Can we fish on stocks that need rebuilding? Illustrating the trade-offs between stock conservation and fisheries considerations

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Abstract

In the Northeast Atlantic, advice for many fish stocks follows the ICES MSY approach, where a zero catch will be recommended if the stock is below its limit reference point, B_{lim} , and cannot rebuild in the short-term. However, zero catch advice are rarely implemented by managers. This study used medium-term stochastic forecasts with harvest control rules (HCRs) to investigate the consequences of allowing reduced fishing below B_{lim} . We applied the method to western Baltic herring and North Sea cod, two contrasting species currently estimated below B_{lim} . We show that the minimum rebuilding probability of 95% required by the MSY approach could be impossible to reach in the short-to medium-term. When this is the case, a lower prob-

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ability may need to be considered instead in the short-term. Recruitment is the largest source of uncertainty in stock response to management, and can exceed differences between HCRs. Reference points should be estimated in accordance with current recruitment levels if they are to be used for short-term advice or as realistic rebuilding targets. For both stocks, it is possible to keep fishing at reduced levels for similar cumulative catch, SSB and risk on the stock in the medium-term compared to no catch below B_{lim} . Medium-term trade-offs between stock conservation and fisheries considerations may be needed when fishery closure cannot be implemented in practice.

Keywords: harvest control rule, management strategies, MSY approach, recovery, scientific advice, stock assessment

1. Introduction

Globally, one third of the marine fish stocks in the world are fished unsustainably (FAO, 2018), i.e. fish abundance is below the abundance at maximum sustainable yield (MSY). While most of those stocks are not scientifically assessed or managed (Hilborn and Ovando, 2014), several managed stocks are still below their limit reference point in the Northeast Atlantic (ICES, 2019h,d,e,j,k,c) and the Baltic Sea (ICES, 2019b). Usually, fisheries management involves two different processes. First, a scientific process where the stocks are assessed and scientific advice are produced to inform managers on sustainable fishing levels. Second, management decisions are taken at the European or national level and, if relevant, total allowable catches (TACs) are given to fishers.

There is currently an international endorsement of the precautionary ap-

proach to fishing (Garcia, 1994; Richards and Maguire, 1998), where fish stocks should be sustainably managed while accounting for uncertainty in stock perception, in management and in risk. Fish stocks are usually managed using reference points, which are used as target to get to or stay above (e.g. fishing mortality and biomass at the MSY equilibrium, F_{MSY} and B_{MSY} respectively) or trigger (threshold) or limit not to fall below (e.g. limit reference point, B_{lim}). Harvest control rules (HCRs) are one management tool that is often used to produce advice for managers on fishing mortality (Kvamsdal et al., 2016) and their shapes are often defined using biological reference points. HCR shapes differ between countries but usually fishing mortality is constant and set to its target when stock biomass is above the trigger or threshold reference point. Fishing mortality then decreased linearly with stock biomass between the trigger and the limit reference point. Some HCRs decrease linearly to zero (New Zealand Ministry of Fisheries, 2011; ICES, 2019a) and others decrease to a lower level of fishing mortality (NRC, 2014; ICCAT, 2019).

According to the United Nations Fish Stocks Agreement (UN, 1995), the risk of the stock falling below its limit reference point should be very low. The precautionary approach below the limit reference point has been applied differently around the world and different levels of risk have also be taken. Risk on the stock, estimated as the probability to fall below the limit reference point, vary between jurisdictions and stocks from 5 to 50% (NRC, 2014; ICES, 2019a; ICCAT, 2019). According to Wetzel et al. (2016), rebuilding probability should be above 60% to allow successful rebuilding above the target within the necessary time frame. Some jurisdictions acknowledge that

39 fishing mortality should be reduced as much as possible when stock biomass is
40 below the limit reference point (NAFO, 2004; DFO, 2009; Australian Govern-
41 ment, 2018; ICCAT, 2019) and others allow for fishery closure (New Zealand
42 Ministry of Fisheries, 2011; ICES, 2017a). While precautionary considera-
43 tions are necessary at low stock size since stock dynamics at these levels are
44 usually unknown and poorly understood; reduced or no fishing below the
45 limit reference point conflicts with fisheries socio-economic considerations.

46 In the Northeast Atlantic, the International Council for the Exploration of
47 the Sea (ICES) provides advice on sustainable fishing opportunities for many
48 fish stocks upon request from clients. Clients are mostly fisheries authori-
49 ties at the international or national level, which use the advice to manage
50 their stocks. Managers request single species advice that ensures sustainable
51 fisheries management but while all clients are subject to the same interna-
52 tional agreements, policies may differ at national levels. Many of the stocks
53 are shared between different fisheries authorities so ICES develops advice
54 consistent with common international agreements. Advice in ICES is given
55 annually by performing short-term stock projections from the intermediate
56 year to the advice year (intermediate year +1) under different fishing scenar-
57 ios. The outputs of these scenarios are presented in the advice sheet but only
58 one scenario is used as advice for managers (stated in the headline of the ad-
59 vice sheet). The advice follows the modeling and reference point assumptions

60 that were agreed on during the last benchmark¹ for the stock.

61 For stocks with reliable quantitative or qualitative assessments (ICES
62 category 1 and 2 stocks), when an agreed and evaluated management plan
63 is not already in place between the different fisheries authorities managing
64 the stocks, ICES advice is based on the maximum sustainable yield (MSY)
65 approach, a framework that is based on MSY considerations and consistent
66 with the precautionary approach (ICES, 2019a). The MSY approach is based
67 on an advice rule that uses reference points as thresholds and targets that
68 define the shape of the HCR. The MSY approach notably stipulates that
69 fishing mortality cannot exceed F_{MSY} , becoming therefore the maximum F
70 that would be advised on a stock. A reduction in F would be recommended if
71 the stock is below the trigger reference point, $MSY B_{trigger}$ ². Also, according
72 to the MSY approach, the stocks should be above the biomass limit reference
73 point, B_{lim} ³ with a 95% probability, meaning that the risk for the stock to
74 fall below B_{lim} should be below 5%. As a result, F_{MSY} is estimated in
75 ICES so that there is less than 5% chance that applying the HCR described

¹Process held every 3-5 years where the data, the model and its configuration are agreed on, the stock is assessed, and reference points are estimated. Inter-benchmarks can be used for minor changes such as model configurations or data modifications. See ICES (2019a) for more detail.

²In ICES, $MSY B_{trigger}$ is usually estimated as the 5th percentile of the spawning stock biomass (SSB) when fished at F_{MSY} , but, when the variations in SSB do not allow for the 5th percentile to be estimated (e.g. the stock was not fished at F_{MSY} for at least 5 years), it can also be set as the 95th percentile (B_{pa}) of the biomass below which the stock is considered to have a reduced reproductive capacity (B_{lim} .) (ICES, 2017a).

³Spawning stock biomass limit reference point used in ICES under which the stock is believed to have impaired recruitment.

above would lead to the stock falling below B_{lim} in the long-term. The precautionary constraint in the estimation of F_{MSY} by ICES differs from other approaches around the world, and necessitates an estimate for B_{lim} before MSY reference points can be estimated. ICES includes an additional precautionary consideration in its advice rule that if a stock is below B_{lim} and cannot rebuild above B_{lim} in a two-year forecast when $F = 0$, zero catch for the following year would be recommended to allow for the stock to rapidly rebuild above B_{lim} (ICES, 2019a).

In 2019, 18 stocks (category 1 and 2) assessed by ICES were estimated below B_{lim} and of those, 13 got a zero catch advice for 2020. However, zero catch is rarely implemented by managers (Rosenberg et al., 2006; Cadrin and Pastoors, 2008; Kvamsdal et al., 2016). For instance, among these 13 stocks, at least 7 got a positive TAC in 2020 (EU, 2019b; EU and Norway, 2019, 2020). One possible reason is that, after implementation of the Landing Obligation (EU, 2013), zero catch cannot be realistically achieved in practice, because many stocks are fished by multiple fleets and sometimes in a mixed fishery. Therefore, a zero catch on a stock could mean an impossibility of fishing on other stocks in an entire geographical area and several fleets going out of business. In other jurisdictions such as in the US, zero catch is never advised as not realistically implementable due to socio-economic and mixed fisheries considerations (U.S. Government, 2007). In case of zero catch advice in ICES, there is little guidance for managers to set a TAC that balances biological and socio-economic sustainability considerations in the medium-term. The medium- to long-term consequences on fish stocks of not following zero catch advice are unclear. It seems therefore necessary to understand the

101 trade-offs between keeping a yield to save a fishery and risking a stock collapse
102 or slowing a rebuilding rate.

103 In this study, we investigated the consequences of allowing fishing when
104 a stock is below B_{lim} compared to the current MSY approach, by developing
105 a stochastic forecast that tests different HCRs setting annual fishing quotas.
106 We were notably interested in the effects induced by these HCRs, on the
107 stock, in terms of stock size and risk, but also on the fishery, in terms of
108 future cumulative catch. We chose to look at different time frames in the
109 short- (0-5 years) to medium-term (5-10 years). Current scientific advice
110 in ICES is largely based on deterministic short-term forecasts (2 years), we
111 simply extended this period and included uncertainties in the key processes
112 to investigate longer-term consequences. The forecast was built to account
113 for uncertainty in the current perception of the stock but also in future
114 dynamics. We did not look at long-term simulations as we were interested
115 in the rebuilding period between unsustainable and sustainable stock levels
116 (Gröger et al., 2007; Rosenberg and Brault, 1991).

117 The simulations were based on different recruitment assumptions, fishing
118 scenarios and fishing targets. The different recruitment assumptions enable
119 to investigate stock rebuilding for different plausible recruitment regimes.
120 We focused on different fishing scenarios that include HCRs where fishing
121 mortality varies with SSB according to limit and target reference points,
122 where reduced fishing is possible or not below B_{lim} . The forecast was devel-
123 oped as an extension to the **stockassessment** R package for the state-space
124 assessment model (SAM) (Nielsen and Berg, 2014; Berg and Nielsen, 2016).

125 We applied the stochastic forecast to two fish stocks currently assessed

126 with SAM: North Sea cod and western Baltic spring-spawning (WBSS) her-
 127 ring. These stocks were chosen because they are currently considered at risk
 128 according to the ICES precautionary approach but they contrast by the fact
 129 that WBSS herring is a pelagic species that has been recommended a zero
 130 catch for two years (ICES, 2018a, 2019i) while North Sea cod is a demersal
 131 fish stock that, despite being currently estimated below B_{lim} , still is esti-
 132 mated to recover in the short-term in the 2019 advice (ICES, 2019f), and
 133 was therefore not subject to recommended fishing closure for 2020. WBSS
 134 herring is a good example of current failure of advice being implemented
 135 into management as the zero catch advice was never applied in practice. The
 136 European Union and Norway still allowed positive TACs to be taken in 2019
 137 and 2020 in the western Baltic, Kattegat and Skagerrak (EU, 2018b, 2019a,b;
 138 EU and Norway, 2019, 2020), despite a zero catch advice for 2019 and 2020
 139 (ICES, 2018a, 2019i). The response from managers was to reduce the TACs
 140 by 42% from 2018 to 2019 (EU, 2017, 2018a) and by 13% from 2019 to 2020,
 141 resulting in a current TAC in ICES Subdivisions 20-24 for 2020 of 34337
 142 tonnes. WBSS herring is taken as bycatch in the industrial sprat fishery in
 143 ICES Division 3.a as well as in mixed stock catches in ICES Divisions 3.a
 144 and 4.a East (ICES, 2019l). A zero catch would mean closing the Norwegian
 145 herring fishery in the eastern North Sea and industrial fisheries operating
 146 in 3.a, and this can explain why it was never applied by managers. Cod
 147 is caught in mixed fisheries and is the choke species⁴ for many fleets in the
 148 North Sea (ICES, 2019g). Such as for WBSS herring, if in the future cod is

⁴In mixed fisheries, stock that has the lowest quota and, due to the Landing Obligation, forces a fleet to stop fishing even if it still has quotas for other stocks.

not estimated to rebuild in the short-term forecasts used for scientific advice, closing the fishery for cod would have important consequences for the fishing industry and has therefore little probability of ever being applied in practice.

2. Methods

2.1. Stochastic forecasts

We developed the forecast function in the SAM package to enable the outcome of HCRs to be implemented in the assessment projections for both the single and multifleet versions of the package. The source code can be found at <https://github.com/vtrijoulet/SAM/tree/master2> for the single fleet version and at <https://github.com/vtrijoulet/SAM/tree/multi2> for the multifleet version.

2.1.1. Forecast method

The stochastic forecast can be run for a specified number of years as a continuity of the assessment model. The process error assumptions from the assessment model are used in the forecast, e.g. process errors in fish numbers, except for process error on fishing mortality. The last year of the assessment model is used as starting point for the forecast. The estimates in the last year of the assessment and their uncertainty are used to simulate replicates of stock numbers at age and fishing mortality at age for each fleet. This enables to account for the uncertainty in the perception of the current stock level. In this study, 5000 replicates were used after checking they were enough to get outputs that were not sensitive to the number of iterations.

Similarly to what is used in forecasts used for advice, in the intermediate year, catch is fixed to the agreed TAC for this fish stock. A management

173 strategy is applied thereafter and until the end of the forecast period to all
174 replicates independently.

175 For convenience, in this study, simulation trials (STs) are defined by a
176 combination of recruitment assumption, fishing scenario or harvest control
177 rule (HCR) and target and limit reference points that inform the shape of
178 the HCR. The different possible ST options are described below.

179 2.1.2. Recruitment assumptions

180 The forecast simulates population development and fishery under three
181 contrasting recruitment assumptions to investigate the robustness of HCR
182 performance to different productivity regimes:

- 183 • Recruitment is randomly sampled with replacement from the assess-
184 ment model recruitment estimates in specified assessment years: this is
185 the most commonly used assumption in short-term forecasts used for
186 scientific advice. For instance, if recruitment is sampled in the final
187 assessment years, this is equivalent to assuming recruitment stays at
188 current levels.
- 189 • Hockey-stick stock recruitment relationship: recruitment varies with
190 spawning stock biomass (SSB) following a segmented regression
191 (hockey-stick) relationship (Barrowman and Myers, 2000). The pa-
192 rameters of the stock-recruitment relationship are estimated using the
193 assessment model estimated pairs of SSB and recruitment in specified
194 years. The standard deviation of the recruitment residuals was used to
195 inform random errors around the recruitment estimates resulting from
196 the hockey-stick relationship. This recruitment assumption is what

resemble the most the assumption taken when estimating the MSY reference points for ICES fish stocks.

- Random walk with negative drift: log recruitment follows a random walk that decreases over time given a specific proportion of the variance estimated for recruitment in the assessment model (if random walk was assumed in the assessment model). Median recruitment decreases over time from the last year of assessment but the variance of log recruitment increases linearly with time whereas the first two recruitment assumptions have constant variance. It is important to note that while a random walk model is adequate for short-term forecasts, recruitment variations under this assumption could increase with time to unrealistic high values so it may not be realistic for longer forecasts.

2.1.3. Harvest control rules

Management was assumed to control the average total fishing mortality ($\bar{F}$) on a fish stock in a forecast year as a function of the SSB in the previous year via HCRs. The shape of the HCRs is informed by a reduced fishing mortality level and three reference points: (i) $MSYB_{trigger}$, which is the biomass reference point that triggers a cautious response within the ICES MSY framework; (ii) B_{lim} , the limit reference point and (iii) F_{target} which is the maximum fishing mortality that is applied on the stock. In the ICES MSY approach, it is set to F_{MSY} .

The HCRs were defined following discussion with a stakeholder representative and differed in how $\bar{F}$ varied when SSB was below $MSYB_{trigger}$ as illustrated in Figure 1. HCR 1 corresponds to the ICES MSY approach

Figure 1: Harvest control rules (HCRs) developed in the stochastic forecast. Five HCRs can be chosen from (1-5) for any given set of reference points (F_{target} , B_{lim} and $MSYB_{trigger}$) and $lowF$ level.

221 (when the stock cannot rebuild in the short-term), where there is no fishing
 222 when SSB is below B_{lim} . For HCR 2, $\bar{F}$ decreases linearly from the targeted
 223 fishing mortality (F_{target}) at $MSYB_{trigger}$ to 0 when $SSB = 0$. HCR 3 is an
 224 option where $\bar{F}$ is reduced to a specified low value when SSB is below B_{lim} .
 225 HCR 4 is similar to HCR 2 but $\bar{F}$ is fixed to this low level for low values of
 226 SSB. Finally, HCR 5 is the case where $\bar{F}$ is reduced to a constant low level
 227 when SSB is below B_{lim} and increases linearly to F_{target} when SSB increases
 228 from B_{lim} to $MSYB_{trigger}$.

229 2.2. Application to WBSS herring and North Sea cod

230 For WBSS herring, the stochastic forecast used the results from the
231 2019 assessment (ICES, 2019l). Assessment model scripts, data files, and
232 results are publicly available on stockassessment.org under the name
233 “WBSS_HAWG_2019”. The assessment was run for the years 1991 to
234 2018. For North Sea cod, the 2019 assessment results were used (ICES,
235 2019m) and can be found on stockassessment.org under the name
236 “nscod19_ass01_October”. Cod was assessed from 1963 to 2019.

237 2.2.1. Simulation trials parameterization

238 The assumptions used for the recruitment assumptions for herring and
239 cod are summarized in Table 1. The years used for the recruitment ran-
240 domly sampled from the assessment estimates were the same as those used
241 in the latest scientific advice for each species (ICES, 2019i,f). Recruitment
242 being low at the end of the time series for both species, this assumption re-
243 sulted in assuming recruitment in the forecast will stay at current low levels.
244 For the hockey-stick recruitment assumption, the starting year used for the
245 SSB and recruitment pairs was the same as the one used to estimate refer-
246 ence points for both stocks (ICES, 2018c, 2017b, 2015). This recruitment
247 assumption is the one that resembles the reference point estimation assump-
248 tions the most. However, it is not identical as reference points for both stocks
249 were estimated using earlier estimates of SSB and recruitment, available at
250 the time of the benchmarks. Also, note that the reference point estimates
251 were obtained using the “Eqsim” procedure based on a weighted average of
252 Ricker, Beverton-Holt and hockey stick stock-recruitment curves. This re-
253 cruitment assumption is the most optimistic as it assumes that recruitment

may increase in the future if SSB increases but it is also the only assumption that can simulate stock collapse below B_{lim} , as the curve decreases to zero. In the most recent assessment period, recruitment has been low but with a slight decreasing trend for herring and stable since 1998 for cod but slightly decreasing since 2010. Therefore, to cover a more pessimistic development for both stocks, a further decrease in median recruitment was implemented. Both stocks were assessed in 2019 assuming a random walk in recruitment in SAM. We used the estimated standard variation of the estimated recruitment for each stock to model a random walk with a negative drift of 10% these standard deviations. This proportion was chosen to get a smooth decrease in median recruitment over time for both species without producing a too unrealistic steep decline. The random walk assumption was the most pessimistic assumption since it assumed median recruitment decreased over time. The resulting recruitment for the three assumptions are illustrated in Appendix A1. Comparing the three recruitment option outputs should give a large range of plausible recruitment scenarios from pessimistic (random walk with drift), neutral (randomly sampled) to more optimistic (hockey-stick).

Reference points and reduced fishing mortality value used to parameterize the HCRs are summarized in Table 2. Three F_{target} levels were considered for the forecasts. F_{MSY} is commonly used in management advice and is notably the current F_{target} in the MSY approach used for management of both WBSS herring and North Sea cod. It was therefore chosen as main F_{target} in the study. We also investigated the effect of reducing or increasing the F_{target} to reflect its uncertainty or even a change in future F_{MSY} . We used two other F_{target} levels for each species defined as the EU Baltic Sea Multiannual

Table 1: Summary of recruitment assumptions for both stocks. The hockey-stick parameters SSB_i and R_i are the x and y coordinates respectively of the inflection point of the stock-recruitment curve with their coefficient of variation (CV) given in parenthesis and sd is the standard deviation around the recruitment residuals on log scale. $\log(\sigma)$ is the estimate of the log of the standard deviation for the random walk taken from the SAM fit (aka. $\log SdLogN$) and used in the forecast. The *drift* parameter is the percentage of standard deviation used to decrease the mean of the random walk in the forecasts.

Assumptions	Sampled		Hockey-stick		Random walk	
Stocks	Herring	Cod	Herring	Cod	Herring	Cod
Years	2013-2017	1998-2018	1991-2018	1988-2019		
Parameters			$SSB_i = 218788$ (CV=0.38) $R_i = 3923183$ (CV=0.35) $sd = 0.35$	$SSB_i = 81331$ (CV=0.05) $R_i = 283433$ (CV=0.13) $sd = 0.64$	$\log(\sigma) = -1.33$ $drift = 10\%$	$\log(\sigma) = -0.23$ $drift = 10\%$
Figure	A1.1	A1.2	A1.3	A1.3	A1.1	A1.2

279 Plan 2018 lower and upper reference points (F_{lower} and F_{upper} ⁵) for herring
 280 (European Commission, 2018a; ICES, 2019i) and the North Sea Multiannual
 281 Plan 2018 for cod (European Commission, 2018b; ICES, 2019f). The low
 282 fishing mortality ($lowF$) for HCRs 3-5 is set to 0.1 for both species, which
 283 corresponds to around one third of F_{MSY} .

284 The catch constraint used in the stochastic forecast for the intermediate
 285 year (2019) was the same as the one used in scientific advice for both species
 286 (ICES, 2019i,f) and is summarized in Table A2.1. The forecast was run for
 287 10 years so to 2028 for both species.

288 In this study, a total of 51 STs were considered. Two base cases are

⁵ F_{lower} and F_{upper} are the mean of the lowest and highest values respectively within the range of F_{MSY} . The range is estimated to obtain no more than a 5% reduction in long-term yield compared to MSY . Similarly than for F_{MSY} , the range of F_{MSY} is restricted to the extra precautionary consideration of less than 5% chance of SSB falling below B_{lim} . See for example Chapter 1, Article 2 of European Commission (2018a) for more detail.

Table 2: Reference points and $lowF$ values used to parameterize the HCRs in this study.

Stock	Herring	Cod	Reference
$MSYB_{trigger}$ (t)	150000	150000	ICES (2018c, 2019i, 2017b, 2019f)
B_{lim} (t)	120000	107000	
F_{target} (y^{-1})	$F_{MSY} = 0.31$	$F_{MSY} = 0.31$	European Commission (2018a); ICES (2019i); European Commission (2018b); ICES (2019f)
	$F_{lower} = 0.216$	$F_{lower} = 0.198$	
	$F_{upper} = 0.379$	$F_{upper} = 0.46$	
$lowF$ (y^{-1})	0.1	0.1	

considered for each of the 3 recruitment options (so 6 STs): one where no fishing occurs for all forecast years after the intermediate year (option “ $F = 0$ ”), and another where the catch by fleet in 2019 is kept constant for all remaining years (option “constant 2019 catch”). The other 45 STs were comprised of the 3 recruitment options, the 3 different values of target fishing mortality (F_{target}) and the 5 HCRs.

2.2.2. Performance metrics

Resulting forecast trajectories for SSB, average fishing mortality ($\bar{F}_{3-6}$ for herring and $\bar{F}_{2-4}$ for cod), total catch and cumulative catch were compared for the 51 STs by taking the median and 95% confidence interval of the 5000 replicates. We compared time for median stock recovery above B_{lim} for the all options. The risk on the stock for every forecast year with management (2020-2028) is calculated as the probability of SSB falling below B_{lim} using the proportion of replicates where $SSB < B_{lim}$.

2.2.3. Additional long-term forecast analysis

To investigate the impact of fishing at the different equilibrium F_{target} on equilibrium stock size and rebuilding probability, we ran 6 additional

stochastic long-term forecasts for both species where $\bar{F}$ is fixed at the different F_{target} values for the two recruitment assumptions where recruitment is randomly sampled in the assessment estimates and when recruitment follows the hockey-stick stock-recruitment relationship. The forecasts were run until the steady-state SSB was reached. We did not run long-term forecast for the random walk with negative drift recruitment assumption because this assumption is not adequate for long-term forecasts. We looked at equilibrium SSB and probability of falling below B_{lim} for these results.

In addition, while the hockey-stick assumption resembled the assumption taken when estimating reference points for both stocks, it was not identical (cf. section 2.2.1). As a result, the equilibrium fishing and biomass corresponding to the recruitment assumptions taken in this study may differ from the reference points used in the HCRs. As a result, we calculated MSY reference points for the same two recruitment assumptions. Note that the MSY reference points estimated in this study should be only considered for illustration. More information on how these were estimated is given in Appendix A3. We did not consider the extra precautionary constraint implied by ICES (less than 5% probability of falling below B_{lim}) in the estimation of F_{MSY} . When recruitment is randomly sampled from the assessment estimates, F_{MSY} corresponds in fact to F at maximum yield-per-recruit, F_{max} .

3. Results

An example of forecast trajectories for SSB, $\bar{F}$ and total catch is given Figure 2 for HCR 1 (MSY approach with no fishing below B_{lim}) with recruitment sampled from the assessment estimates, so staying at current low

330 levels. Here, cod rebuilt rapidly above B_{lim} after closure of the fishery for two
 331 years no matter the F_{target} value, whereas herring necessitated three years of
 332 closure and presented oscillations around B_{lim} when $F_{target} \geq F_{MSY}$. This
 333 resulted in consequent large changes in fishing mortality and total catch in
 334 the forecasts with $\bar{F}$ oscillating between 0 and large values over time.

335 The results for all STs (all recruitment assumptions, F_{target} , HCRs and
 336 base cases) are given in A4. The results were very different between fish
 337 stocks and were sensitive to the recruitment assumption. WBSS herring
 338 showed difficulties to get a stable recovery above B_{lim} over time for all HCRs
 339 and recruitment assumptions (Figures A4.3 and A4.19) except when recruit-
 340 ment was more optimistic and increased when SSB increased (hockey-stick
 341 assumption, Figure A4.11). For all recruitment scenarios, some big jumps
 342 in fishing mortality were observed notably for HCR 1, HCR 3, and HCR 5
 343 where $\bar{F}$ varied between its lower limit (0 for HCR 1 or 0.1 for HCRs 3 and
 344 5) and higher values while the other HCRs had a smoother change in $\bar{F}$ (Fig-
 345 ures A4.4, A4.12 and A4.20). These changes induced subsequent variations
 346 in total catch (Figures A4.5, A4.13 and A4.21). North Sea cod rebuilt in few
 347 years above B_{lim} and even sometimes $MSYB_{trigger}$ no matter the ST con-
 348 sidered (Figures A4.2, A4.7, A4.15 and A4.23). Even if median rebuilding
 349 was successful in medium-term, for all recruitment and F_{target} assumptions,
 350 it still necessitated reducing $\bar{F}$ for 2 years for all HCRs notably to its lower
 351 limits 0 and 0.1 for HCR 1 and HCRs 3, 5 respectively (Figures A4.8, A4.16
 352 and A4.24).

353 Figure 3 summarizes the time frame for median recovery for all STs result-
 354 ing in rebuilding for WBSS herring and North Sea cod. For WBSS herring,

Figure 2: Historical and forecast spawning stock biomass (SSB), mean fishing mortality and total catch for HCR 1 (MSY approach) with recruitment sampled from the assessment estimates. The points are medians and the segments the 95% confidence intervals estimated from the 5000 replicates. For SSB, the red dashed line is $MSY B_{trigger}$ and the blue dotted line is B_{lim} . For $\bar{F}$, the red dashed line is the F_{target} and the blue dotted line is the reduced $F = 0.1$.

about 73% (37 out of 51) of the STs allowed rebuilding above B_{lim} but the recovery was often not stable to the end of the simulation with the median SSB declining below B_{lim} after few years. Stable herring recovery by the end of the simulation (SSB went above and stayed above B_{lim}) was reached for 51% (26 out of 51) of the STs. Having a low value for F_{target} increased the probability for medium-term (2028) recovery. Only HCR 1 enabled stock rebuilding as quickly as the fishing closure base case $F = 0$ and most of the other options allowed rebuilding a year or two later. All STs applied to North Sea cod resulted in stable rebuilding of median SSB above B_{lim} by the end of the forecast period. For 82% (42 out of 51) of the STs rebuilding above B_{lim} started in 2021, time frame considered for current scientific advice. Keeping the 2019 catch constant was the ST showing the slowest rebuilding and rebuilding time was sensitive to the stock recruitment assumption.

Figure 4 shows the median total catch against the probability of SSB falling below B_{lim} for HCR 1. It highlights the oscillating behavior (cf. Figure 2) observed for WBSS herring when median recruitment was assumed to stay at the current low levels (sampled in 2013-2017) or decreased further (random walk with negative drift). Similar behavior was observed for HCRs 3 and 5 (Figures A4.6 and A4.22). For all recruitment assumptions and F_{target} levels, the risk on herring decreased in the first forecast years (2020-2022) following the absence of fishing. Then median catch increased and risk stayed low as fishing started again. However when $F_{target} \geq F_{MSY}$, for all recruitment assumptions except the hockey-stick, median catch decreased and risk increased until the fishery was closed again until the end of the forecast period. When recruitment increased with increasing SSB, risk on

Figure 3: Simulation trials (STs) for which median SSB recovered above B_{lim} . The points represent the years for which $SSB \geq B_{lim}$ in the forecasts. The lines highlight the consecutive years where $SSB \geq B_{lim}$. Each row is a ST (set of recruitment (Rec), F_{target} and HCR assumption) and 6 STs are base cases where $F = 0$ or the catch in 2019 is kept constant. The notation “sampled” is given when recruitment is randomly sampled from the assessment estimates, “HS” when log recruitment follows an hockey-stick stock-recruitment relationship, and “RW” stands for random walk with negative drift.

Figure 4: WBSS herring median total catch against probability of SSB falling below B_{lim} for HCR 1 (MSY approach). The numbers correspond to the forecast years (2020–2028). Each color represents a F_{target} option.

380 herring stayed below 20% by 2028. Similar figures for all STs and for North
 381 Sea cod are given in Appendix A4. Similarly oscillations can be seen for cod,
 382 to a lesser degree, for the random walk assumption (Figure A4.26).

383 Figure 5 summarizes the change in WBSS herring median cumulative
 384 catch against median SSB in the forecast years for all STs except $F = 0$. It
 385 is clear that median recovery between B_{lim} and $MSY B_{trigger}$ (yellow zone)
 386 or above $MSY B_{trigger}$ (green zone) is difficult for herring when median re-
 387 cruitment stayed at current low levels (sampled in 2013–2017) or decreased
 388 (random walk with negative drift). Overall, all the HCRs resulted in similar
 389 level of cumulative catch by the end of the forecast period but the path to
 390 get there and the final median SSB differed between HCRs.

Similar results including variation in replicates are presented in Figure 6 for $F_{target} = F_{MSY}$, current F_{target} used in ICES, and for three different time frames (short-term 2022, early medium-term 2025 and late medium-term 2028). Overall, for herring, it was difficult to get to a probability of SSB falling below B_{lim} of less than 5%, except in 2028 when recruitment was assumed to increase when SSB increases (hockey-stick). In the medium-term (2025 and 2028), HCR 1 and HCR 3 resulted in similar cumulative catch, SSB and risk on the stock but HCR 3 allowed for fishing at low level below B_{lim} while HCR 1 assumed fishery closure below B_{lim} . HCR 1 was overall more variable than the other STs, due to larger differences in $\bar{F}$ between replicates (cf. Figures A4.4, A4.12 and A4.20) .

Comparing median cumulative catch with median SSB over time for cod (Figure 7) highlights that no matter the HCR considered and the assumption on recruitment and F_{target} , the level of cumulative catch and SSB obtained at the end of the forecast period were similar despite different fishing behaviors assumed below $MSY B_{trigger}$ (cf. Figure 1). Assuming the 2019 catch constant in the forecast resulted in largely different results compared to the HCRs. Getting to a risk on the cod stock lower than 5% was possible to achieve in the short-term (2022) for HCRs 1-3 and for all recruitment assumptions except the random walk despite the fact that this latter assumption resulted in positively skewed SSB (Figure 8). Similar to what was observed for WBSS herring, HCR 1 showed larger span in cumulative catch and SSB than other STs, notably when recruitment was more variable (hockey-stick and random walk). The variations in the cumulative catch for all forecast years are given for both species in Figures A4.27 and A4.28.

Figure 5: WBSS herring median cumulative catch against median SSB in the forecast period. The numbers correspond to the forecast years (2019-2028). The red zone is when $\text{SSB} < B_{\text{lim}}$, the yellow zone is when $B_{\text{lim}} \leq \text{SSB} \leq \text{MSY} B_{\text{trigger}}$, the green zone is when $\text{SSB} > \text{MSY} B_{\text{trigger}}$.

Figure 6: Boxplot of WBSS herring cumulative catch and SSB (thousand tonnes) from the 5000 replicates when $F_{target} = F_{MSY}$ for different time frames (2022, 2025 and 2028) and for 4 chosen STs. The numbers are the probability of SSB falling below B_{lim} in percent for the corresponding ST. The red zone is when $SSB < B_{lim}$, the yellow zone is when $B_{lim} \leq SSB \leq MSY B_{trigger}$, the green zone is when $SSB > MSY B_{trigger}$.

Figure 7: North Sea cod median cumulative catch against median SSB in the forecast period. The numbers correspond to the forecast years (2019-2028). The red zone is when $SSB < B_{\text{lim}}$, the yellow zone is when $B_{\text{lim}} \leq SSB \leq MSY B_{\text{trigger}}$, the green zone is when $SSB > MSY B_{\text{trigger}}$.

Figure 8: Boxplot of North Sea cod cumulative catch and SSB (thousand tonnes) from the 5000 replicates when $F_{target} = F_{MSY}$ for different time frames (2022, 2025 and 2028) and for 4 chosen STs (constant 2019 catch and HCRs 1-3). The numbers are the probability of SSB falling below B_{lim} in percent for the corresponding ST. The red zone is when $SSB < B_{lim}$, the yellow zone is when $B_{lim} \leq SSB \leq MSY B_{trigger}$, the green zone is when $SSB > MSY B_{trigger}$. Please note that due to very large confidence intervals for the random walk recruitment assumption (cf. Figure A4.23), for convenience, the outliers were removed from the figure.

416 The results of the long-term forecasts are given in Appendix A5. These
 417 results highlight that, current F_{target} reference points for WBSS herring do
 418 not allow rebuilding of the stock above B_{lim} for the current low recruitment
 419 levels, even if $F_{target} = F_{lower}$ (Figure A5.1). Rebuilding is however possible
 420 with relatively high probability when a stock-recruitment relationship is used
 421 in the forecast (Figure A5.2). For North Sea cod, rebuilding above B_{lim}
 422 is possible for all F_{target} values and recruitment scenarios, but rebuilding
 423 probability is improved when a stock-recruitment relationship is assumed,
 424 notably for $F_{target} = F_{upper}$ (Figures A5.1 and A5.2). Assuming these two
 425 recruitment regimes in the estimation of F_{MSY} resulted in F_{MSY} consistent
 426 with the current value of 0.31 y^{-1} for cod but not for herring (Tables A5.1
 427 and A5.2). For herring, either a large F_{MSY} was estimated coupled with low
 428 B_{MSY} and MSY values when recruitment was sampled from the assessment
 429 estimates, or a F_{MSY} of $\sim 0.25 \text{ y}^{-1}$ was estimated, associated with values of
 430 B_{MSY} and MSY significantly larger than current stock and catch levels.

431 4. Discussion

432 This study exhibited large contrasts between the two considered stocks.
 433 On one hand, WBSS herring, which has been recommended a zero catch
 434 for two years, had difficulty rebuilding in the short- to medium-term despite
 435 consequent reduction in fishing mortality compared to current levels. On
 436 the other hand, North Sea cod benefited from two years of reduced fishing
 437 mortality implied by all HCRs at the beginning of the forecast period, and
 438 rebuilt quickly, even when recruitment was assumed to decrease in the future.
 439 For both species, all F_{target} values were below the current $\bar{F}$ (in last year of

assessment) and when $F_{target} \leq F_{MSY}$, below any historical $\bar{F}$. The difference between stocks' recovery cannot be explained by a difference between current fishing pressure and F_{target} and other reasons are discussed below.

WBSS herring recovery is compromised with the current reference points used in ICES since while rebuilding above B_{lim} was possible for the two most pessimistic recruitment assumptions (sampled in 2013-2017 and random walk with negative drift), it was not stable until the end of the forecast period. This oscillating pattern around B_{lim} is due to the fact that the F_{target} and B_{lim} values are inconsistent with the current recruitment regime and this was clearly illustrated by the reference points estimated in this study (Tables A5.1 and A5.2). Reference points for WBSS herring used in the HCRs were estimated using the entire historical SSB and recruitment time series (ICES, 2018c), which included an early period of large productivity, so assuming recruitment stays at low levels or decreases was more pessimistic. On the contrary, when recruitment was assumed to follow a hockey-stick stock-recruitment relationship, herring could rebuild in the medium-term. This is because the hockey-stick recruitment assumption is more in line with the assumptions taken when estimating the reference points used in the HCRs. Indeed, when a hockey-stick was assumed when estimating the MSY reference points in this study, SSB at F_{MSY} is more than 4 times the SSB in 2018 while it is estimated to be lower than the current SSB by $\sim 35\%$ when recruitment is assumed to stay at low levels (Tables A5.1 and A5.2). Rebuilding above $B_{lim} = 120000$ t with current recruitment levels when the corresponding B_{MSY} is 48400 t is therefore not realistic. For this stock, it would be interesting to investigate what would be the real F_{MSY} and B_{MSY} values when

a stock recruitment relationship is assumed removing the SSB and recruitment pairs at high values, since the values estimating here corresponds to yield per-recruit estimates rather than MSY reference points. These inconsistencies between current recruitment regimes and reference point estimates explains why rebuilding for North Sea cod occurred more readily. Indeed the reference points for cod were estimated using SSB and recruitment pairs removing the early period of high productivity (ICES, 2015, 2017b), so the period used corresponds already to a relatively low recruitment levels and all recruitment options allowed the stock to recover in the forecast above B_{lim} and sometimes $MSY B_{trigger}$. This is validated by the reference point estimation conducted in this study, where for both recruitment assumptions, F_{MSY} was estimated around the current F_{MSY} value of 0.31 y^{-1} and led to equilibrium SSB values around 1.7-2.9 times the SSB estimated in 2018 (Tables A5.1 and A5.2). In addition, long-term simulations with constant $\bar{F} = F_{target}$ also showed that the probability of cod rebuilding is mainly improved for $F_{target} = F_{upper}$ when the stock-recruitment relationship is used, and assuming current recruitment levels did not compromise cod recovery for the other two F_{target} values (Figures A5.1 and A5.2). Using favorable recruitment regimes for scientific advice could result in unrealistically optimistic predictions (Caddy and Agnew, 2004) but, we also demonstrate here, that using pessimistic recruitment regimes for scientific advice compared to regimes used for reference point estimation could result in an impossibility to reach biomass reference points. Reference points should therefore be in accordance with current recruitment regimes if they are to be used for practical management advice. This type of medium-term forecasts could therefore

highlight possible problems with current reference points that could motivate proposing a benchmark or inter-benchmark to revise them. In practice, when changes in productivity may be difficult to identify or when high productivity estimates are necessary to fit a stock-recruitment relationship used to estimate F_{MSY} ; simple long-term projections of the stock assuming current recruitment levels for constant $\bar{F} = F_{MSY}$ could illustrate possible problems with reference points being inconsistent with current low stock size and recruitment regime (Appendix A5) and should be tested during reference point estimation.

In this study, recruitment was the largest source of uncertainty in future stock response to management as the results were clearly sensitive to the recruitment assumption. For both species, the difference in the recruitment assumption often induced more variability in SSB and cumulative catch than the difference in the HCRs (Figures 6 and 8). This means that the recovery of fish stocks is very dependent on future recruitment. Since recruitment may be difficult to predict, it is therefore very important to test different plausible recruitment assumptions when considering HCRs. Obtaining reliable stock productivity estimates should improve in the future with improvements in predicting oceanic systems in the medium-term (ICES, 2018b), but meanwhile, it is relevant to compare optimistic recruitment assumptions with more pessimistic ones to have the full range of worst to best case scenarios with corresponding uncertainty. This could possibly highlight the stability of certain HCRs to recruitment regimes or could be used to present managers with the different stock trajectories obtained for the different recruitment assumptions. For instance, this study shows that for North Sea cod, the recruitment

assumption may not limit the stock recovery since rebuilding above B_{lim} was achieved under all the considered recruitment assumptions. For WBSS herring, however, recruitment led to more variable rebuilding outcomes, notably rebuilding above current targets is compromised if recruitment does not improve in the future. These simulations highlight therefore the necessity to maybe consider exceptional precautionary approaches for this stock if rebuilding is required in the medium-term.

Any management strategies study using HCRs (Kvamsdal et al., 2016; Punt et al., 2016), is limited by the uncertainty in the reference points used (Rice and Rivard, 2007). Reference points are uncertain due to modeling choice and errors but also due to lack of understanding of biological and environmental drivers of the variations in productivity. Also, reference points usually ignore external factors that can affect fish mortality such as environmental factors or multispecies interactions (Trijoulet et al., 2018, 2019, 2020). Reference points such as F_{MSY} are obtained from long-term equilibrium estimation and are highly dependent on the stock-recruitment relationship used during the estimation process. The stock-recruitment relationship is in itself uncertain and possibly biased as it is usually fitted outside the assessment model without taking into account the variances and covariances in the SSB and recruitment pairs (Brooks and Deroba, 2015; Albertsen and Trijoulet, in press). Also, in ICES, the biomass reference point, B_{lim} , is either obtained by fitting a hockey-stick relationship to the SSB and recruitment pairs or by a human choice following the ICES guidelines for semi-quantitative estimation of B_{lim} . In the case of the two species considered in this study, the latter method was used (ICES, 2015, 2018c). In situations where the productivity

regime may have changed using historical stock-recruit pairs or the lowest observed biomass to determine B_{lim} may not be an appropriate way to define rebuilding targets. In other jurisdictions, B_{lim} is often calculate as a fraction of B_{target} (e.g. B_{MSY}) rather than estimated semi-quantitatively (DFO, 2009; ICCAT, 2019). This would provide an objective estimate of B_{lim} and could be envisaged in ICES, but may still result in a B_{lim} value difficult to rebuild above, if B_{MSY} is estimated assuming an optimistic stock recruitment relationship. Also, it would not allow the precautionary constraint in the estimation of MSY reference points (less than 5% chance to fall below B_{lim}) since in that case B_{lim} has to be estimated first.

The forecasts account for uncertainty in the current perception of the stock and current fishing pressure by simulating 5000 replicates of numbers at age and fishing mortality at age. However, uncertainty in observations (e.g. weight at age or natural mortality) and model parameters are not considered. The results also do not account for implementation error, which means that the $\bar{F}$ that was obtained from a HCR is the assumed realized $\bar{F}$ applied on the stock. Exploratory runs were conducted in this study to compare HCR outputs and to highlight trade-offs between fishing opportunities and stock conservation in the medium-term rather than to choose an HCR for real management purpose so the results need to be seen in this context. Comparing HCRs may be difficult to illustrate if implementation and observation errors significantly changes the outputs of the HCRs. However, accounting for implementation error, observation errors and parameter uncertainty will be required if the simulations were used to evaluate robust rebuilding strategies, for instance, for a management plan.

565 Management decisions can suffer from the uncertainty in stock projec-
 566 tions. Managers are often presented with median projection results where
 567 the uncertainty or variability in the results could be missing or not well pre-
 568 sented. This could result in misunderstandings if the outputs of the forecast
 569 are different from what is assessed the following year (Kelly et al., 2006).
 570 This could also result in a lack of trust in fisheries scientists from managers
 571 and stakeholders. It is therefore important to present and discuss uncer-
 572 tainty with managers (Rosenberg and Brault, 1991; Peterman, 2004; Kvams-
 573 dal et al., 2016). It is important to compare the outputs and variability of
 574 different fishing scenarios or HCRs and quantify the subsequent risk on the
 575 stock (Deroba and Bence, 2008; Sethi, 2010). Here, we notably show that
 576 HCRs that allowed large variations in $\bar{F}$ around B_{lim} were usually less stable
 577 (e.g. HCR 1), notably in the short-term. This is due to the low size of the
 578 stocks in the first years of forecasts that resulted in large variations in $\bar{F}$ de-
 579 pending on where the simulated stock biomass fell compared to the biomass
 580 thresholds for each replicate. As the stocks approached $MSYB_{trigger}$, less
 581 variations were observed among the HCRs as the shape of the HCRs mainly
 582 differed below B_{lim} (Figure 1).

583 Managers and fishers have usually a preference for small variations in
 584 TACs (Kell et al., 2006; Kelly et al., 2006). A decrease in TACs could
 585 threaten fishers' livelihood, but an increase in fishing mortality could also
 586 mean higher costs such as for fuel or capacity, or difficulties to increase cur-
 587 rent production. Some studies investigated management rules where the
 588 variability in catch was bounded so that the fishing mortality couldn't de-
 589 crease or increase as rapidly as the variations in SSB (Kell et al., 2006; Kelly

et al., 2006). Both studies concluded that, for stocks that are already low, reducing the variability in catch in the forecasts induced a longer time for stock rebuilding and a higher risk on the stock. This was also observed here, notably for North Sea cod where, in the short- (2022) and early medium-term (2025), keeping the 2019 catch constant resulted in smaller projected SSB and higher risk on the stock compared to the HCRs no matter the recruitment assumption (Figure 8). However, this is mainly due to the fact that all HCRs resulted in a decrease in catches compared to 2019 at the beginning of the forecast. The higher $\bar{F}$ associated with the 2019 catch is therefore less precautionary. We show that applying the MSY approach (HCR 1), or any other HCR that induces a steep decrease in $\bar{F}$ when SSB decreases below B_{lim} (e.g. HCRs 3 and 5), resulted in large variations in $\bar{F}$ and in subsequent catch no matter the recruitment assumption. This happened in the transition period for cod but over the entire forecast period for WBSS herring. From a management point of view, the catch resulting from these HCRs are less likely to be applied in practice as a smoother change in $\bar{F}$ may be preferred by managers.

Stock recovery may necessitate prompt management actions (Caddy and Agnew, 2004; Shertzer and Prager, 2006). Shelton and Morgan (2014) evoke the problem of lag between fish stock assessment and TAC implementation as a reason for the possible lack of success in stock rebuilding when fishing mortality is not reduced fast enough so stock perception changes faster than managers' response. This raises the question of when it is best to act. The case of WBSS herring can easily illustrate this problem. The perception of the stock changed in 2017 and resulted in a benchmark for the stock a year

615 later (ICES, 2018c). Since then, ICES has recommended a zero catch ad-
616 vice which was never implemented and a rebuilding plan which was never
617 followed up by a request from managers (ICES, 2019i, 2018a). This study
618 shows that recovery for the stock is compromised and will be dependent on
619 future recruitment. Ideally, even if managers react before the stock falls be-
620 low its biomass threshold, significant changes in stock perception can still
621 occur independently of management, notably after benchmarks where new
622 data, models or configurations are often implemented. This motivates the
623 importance of reacting promptly to changes in stocks, maybe already when
624 the stock approaches B_{lim} , instead of waiting for the stock to fall below it.
625 The ICES harvest rule with decreasing $\bar{F}$ from F_{MSY} to zero for SSB below
626 $MSYB_{trigger}$ induces larger $\bar{F}$ below $MSYB_{trigger}$ than other frameworks
627 that assume that $\bar{F}$ decreases from F_{target} at the biomass trigger reference
628 point to a reduced $\bar{F}$ or zero at B_{lim} and below it (NAFO, 2004; New Zealand
629 Ministry of Fisheries, 2011; ICCAT, 2019). Also F_{target} is F_{MSY} in ICES,
630 but other jurisdictions use a F_{target} below F_{MSY} as a precautionary approach
631 to avoid falling below B_{MSY} for reasons such as uncertainty in B_{MSY} and
632 difficulty to keep the realized $\bar{F}$ at F_{MSY} (e.g. NAFO, 2004; NRC, 2014;
633 ICCAT, 2019). Harvest rules with $F_{target} < F_{MSY}$ induce therefore lower
634 $\bar{F}$ for any SSB value than the ICES harvest rule. Moreover, given the way
635 $MSYB_{trigger}$ is estimated in ICES, its value is often close to B_{lim} . This short
636 distance and high $\bar{F}$ below $MSYB_{trigger}$ provides therefore less protection to
637 the stock falling below B_{lim} . According to NRC, 2014, HCRs that reduce
638 fishing mortality promptly and smoothly when SSB is below B_{MSY} can re-
639 duce the probability of the stocks falling below their limit reference point.

640 Future research in ICES should look into HCRs where $\bar{F}$ is reduced as soon
 641 as SSB is below a higher trigger reference point such as B_{MSY} , or a fraction
 642 of it, rather than below a lower value such as $MSY B_{trigger}$. Simulation eval-
 643 uations using different trigger points could be used in the future to highlight
 644 the trade-offs between the level of risk of falling below B_{lim} , catch levels and
 645 variability in catches.

646 The risk on WBSS herring, measured as the probability of falling below
 647 B_{lim} , was only below 5% at the end of the forecast period when an optimistic
 648 recruitment (hockey-stick) was assumed (Figures 6, A4.6, A4.14 and A4.22).
 649 For the other two recruitment regimes, even if SSB could increase in the
 650 short-term, probability of falling below B_{lim} was high and even low values
 651 of F_{target} only allowed the probability to decrease to between 20 and 50%.
 652 When probability decreased, it often oscillated back to larger values after a
 653 few years, reducing the probability of stable recovery for the stock to the end
 654 of the forecast. With the current reference point estimates, it seems therefore
 655 difficult, if not impossible, to reduce the risk on herring if recruitment does
 656 not improve in the future, whereas it is possible to have a risk below 5%
 657 for cod in the short-term as long as the recruitment does not decrease in
 658 the future (random walk with negative drift assumption, Figures 8, A4.10,
 659 A4.18 and A4.26). The risk threshold implied by the ICES MSY approach
 660 may therefore not be relevant for stocks that do not rebuild in short-term
 661 advice and a higher risk may be acceptable (Kell et al., 2006). For these
 662 stocks, as it is sometimes done in other jurisdictions (New Zealand Ministry
 663 of Fisheries, 2011; NRC, 2014; Australian Government, 2018; ICCAT, 2019),
 664 it may therefore be necessary for scientists and managers to agree on what an

665 acceptable deviation from the 5% risk on the stock is in the short- to medium-
 666 term, while the low risk level could still be considered in the long-term.
 667 For stocks that are low and cannot rebuild in short-term forecasts used for
 668 advice (e.g. WBSS herring in this study), the time frame for the evaluation
 669 of management strategies has also to be realistic as recovery may be slower
 670 than expected and could necessitate looking at medium-term horizons rather
 671 than the common short-term advice time frames (Rosenberg et al., 2006;
 672 Gröger et al., 2007; Shelton and Morgan, 2014).

673 Previous studies showed that pelagic stocks can recover after fishery clo-
 674 sure if conditions are favorable (Gullestad et al., 2018; Dickey-Collas et al.,
 675 2010). According to Murawski (2010), success of rebuilding plans in Canada
 676 and in the US usually follows a large decrease in fishing mortality at the
 677 beginning of the management years. In this study, for both cod and herring,
 678 assuming a HCR where $\bar{F}$ varies with SSB resulted in a decrease in $\bar{F}$ at the
 679 beginning of the forecast for all HCRs. It is therefore difficult but necessary
 680 to find a balance between HCRs that ensure both stock sustainability and
 681 maintaining fishers' livelihood in the short-term. These considerations are ac-
 682 knowledged in other jurisdictions (e.g. DFO, 2009; New Zealand Ministry of
 683 Fisheries, 2011; ICCAT, 2019). In the US, catch agreed by managers cannot
 684 exceed the scientific catch advice given by the Scientific and Statistical Com-
 685 mittees (U.S. Government, 2007; NRC (National Research Council), 2014),
 686 but this is not the case in other jurisdictions including in ICES. Currently
 687 scientific advice from ICES for depleted stocks without adopted management
 688 plans is solely given to ensure stock sustainability and this explains why there
 689 is often a discrepancy between what is recommended by scientists and what

is applied by managers. In this study, we show that, if cod recruitment does not decrease in the future, the median cumulative catch in the medium-term can be similar and the risk on the stock low for all HCRs, demonstrating that a smooth change in $\bar{F}$ is a reasonable option for ensuring a sustainable fishery on the stock. For WBSS herring, HCRs 1 and 3 resulted in similar median cumulative catch and risk on the stock in the medium-term (Figure 6) but HCR 1 closed the fishery for 3 consecutive years whereas HCR 3 allowed for a low $\bar{F}$ for 4 consecutive years. It is therefore possible to keep fishing in the short-term for the same trade-offs in the medium-term. A lower F_{target} (F_{lower}) also improved the probability of rebuilding for both species for often little concession in median cumulative catch. For depleted stocks, delivering advice on scenarios that ensure stock rebuilding in medium-term rather than in the short-term while maintaining fishing over time may therefore be more appropriate than using the MSY approach.

This type of medium-term forecasts would be relevant for stocks in need of rebuilding plans (Garcia et al., 2018). They could be used to guide development of rebuilding plan requests. For instance, to define realistic rebuilding objectives for specific stocks such as rebuilding targets, rebuilding time frame, rebuilding probability or HCRs. In ICES and many other jurisdictions, management strategy evaluations (MSE) are usually used to choose a fishing scenarios or HCR that will be used as advice within a management plan. However, MSEs suffer from complex modeling implementations and need of extensive computer power (Punt et al., 2016; ICES, 2019n). This usually results in outcomes not being available before months or years after a rebuilding plan evaluation is requested. When zero catch is advised for a

715 stock and no management plan is already in place, medium-term forecasts
716 could be used as a platform to illustrate the trade-offs between rebuilding
717 time, rebuilding probability, stock trajectories and predicted catches to pro-
718 vide quick guidance to managers during scientific advice or quota allocation,
719 notably when zero catch cannot be realistically implemented.

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