocks are created from life-history parameters are available in Fischer et al. (2020).

Given performance of HCRs can be sensitive to initial depletion (Carruthers *et al.*, 2014, 2016) and the stock and exploitation status of many data-limited stocks are essentially unknown, initial depletion was considered a key uncertainty in this analysis. For this reason, three historical fishing scenarios of increasing severity were applied to the age structured stock of sprat described above over a 25-year "spin-up" period to simulate different levels of depletion prior to the implementation of harvest strategies: (FH1) the Patterson scenario where fishing mortality is increased exponentially to F_P, where F_P is the level of fishing mortality corresponding to an exploitation rate (F/Z) of 0.4, thought to be appropriate for small pelagic fishes (Patterson, 1992); (FH2) the one-way trip scenario where fishing mortality is increased exponentially to $1.5F_P$; and (FH3) the roller-coaster scenario where fishing mortality is increased exponentially to $1.5F_P$ in 12 years, stays at this level for 7 years and then decreases exponentially to F_P by the end of the spin-up period.

Survey observations

Advice for Channel sprat relies on the biomass index produced by the PELTIC acoustic survey (ICES, 2015a; Doray *et al.*, 2021) carried out each October since 2013. From 2013 to 2016, coverage relevant to Channel sprat was limited to the UK waters of the western English Channel (Figure 1). From 2017, coverage expanded into the French waters of Division 7.e; however, only the consistently covered core area (Figure 1) has been used for advice. This core area covers what appears to be the main resident Channel sprat population (and the most important area for the English sprat fishery) in Lyme Bay. However, the expanded coverage in French waters confirmed that a smaller and more variable component of the population also resides there. In 2018, the survey expanded into the eastern English Channel but found low sprat biomass, suggesting a clear separation between Channel and North Sea Sprat stocks (ICES, 2018c, 2019c). The stock structure of sprat in the northeast Atlantic is, however, not clear, despite several genetic and statistical studies (Mckeown *et al.*, 2020; Quintela *et al.*, 2020; Lindegren *et al.*, 2022).

Observations based on the PELTIC survey were generated from the OM as follows:

$$I_{a,y} = q_a \, N_{a,y} e^{-t_s(F_a+M_a)} e^{\varepsilon_{a,y}}, \tag{2}$$

where q_a is the survey catchability-at-age, $N_{a,\,y}$are stock numbers-at-age a and year y taken from the OM, $t_s = 3.5$ is the October timing of the survey in relation to the beginning of the model year (July), F_a and M_a are fishing and natural mortalities-at-age, respectively, and the observation error $\varepsilon_{a,y} \sim N(0,\ \sigma_s)$ (as detailed below).

Quantitative estimates of catchability that relate survey observations to the true underlying population are lacking, making survey catchability a key uncertainty for this analysis. Given this uncertainty, and low presence of 0-group fish in some years (ICES, 2018c), survey catchability-at-age was modelled as a logistic function under three overestimation scenarios: 0%, 50%, and 100% where, without observation error, the survey was assumed to detect all, 1.5 times, or double the number of fish fully selected by the survey, respectively, from the OM (Figure 3). The Western Channel stratum of the PELTIC survey, which provides an index for advice, covers the main resident sprat population in Lyme Bay; hence, the annual advice assumes a direct conversion of acoustic biomass to abundance, equivalent to our 0% overestimation scenario. Although generally considered an underestimate of the population, because this stratum covers only part of the management unit, the acoustic biomass could also overestimate the

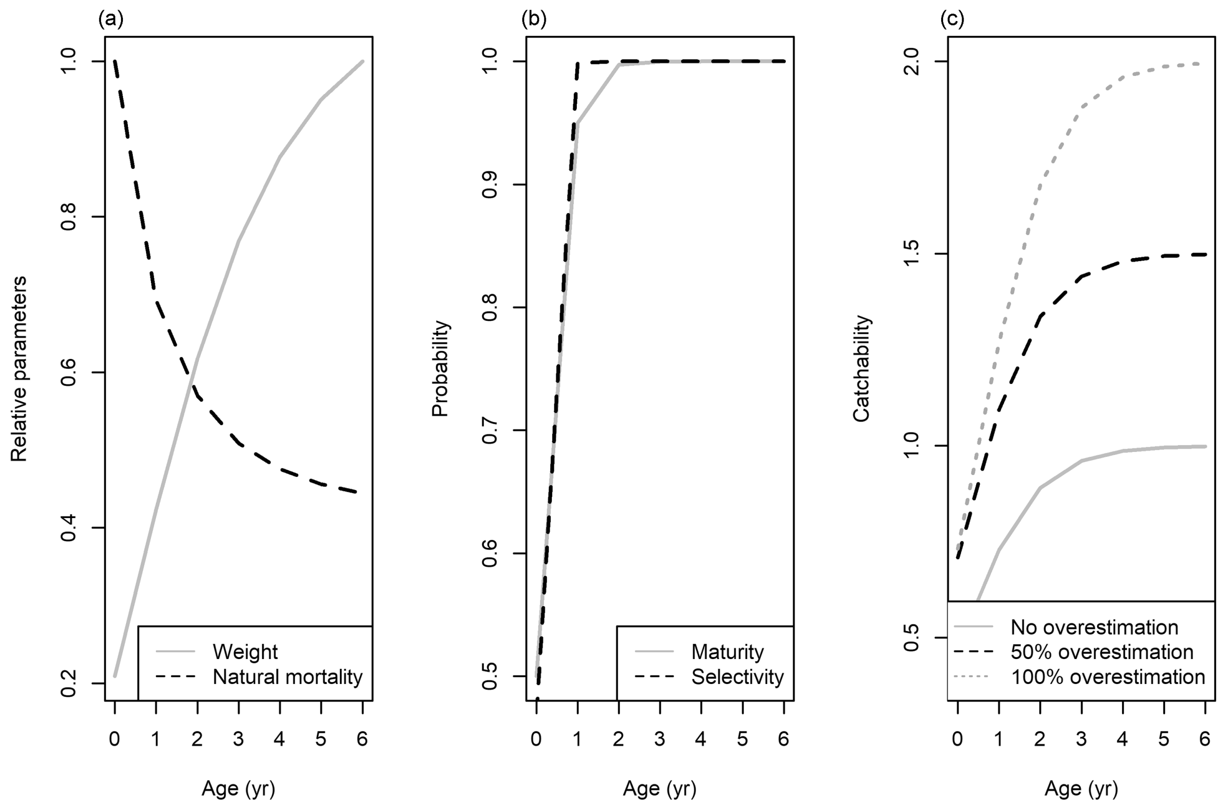

Figure 3. Life-history relationships for the modelled reference stock of sprat. (a) Stock weights and natural mortality at age relative to the maximum; (b) maturity and fisheries selectivity at age; and (c) survey catchability at age assuming 100%, 50%, and no overestimation.

population. This could be due to the trawl under-sampling other species or providing non-representative length–frequency distributions, or due to an error in the conversion of acoustic backscatter to abundance (Doray *et al.*, 2021). Our overestimation scenarios therefore reflect the potential of the acoustic survey to overestimate biomass and were chosen to retain a degree of caution for this data-limited stock.

Although catches from the PELTIC survey include fish from ages 0 to 6, interannual variability in the catchability of the different ages hindered cohort tracking (e.g. Hjort, 1914). For this reason, we adopted a standard deviation of $\sigma_s = 0.5$ in the lognormal error term. This value is close to that estimated for the North Sea sprat stock (ICES, 2020c) and ensures both poor internal consistency and low correlation between the numbers-at-age in the modelled stock and the simulated survey observations (ICES, 2019b).

Management procedure

Estimation method

Catch options for Channel sprat are provided by the ICES Herring Assessment Working Group (HAWG) every March based on observations from the PELTIC survey the previous October. Acoustic survey observations are converted to an estimate of population biomass that feeds into an empirical HCR for the provision of ICES advice. Until 2022, this advice was for the following year (January–December). The formulation here advises for the immediate period, July of the current year to the following June (Supplementary Section S1). The process of obtaining a biomass index was emulated in the MP by multiplying the modelled survey observations by stock weights-at-age as follows:

$$B^s_y = \sum_a w_a I_{a,y}, \tag{3}$$

where w_a are stock weights-at-age (Figure 3) and the s superscript refers to modelled survey index.

Harvest control rules

After the 25-year spin-up period, management was implemented based on an HCR for a 25-year projection period. The primary HCR considered in this study is a CHR where the catch advice for the following year corresponds to a fixed proportion (α) of the observed survey biomass index (Equation 3):

$$A_{y+1} = \alpha B^s_y. \tag{4}$$

Performance of the CHR was compared to variants of the trend-based catch rule (Equation 1) relevant to the recent management of this stock and advice for short-lived species (Table 2). The trend component (r) was taken as a 1-over-2 rule

$$r = \frac{B^s_y}{\sum_{i=y-2}^{y-1} B^s_i/2}. \tag{5}$$

The exploitation proxy (f) was omitted as the underlying assumption of an equilibrium length structure is inappropriate for short-lived species (ICES, 2018b). The biomass safeguard (b), when included, was taken as a multiplicative factor that reduces the catch advice when the biomass index falls below a certain threshold, I_{stat}:

$$b = min\left(1, \frac{B^s_y}{I_{stat}}\right); \tag{6a}$$

Table 2. HCRs considered in this study to set advice, "*A*", for the following management year, A_{y+1}, where UC refers to uncertainty cap.

Rule	Formulation	Uncertainty cap	Rational
CHR	αB_y^s	None	This study
1-over-2 (1o2)	$A_y r$	None	Considered by ICES WKDLSSLS (ICES, 2019a)
1-over-2 with UC (UC20)	$A_y r$	±20%	Applied in 2020 to provide advice for 2021 (ICES, 2021b)
1-over-2 with UC (UC80)	$A_y r$	±80%	Suggested by ICES WKDLSSLS (ICES, 2019a)
1-over-2 with UC and safeguard (UCIstat)	$A_y r b$	±80%	Suggested by WKDLSSLS2 and adopted in the ICES technical guidance for stocks in Category 3 (ICES, 2020b, 2022)

$$I_{\mathrm{stat}} = e^{\overline{\ln(B^s)} - 1.645\sigma_{\ln(B^s)}}, \tag{6b}$$

where I_{stat} was calculated from the modelled survey observations generated during the 25-year spin-up period. Uncertainty caps (UC) were applied to limit the interannual change in advice.

Implementation error was not considered; hence, the advised catch was removed from the OM without error as far as the population supported it in the following year, with the population collapsing otherwise.

Simulations

Because errors are imposed on modelled recruitment ($SD = 0.78$) and survey observations ($SD = 0.5$), each simulation was run with 500 replicates. Errors were compiled prior to running the MSE and were identical for all simulations.

Performance statistics

Performance of the HCRs was evaluated based on six statistics. Statistics (i) to (v) were calculated over the short (first five years; 1–5), medium (next ten years; 6–15), and long term (last 10 years; 16–25) of the projection period.

(i) Risk: The average probability of SSB being below the limit reference point B_{lim}, where the average is taken across replicates and the specified years of the projection period (ICES, 2013a). B_{lim} was taken as 308 (units relative to the virgin size of 1000), which is the value of SSB at the breakpoint of the segmented regression (the stock recruitment defined given virgin spawning biomass and the steepness of reference; see "Population dynamics and fisheries"), below which recruitment is impaired. HCRs with risk below 5% are considered precautionary (ICES, 2013a).

(ii) Mean yield: Median of the mean catch of the projection period across replicates.

(iii) Mean SSB: Median of the mean SSB of the projection period across replicates.

(iv) Mean *F*: Median of the mean fishing mortality for reference ages 1–3, $\bar{F}$, of the projection period across replicates.

(v) Mean Interannual Catch Variability (ICV): Median of the mean ICV of the projection period across replicates, where ICV is calculated as follows:

$$ICV = \left| \frac{C_{y+1}}{C_y} - 1 \right|. \tag{7}$$

(vi) Collapse: The proportion of replicates where SSB falls below 0.1% of virgin SSB.

Defining a precautionary CHR

Without a quantitative assessment to provide stock and exploitation status, it is unknown if a data-limited stock is overfished or undergoing overfishing. For this reason, we do not base the CHR on historical observations or simulations but use an iterative approach to search for the CHR that maximizes yield at acceptable levels of risk [as defined by performance statistics (i) and (ii)]. For the reference stock with each combination of fishing history and survey catchability (nine simulations in total), the model was projected forward for a range of CHR values, starting with a CHR of 1% of the modelled survey biomass index. This CHR was then increased by 1% for every subsequent simulation until all the risk statistics (i.e. short-, medium-, and long-term risk) exceeded 5%.

OM uncertainty

A sensitivity analysis of CHRs to fixed parameters and assumptions in the OM was conducted. This included investigations into growth, weight, steepness, and recruitment variability (Table 1) and resulted in a grid of 216 model runs. Uncertainty in maturity, natural mortality, and fishery selectivity was explored somewhat implicitly through use of interspecific relationships. Full details and results of this analysis are provided in Supplementary Section S3.

Comparison to trend-based rules

To evaluate whether CHRs can offer improved management of data-limited short-lived stocks, performance of the CHRs defined for the 50% overestimation scenario were compared to performance of the HCRs described in Table 2 also under the 50% overestimation scenario. This survey overestimation scenario was considered precautionary because the survey does not cover the entire distribution of the stock. Because trends in modelled biomass indices are relatively unaffected by the level of survey catchability, relative performance of the HCRs is expected to be similar for the other catchability scenarios.

Catchability misspecification

To investigate the consequences of misspecifying (under- or overestimating) survey catchability, performance of the CHRs defined for the 50% survey overestimation scenario were evaluated against trend-based rules under the higher and lower survey catchability scenarios.

Results

Defining a precautionary CHR

The three historic fishing scenarios resulted in median depletions to 43% for FH1 (median SSB = 431 units; 2.5th, 25th, 75th, and 97.5th percentiles of 179, 319, 593, and 1201), 30%

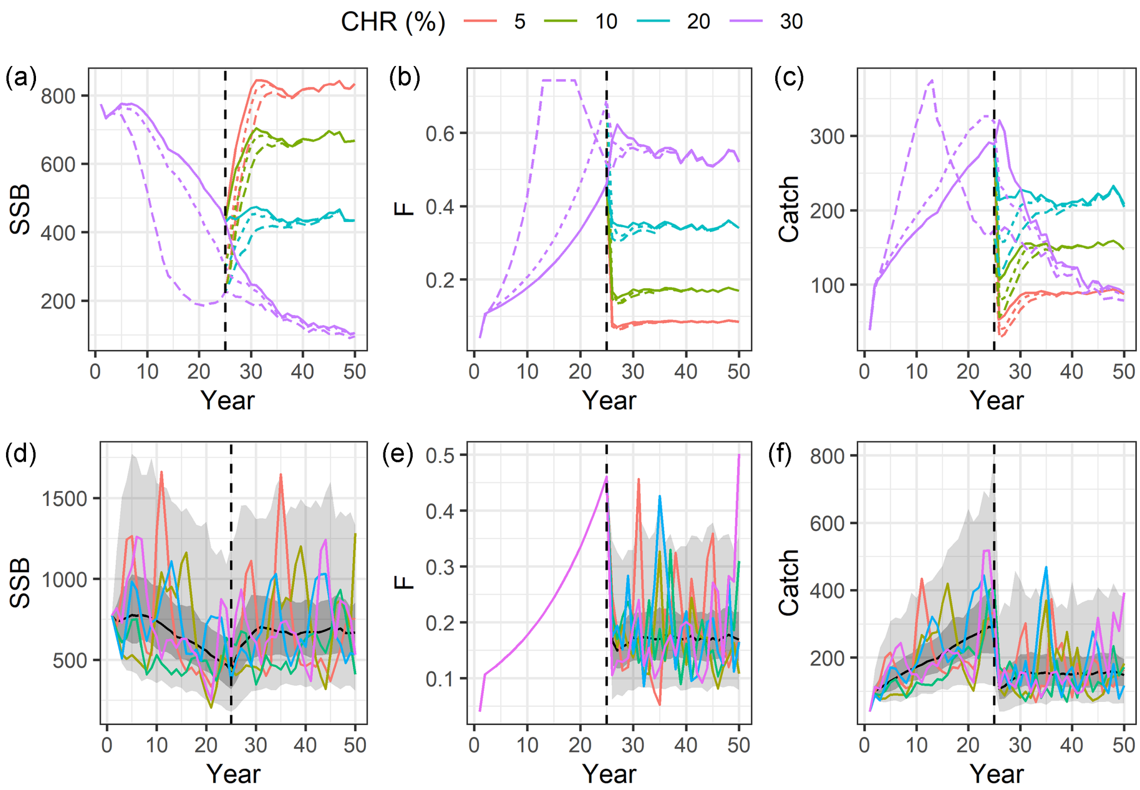

Figure 4. Top: Median trajectories for (a) SSB, (b) mean fishing mortality on reference ages 1–3, and (c) catch under three historic fishing scenarios followed by four CHRs (5%, 10%, 20%, and 30%). The Patterson fishing history is represented by solid lines, the one-way trip by dotted lines and the rollercoaster by dashed lines. Bottom: Median trajectories for the Patterson fishing history (FH1) followed by a 10% CHR for (d) SSB, (e) mean fishing mortality, and (f) catch, showing 50% and 95% confidence intervals (shaded) and individual trajectories for the first five replicates. Vertical dashed lines represent the start of the projection period.

for FH2 (median SSB = 298 units; percentiles of 88, 205, 427, and 906) and 23% for FH3 (median SSB = 225 units; percentiles of 16, 108, 371, and 799) of virgin spawning biomass, respectively, at the end of the spin-up period. For the Patterson (FH1) and one-way trip (FH2) scenarios, the stock was at its lowest level and declining and for the rollercoaster scenario (FH3), the stock was beginning to recover (Figure 4). Median trajectories under differing CHRs illustrate the need to adopt an appropriate level robust to uncertainty: setting the CHR too low results in an unnecessary loss of yield, while setting it too high can lead to large reductions in SSB and therefore lower catches (Figure 4).

The maximum CHRs that the simulated stock could sustain whilst keeping risk <5% ranged from 0% to 19% (Figure 5). In the short term for both the one-way trip (FH2) and rollercoaster (FH3) fishing histories, there was no sustainable CHR (i.e. even a 1% CHR resulted in risks that exceed 5%). Meanwhile a maximum sustainable CHR of 19% was obtained for the scenarios with no survey overestimation in the medium (FH1 only) and long term (all fishing histories).

The maximum precautionary CHR decreased with increasing levels of survey biomass overestimation because overestimations result in larger catches being advised and removed from the OM, and therefore larger decreases in stock size. The maximum precautionary CHR appears insensitive to past exploitation and initial depletion levels as all simulated fishing histories arrived at the same CHR value in the long term for each of the catchability scenarios. There was more variation in the short- and medium-term risk statistics because the more extreme fishing histories (FH2 and FH3) resulted in greater depletions during the spin-up period (Figure 4a). In these cases, risk was >5% at the beginning of the projection period and, even with no fishing, SSB could not increase to a level where risk was <5% in the short term. Given an appropriate CHR however, all trajectories show SSB to recover to a stationary phase in the medium to long term.

Comparison to trend-based rules

The 1-over-2 rule with 20% uncertainty cap (UC20) was the riskiest HCR, resulting in the highest levels of long-term risk and collapse for all fishing histories (Table 3). Widening the uncertainty cap to 80% (UC80) or removing it (1-over-2) reduced long-term risk substantially and reduced the probabilities of collapse to 1% or less. The 1-over-2 rule with 80% uncertainty cap and biomass safeguard (UCIstat) was the only trend-based rule that was precautionary for all fishing histories but also resulted in the lowest long-term yields.

A 12% CHR (the maximum value that can keep the risk of falling below $B_{\text{lim}} < 5\%$ in the long term; Figure 5) had the lowest short- to medium-term risks and the highest medium- to long-term yields for all fishing histories. Although the 1-over-2 rule with 80% uncertainty cap and biomass safeguard (UCIstat) resulted in slightly lower levels of long-term risk for FH1 and FH2, the potential yield forgone was more than 60%. The 12% CHR had the lowest long-term risk for FH3 because it was quickest to react to, and recover from, the high levels of depletion at the beginning of the projection period. Furthermore, medium to long-term yields converged to ap-

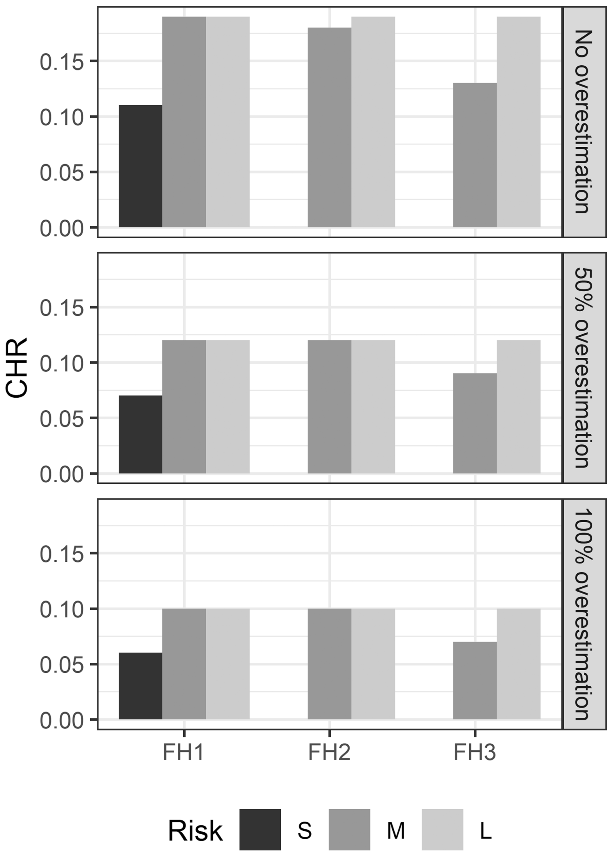

Figure 5. The maximum precautionary CHRs (risk <5%) for the modelled stock of sprat in the short (S), medium (M), and long (L) terms for each combination of survey overestimation (rows) and fishing history (columns).

proximately the same value for all fishing histories, providing further evidence that a CHR strategy is relatively unaffected by initial stock status. The CHR had either similar or higher levels of ICV in comparison to the 1-over-2 rules with an 80% uncertainty cap (UC80 and UCIstat) but, given the objective of maximizing yield whilst keeping risk <5%, a 12% CHR is the most effective strategy (Table 3).

Catchability misspecification

The effect of overestimating survey catchability by 50% when it is unbiased (i.e. adopting a CHR of 12% when the stock can sustain a rate of 19% because biomass is not overestimated; circles in Figure 6) unsurprisingly results in lower risks and lower yields. However, a CHR of 12% still results in higher long-term yields than any trend-based rule achieving long-term risk <5%. The effect of underestimating survey catchability (i.e. adopting a CHR of 12% when the stock can only sustain a rate of 10% because biomass is overestimated by 100% rather than 50%; squares in Figure 6) results in both higher risks and yields. In this case, a 12% CHR is still more precautionary than all trend-based rules in the short to medium term and all but the UCIstat (and UC80 for FH1) in the long term. Furthermore, 2%–3% increases to long-term risk beyond the precautionary 5% results in yields that are 1.7 to 3.7 times higher than those obtained with the trend-based rules achieving risks <5%.

Application to the channel sprat stock

Extra caution is needed when translating the results from simulations to real stocks of short-lived species, as the annual time-step in the model does not capture within year growth, which can be significant for small fast-growing pelagic fishes. A per recruit analysis was conducted to determine a correction factor for the level of bias introduced by implicitly assuming spawning weights at the time of the PELTIC survey (instead of the weights at survey time), yielding a corrective multiplier of 0.714 (Supplementary Section S4). Applying this multiplier to the 12% obtained under the 50% survey overestimation scenario, considered risk adverse given the uncertainty in true survey catchability, yields a CHR of 8.6%. This compares to an average harvest rate of 6.2% experienced by the Channel sprat stock between 2013 and 2019 (excluding the outlier in 2016; ICES, 2021b).

Discussion

Our initial case study used simulation testing to define a sustainable and precautionary CHR for the stock of sprat in the English Channel. In our evaluation, we followed the precautionary approach to ensure the sustainability of the stock, without disregarding the needs for this fishery to be viable. Our results show a CHR strategy outperforms the 1-over-2 rule, which is starting to be used to manage data-limited stocks of short-lived species in the northeast Atlantic. This is consistent with Fischer et al. (2021) who concluded that the *rfb*-rule does not work well for short-lived species and Carruthers et al. (2014) who proposed fixed exploitation strategies relying on current information may be particularly suited to short-lived life history types.

There are several reasons why a CHR strategy is suited to the management of short-lived stocks: A CHR is essentially a 1-over-1 rule: It depends only on the most recent index observation and is therefore quick to react to the fluctuations in stock size typical of short-lived pelagic species (Fischer *et al*., 2021). A 1-over-2 rule, on the other hand, depends on the most recent observation and the two before. For species that typically live to a maximum of 6 years, with the bulk of the population in ages 1–3, the advice derived from the index is influenced partly by fish that will be removed from the population before the advice is implemented. In the event of a sudden boom or bust in recruitment, the rule responds to the incoming cohorts, but relative to the strength of previous cohorts (as encapsulated in the indices of the two previous years). These fluctuating recruitment events will continue to influence the advice somewhat for 3 years and can lead to some dissociation between the advice and the reality of the population dynamics. Thus, the CHR-based advice will always mirror closer the boom or bust of these highly fluctuating short-lived populations.

Our results show a CHR strategy to be relatively insensitive to past fishing pressure and depletion; a desirable property when managing stocks that lack a quantitative assessment of stock and exploitation status. However, basing management on a single observation carries the undesirable properties of higher sensitivity to erratic survey observations and higher ICV, although these are, to some extent, inherent from the variable dynamics of short-lived species. Conversely, a benefit of the CHR rules is that an occasional major observation error would not affect the advice longer than a single year. In

Table 3. Performance statistics for each HCR (ordered by long-term risk) under the 50% survey overestimation scenario in the short (S), medium (M), and long (L) terms. Acronyms of compared Harvest Control Rules are defined in Table 2 where, in this case, CHR_{12} corresponds to a 12% constant harvest rate.

HCR	Risk			Collapse	Yield			Mean SSB			Mean F			Mean ICV		
	S	M	L		S	M	L	S	M	L	S	M	L	S	M	L
Patterson (FH1)																
UCIstat	30%	10%	1%	0%	207	110	74	473	708	866	0.345	0.125	0.070	0.420	0.370	0.307
CHR_{12}	7%	3%	3%	0%	162	189	189	598	662	654	0.207	0.220	0.220	0.439	0.394	0.378
UC80	33%	20%	4%	0%	222	151	122	450	601	759	0.386	0.216	0.131	0.387	0.378	0.330
1o2	36%	30%	13%	0%	240	184	177	433	506	615	0.426	0.292	0.226	0.443	0.487	0.428
UC20	37%	40%	41%	36%	241	159	107	411	498	551	0.447	0.338	0.244	0.180	0.181	0.178
One-way trip (FH2)																
UCIstat	52%	13%	1%	0%	171	76	56	340	689	895	0.388	0.093	0.049	0.498	0.393	0.299
CHR_{12}	20%	4%	3%	0%	136	188	189	529	658	654	0.198	0.219	0.220	0.510	0.403	0.378
UC80	58%	35%	10%	0.4%	195	136	119	289	504	706	0.533	0.227	0.143	0.428	0.407	0.350
1o2	61%	49%	25%	0.2%	209	175	189	268	366	516	0.599	0.353	0.286	0.489	0.581	0.478
UC20	67%	68%	68%	65%	224	46	0	190	12	0	0.884	1.986	2.000	0.200	0.451	0.483
Rollercoaster (FH3)																
CHR_{12}	35%	9%	4%	0%	112	181	188	460	644	654	0.185	0.216	0.219	0.514	0.418	0.378
UCIstat	61%	27%	4%	0%	157	115	92	264	561	820	0.417	0.166	0.091	0.451	0.421	0.325
UC80	62%	39%	12%	1%	161	134	120	249	470	676	0.476	0.242	0.147	0.417	0.419	0.351
1o2	66%	58%	37%	1%	177	158	178	220	290	455	0.571	0.394	0.306	0.504	0.584	0.515
UC20	60%	44%	39%	36%	159	109	76	256	474	607	0.438	0.301	0.204	0.178	0.182	0.178

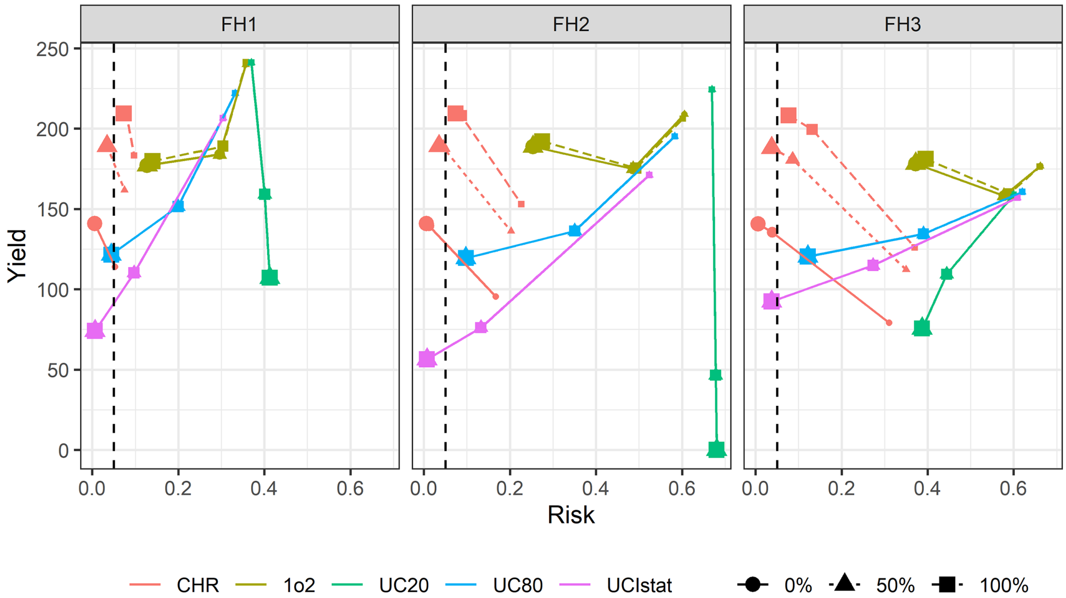

Figure 6. Trade-off graphs of risk and yield. Lines show evolution of yield against risk through the short, medium, and long terms with increasing symbol sizes, and shapes represent the statistics for different survey overestimation scenarios. HCRs are defined in Table 2 where, in this case, CHR corresponds to a 12% constant harvest rate: the optimum for a 50% overestimation of survey biomass. The vertical dashed line represents 5% risk and percentages (symbols) refer to 0%, 50%, and 100% overestimation of the survey relative to the actual population.

any case, errors in observations propagate into errors in catch advice and in realized harvest rates vs. the intended ones, increasing risks. For that reason, the MSE must duly account for observation errors (Siple *et al.*, 2019; Sánchez-Maroño *et al.*, 2021) and selected CHRs must show robustness to such key uncertainty. Future applications of CHR could add further precaution by considering a biomass safeguard that reduces catch advice when the index falls below a threshold level. However, for many data-limited stocks, such a threshold cannot be directly aligned with stock status and reproductive capacity, and may have little influence on the advised catches (ICES, 2020b; Fischer *et al.*, 2021). Here, we showed a 12% CHR conformed to the precautionary approach by minimizing risks to <5% (8.6% CHR after applying the corrective multiplier to account for intra-annual differences in weight). To cope with ICV, uncertainty caps could be considered in conjunction with a CHR but, as for trend-based rules applied to short-lived species, may introduce unnecessary risks to the stock when requiring rapid reduction of catches and/or prevent recovery of yield following a drop of catch advice (Fischer *et al.*, 2020, 2021; Sánchez-Maroño *et al.*, 2021).

CHRs are commonly selected based on biological reference points or the experience of the fishery, since MSE often requires high amounts of data and time (Caddy and Mahon, 1995). CHRs have been used for decades in the northeast Atlantic to manage Norway lobster stocks where abundance indices are available. For these stocks, the CHR has been based on biological reference points ($F_{\max}$, $F_{0.1}$, $F_{35\%}$) estimated by a per recruit analysis, whereas for other data-limited stocks, it has been borrowed from neighbouring stocks with similar characteristics (ICES, 2013b).

While biological reference points could be considered a valid data-limited method to estimate CHRs, they do not consider the uncertainty associated with observation errors or the population dynamics (e.g. shape of the stock–recruitment relationship). Therefore, the appropriateness of a CHR estimated with this approach will depend on whether the assumptions used in the estimation are met (Deroba and Bence, 2008). Unlike MSE, biological reference points cannot be used to identify an optimal harvest policy that meets multiple management objectives (e.g. maximize yield and minimize risk of depletion). MSE frameworks specifically designed for stocks lacking a quantitative stock assessment (e.g. Fischer *et al.*, 2020; Sánchez-Maroño *et al.*, 2021) are an opportunity to make progress in the development of effective science-based management policies for data-limited fisheries.

Several studies have highlighted the importance of tuning OMs and MPs in MSEs to specific stocks where data allow (Jardim *et al.*, 2015; Carruthers *et al.*, 2016; Dowling *et al.*, 2019; Siple *et al.*, 2019; Mildenberger *et al.*, 2021). This is especially important when considering a CHR strategy because the fixed proportion of the survey biomass index, used to inform catch advice, is directly related to the unknown underlying population. We therefore considered survey catchability and initial stock status to be the key uncertainties and developed our simulation trials via a factorial design with three contrasting scenarios for each. Our results suggest that the performance of a CHR strategy is relatively unaffected by initial stock status but sensitive to survey catchability, where the converse is true for trend-based catch rules. For this reason, we select a conservative 50% overestimation of the survey catchability when proposing a CHR. Because some information was available to parameterize the stock biology, dynamics, and observation CV, a reference case was adopted based on expert opinion and precautionary considerations. Alternative conditionings of the OM were explored in Supplementary Section S3 and suggest that our CHR is reasonably robust to a wide range of plausible life histories.

It was necessary to borrow some stock characteristics from studies of North Sea sprat. Recruitment variability was implemented as log-normal error with high standard deviation

(ICES, 2020c). While this is not ideal, the approach creates an evidence-based range where the extent of uncertainty on a logarithmic scale may be representative of the true scale. Autocorrelation in recruitment was also not implemented based on the North Sea stock (ICES, 2019b). This may be expected of the Channel stock owing to their short lifespan, high natural mortality, and lack of any apparent interannual associations in stock sizes, length, or age class structures. Without information on recruitment and vital rates, it was necessary to condition the OM based on established interspecific relationships (Fischer *et al.*, 2020). The stock–recruitment relationship was parameterized based on a conservative value of steepness (as detailed below), while maturity and natural mortality were parametrized according to the fitted growth parameters. This resulted in a relatively high natural mortality that, along with high recruitment variation, gives rise to the "boom and bust" dynamics characteristic of short-lived species (Siple *et al.*, 2021).

Current best practice is to adopt conservative parameter values in the absence of informative data (Punt and Donovan, 2007; Dowling *et al.*, 2019), which is the approach we have taken in setting up our OMs: the steepness is based on a meta-analysis (Myers *et al.*, 1999) but can be considered an underestimate (Thorson, 2020), the SDs on recruitment and survey observations are borrowed from the North Sea sprat stock and represent values towards the higher end of the expected ranges (but consistent with clupeiods; Thorson *et al.*, 2014), our value of B_{lim} used to define risk is higher than the usual default of 20% of virgin SSB (Punt *et al.*, 2016), and we adopt 50% overestimation of survey catchability even though the PELTIC survey likely underestimates biomass due to incomplete coverage of the stock area (see "Operating Model uncertainty" in Supplementary Section S3). This precaution comes at the expense of lower advisable catches; however, realized harvest rates of the sprat fishery have rarely exceeded 10% (average excluding the outlier in 2016 = 6.2%; ICES, 2021b). A CHR of 8.6% may therefore be sufficient and will prevent unnecessary reductions in catches, which can arise from trend-based catch rules coupled with advice change limits and precautionary buffer reductions. Use of simulation testing to select CHRs robust to the uncertainties of the fundamental parameters affecting the fisheries, monitoring systems, and population dynamics of data-limited stocks (by selecting often risk adverse parameters for precautionary reasons) may result in low sustainable harvest rates relative to the F_{MSY} targets of the fisheries policies in the European Union and the United Kingdom. This trade-off affects the management of data-limited stocks, which can only be precautionary at the expense of losing catch opportunities (vs. MSY) given the limited knowledge available (Fischer *et al.*, 2020). This is a weakness of the current approach, and may be problematic for adoption in fisheries that have exerted significant harvest rates in the past, and where other procedures might be required (Carruthers *et al.*, 2016; Fischer *et al.*, 2021). However, this was not the case for Channel sprat and facilitated the acceptance of the proposed CHR among stakeholders, overcoming some of the problems (like reducing catch opportunities) that had arisen while trying to manage this data-limited short-lived species in recent years.

Care must be taken when applying results from our initial simulation study to the real-world stock. A sensitivity analysis (Supplementary Section S3) suggests CHRs are sensitive to growth rates, resilience, and recruitment variability. While our reference case was conditioned on existing data and adopts precautionary values of steepness, catchability, and recruitment variability, inaccuracies in the estimated growth rate may contribute to increased risks. Given the fast growth of short-lived species, within-year increments in weight and other biological processes could be substantial, particularly for younger ages. We attempted to account for differences in weight at the time of the survey vs. the time of spawning via a per recruit analysis and applied a corrective multiplier to downscale the CHR. In future, it would be ideal to condition OMs based on sub-annual time steps and to include these time-dynamic processes explicitly in the modelling.

The stock structure of sprat in the northeast Atlantic is uncertain, with no clear genetic separation from the sprat that reside in the Celtic Sea to the west or the North Sea stock to the east (Mckeown *et al.*, 2020; Quintela *et al.*, 2020). Allied to this is a lack of certainty in the potential degree of annual mixing. This was not explicitly accounted for in our simulations, although the observation error does generate erratic survey observations that could be representative of a range of factors including immigration and emigration and high variability in natural mortality, thereby acknowledging some of the associated uncertainty with respect to survey catchability. Furthermore, distributions of sprat eggs showed hot spots generally to the east and west of the border between ICES divisions 7.d and 7.e (Milligan, 1986), suggesting quite strong separation between the western and eastern English Channel. This is supported by recent PELTIC surveys, which have indicated that sprat are present outside the dominant fishing area of Lyme Bay at much lower abundances (ICES, 2018c, 2019c) that would not warrant fishing activity. This, in addition to their common inshore schooling behaviour, would suggest mixing to be restricted; however, movement from summer spawning grounds to winter feeding grounds is still to be fully elucidated.

Extreme annual stock size changes are problematic to manage, especially for short-lived species, with management systems not able to respond appropriately if based on data and advice that are not current (ICES, 2020b; Sánchez-Maroño *et al.*, 2021). Progress in the management of the Channel sprat stock is two-fold. First, as of July 2022, advice moved from a calendar year schedule (with an intermediate year between the last survey observation and implementation of the associated catch advice) to a seasonal July to June cycle based on the October PELTIC survey, such that advice is closely associated with the stock status intercepted by the persecuted fishing activity. Further, with advice based on the most recent biomass index and a CHR, it is decoupled from the direct influence of the proceeding 2 years' biomass index that are shown here, through simulation testing of trend-based rules, not to improve performance of a sustainable CHR.

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Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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Author contributions

N.W. designed the research; R.O., J.v.d.K., and P.C. performed data processing; N.W. performed the analysis with input from all authors; N.W. drafted the first version of the manuscript; and all authors took part in writing and revising subsequent versions.

Data availability

The data and code underlying this article will be shared on reasonable request to the corresponding author.

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