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Model-free HCR: literature review for NAFO Cod 3M

Marga Andrés[a], Dorleta Garcia[a], Agurtzane Urtizberea[b]

[a]Azti-Tecnalia, Txatxarramendi ugartea z/g, 48395 Sukarrieta, Spain
[b]Azti-Tecnalia, Herrera Kaia, 20000 Pasaia, Spain

ABSTRACT

In this document we describe some existing model – free Harvest Control Rules (HCR) taken from the literature. The pros and cons are detailed for some of the HCR. Firstly, the HCR are explained then they are summarized in a table.

HCR 1: HCRs ICES approaches (SEAFO fisheries)

In this section, the ICES approaches on HCRs are described. This information is based on 'Empirical Harvest Rules Their use in the development of advice for the SEAFO fisheries'[1].

HCR 1.1. Simple approach (Index)

Trend of stock (or indicator)	No Overfishing	Overfishing or Unknown Exploitation Status
Decreasing stock trend	Reduce catch from recent level at rate of stock decrease	Reduce catch from recent level at rate greater than the rate of stock decrease
Stable stock trend	Maintain catch at recent level	Reduce catch from recent level
Increasing stock trend	Increase catch from recent level at rate of stock increase	Maintain catch at recent level

[1] http://www.siofa.org/sites/siofa.org/files/documents/meetings/SAWG%282018%29-01-INF07%20SEAFO_EmpiricalHarvestRules.pdf

HCR 1.2. Survey-based assessments indicate trends

Stocks for which survey-based assessments indicate trends: The advice is based on a comparison of the two most recent index values with the three preceding values, combined with recent catch or landings data and apply the uncertainty to the catch advice.

1. Calculate $B_{now} = (B_Y+B_{Y-1})/2$
2. Calculate $B_{ref} = (B_{Y-2}+B_{Y-3}+B_{Y-4})/3$
3. Calculate the TAC as follows:
   $TAC_{Y+2} = \gamma\, TAC_{Y+1}$
   where
   $$\gamma = \begin{cases} 1+\beta & , B_{now}/B_{ref} > 1+\alpha \\ f(B_{now}/B_{ref}) & , 1-\alpha \le B_{now}/B_{ref} \le 1+\alpha \\ 1-\beta & , B_{now}/B_{ref} < 1-\alpha \end{cases}$$
   where f is a function of B_{now}/B_{ref} according to the HCR being applied (HCR 2 HCR 4)

In general ICES considers alpha = 0.2 and beta = 0.15 and f(Bnow/Bref) = 1.

HCR 1.3. Data-poor stocks (only landings data)

- If there is no indication of where F is relative to proxies and no marked positive trends in stock indicators: Calculate the recent catch (C_{y-1}) as the average catch over the 2-3 last years, calculate the catch advice (C_{y+1}) as $C_{Y+1} = C_{Y-1}$ and apply the -20% precautionary Buffer to the catch advice.
- If catches have declined significantly over a period of time and this is considered to be representative of a substantial reduction in biomass a recovery plan and possibly zero catch is advised.

HCR 1.4. HCR based on an index (CPUE or survey index)

Greenland Halibut (NAFO): The indicator is the slope of the abundance Index:

$$TAC_{y+1} = \begin{cases} TAC_y \times (1+\lambda_u \times slope) & if \quad slope \ge 0 \\ TAC_y \times (1+\lambda_d \times slope) & if \quad slope < 0 \end{cases}$$

Slope: average slope of the Biomass Indicator (CPUE, Survey) in recent 5 years

Where λ_u :TAC control coefficient if slope > 0 (Stock seems to be growing) : λ_u=1

λ_d: TAC control coefficient if slope < 0 (Stock seems to be decreasing) : λ_d=2

TAC generated by the HCR is constrained to ± 5% of the TAC in the preceding year.

(Shelton and Miller 2009) also described a similar model-free index-based TAC adjustment strategy. It constitutes a simple TAC adjustment strategy that uses the change in perceived status of the stock (from research surveys) to adjust the TAC according to:

$TAC_{y+1} = TAC_y \cdot(1+\lambda \cdot slope)$

Where:

slope = unweighted average slope of log-linear regression lines fit to the last five years of each index (all ages combined), i.e. y-5 to y-1

λ = an adjustment variable for the relative change in TAC to the perceived change in stock size

HCR 1.5. HCR based on trends in the CPUE and survey CPUE.

Australian HCR for Spanner Crab. There is a base TAC calculated from historical data- Maximum (Cap) TAC of 2000 tons.

Indicators used: Trends in the commercial CPUE and the survey CPUE (Difference to Base levels)

Harvest Control Rule:

- If both indices increased more than 10% and are positive:
  - $C_{Y+1} = C_{Y-1} \times 0.5 \times \frac{I_{Obs}}{I_{Base}}$ (Max is TACCap)
- If at least one of the indices decreased more than 10%:
  - $C_{Y+1} = C_{Y-1} \times 1.0 \times \frac{I_{Obs}}{I_{Base}}$

HCR 2: Tier based HCRs (Smith, Smith et al. 2008)

For the Southern and Eastern Scalefish and Shark Fishery (SESSF). The framework involves the application of a set of tier-based harvest control rules (HCR) designed to provide a precautionary approach to management. The four Tier rules are designed to apply to three types of assessments. Tiers 1 and 2 are used for stocks for which there is a quantitative stock assessment that provides estimates of current absolute and relative biomass (Tier 1 if the assessment is regarded as "robust", Tier 2 for a less certain or preliminary assessment). Tier 3 is based on estimates of current fishing mortality derived from catch curves (requiring age and/or length frequency data, but not catch rates or abundance estimates). Tier 4 is based on recent trends in (commercial) catch rates.

The Tier 1 and Tier 2 harvest control rules are not model free HCRs. The Tier 3 harvest control rule applies to stocks where there are robust estimates of M and current fishing mortality rate F_{CUR}, but no direct estimates of current biomass. Under Tier 3, the RBC(~TAC) is calculated by varying the current catch level up or down depending on whether F_{CUR} is above or below the estimate of M. The current catch level C_{CUR} is calculated as the average catch over the past 4 years (where catch = landings + estimated discards). The HCR for calculating the RBC for Tier 3 stocks is:

$$\text{RBC} = \begin{cases} 0 & \text{if } F_{\text{CUR}} > 2M \\ 0.5C_{\text{CUR}} & \text{if } 2M \geq F_{\text{CUR}} > 1.5M \\ 0.8C_{\text{CUR}} & \text{if } 1.5M \geq F_{\text{CUR}} > 1.25M \\ 0.9C_{\text{CUR}} & \text{if } 1.25M \geq F_{\text{CUR}} > M \\ C_{\text{CUR}} & \text{if } M \geq F_{\text{CUR}} > 0.75M \\ 1.1C_{\text{CUR}} & \text{if } 0.7M \geq F_{\text{CUR}} > 0.5M \\ 1.2C_{\text{CUR}} & \text{if } F_{\text{CUR}} < 0.5M \end{cases}$$

The Tier 4 harvest control rule applies to stocks with the least amount of information about current stock status. At this Tier level, there is no reliable information available on either current biomass or current fishing mortality, but there is information on current catch levels and on trends in catch rates. The steps in calculating RBC:

1. Set the current catch, C_{CUR}, to the average catch (landings plus discards) over the past NC years, where NC depends on the period of "stable" effective (=binding) TACs. The default for NC is 4.
2. Calculate the slope of the trend in CPUE over the past NS years. NS depends on whether trends in CPUE tend to be relatively stable, or cyclic. For "stable" stocks, it is suggested that NS =NC (i.e. 4 years). For "cyclic" stocks, NS would need to be set at about 2 cycle periods.
3. Calculate the RBC as RBC = (1 + αslope) C_{CUR} , where the value of α is yet to be determined, and may need to increase as the (negative) slope increases (the default values for α since 2005 have been 1, 2 and 4).

Note that this HCR is very similar to the Greenland Halibut HRC.

Cons:

- There was more resistance to decreasing TACs for Tier 3 and 4 species than for Tier 1 or 2 species;
- There were problems in applying Tier 3 and 4 assessments and rules due to uncertainties about spatial structure of some stocks and to the absence of agreed catch histories for several species new to the quota system or where species identification was uncertain.
- It was clear that there were problems with the Tier 4 rule, application of which for several stocks resulted in higher RBCs than applications of other Tier rules for the same stock (for Tier 1 stocks, all other Tier rules can also be applied). Thus Tier 4 failed to meet design criterion.

HCR 3: CPUE based HCR (Tier 4)

An HCR based on catch and catch per unit effort (CPUE) was developed for the southern and eastern scalefish and shark fishery of Australia, stocks that lack the data needed to conduct a full statistical catch-at-age assessment (Little, Wayte et al. 2011). A Tier 4 HCR was developed in Little (2011) using the formula:

$$\mathrm{RBC} = C_{\mathrm{targ}} \max\left(\frac{\overline{\mathrm{cpue}} - \mathrm{cpue}_{\mathrm{lim}}}{\mathrm{cpue}_{\mathrm{targ}} - \mathrm{cpue}_{\mathrm{lim}}}, 0\right),$$

Where $cpue_{targ}$ is the target cpue, $\mathrm{cpue}_{\mathrm{lim}}$ the limit cpue, cpue the average $\overline{cpue}$ observed over the past m years, and C_{targ} a catch target. Under this HCR, the RBC is zero if $\overline{cpue}$ is less than $cpue_{lim}$, then increases linearly to reach C_{targ} when $\overline{cpue}$ is at $cpue_{targ}$. Although no maximum RBC is specified, the eastern scale fish and shark fishery has a management rule that the TAC cannot change by more than 50% from year to year. Also, the TAC does not change if the difference in the recommended value from that of the previous year is ,10%. This rule was instituted by the management agency, on advice from industry and scientists, with the intent of preventing inconveniently small incremental changes from year to year.

Cons:

- The key components of the HCR are the parameters $\mathrm{cpue}_{\mathrm{targ}}$ and C_{targ}. The relationship between these parameters is critical. For example, they must correspond to a stable equilibrium point, or $\mathrm{cpue}_{\mathrm{targ}}$ and C_{targ} cannot be achieved simultaneously, and the cycling pattern evident in some of the figures would be expected. Miscalculating this relationship is very likely, especially for a stock which has only been fished down, with no period of stable catches and cpue.
- Its weakness is the reliance on fishery dependent cpue values and catches as the sole sources of information. Catch-rate series are often noisy and may not reflect relative abundance, particularly for short-lived, highly variable species such as school whiting, or deep, densely schooling species.
- The HCR failed to achieve the target biomass goal when the biomass in the reference period not correspond to the target biomass.

HCR 4: HCRs using catch rate data (O'Neill, F. et al. 2010).

This paper analyses the Australian spanner crab fishery.

The base quota (Q_{base}) and target catch rates (fishery = $c_{f,\mathrm{target}}$ and survey = $c_{s,\mathrm{target}}$) were set, by the working group, equal to their annual average between 2000 and 2007, and they were fixed. Upper and lower intervals of +10% were set on target catch rates. The stock performance indicators were the average fishery (c_f) and survey (c_s) standardized catch rates in the most recent biennial quota period. Standardized catch rates from the fishery and the survey were compared in a decision matrix (Table 1). As no prior evidence was available that either catch rate source was more accurate or reliable than the other, the two indices of spanner crab abundance were given equal weight in the assessment process. The spanner crab quota was calculated from the base quota (Q_{base}) and was made no larger than the maximum tonnage allowed (Q_{max}). New quota was compared with the tonnage set 2 years earlier. If the new quota was within 5% of the previous quota, then the quota remained unchanged. Quota for Queensland and New South Wales was calculated according to the equation:

$$Q_{t+1,t+2} = \min\left[\begin{Bmatrix} Q_t, & \text{if } (0.95Q_t \leq \lambda Q_{\text{base}} \leq 1.05Q_t) \\ \lambda Q_{\text{base}}, & \text{otherwise} \end{Bmatrix}, Q_{\max}\right],$$

where Q is the quota tonnage for biennial setting in years t + 1 and t + 2, and λ was from:

Pros:

- It was seen that survey-based operational management procedures can perform well in the absence of commercial data and can also inform aspects of survey design with respect to acceptable levels of error or bias in the surveys.
- For Australian spanner crabs, the components were successfully brought together in a quantitative assessment tool that permits simple, rapid, cost effective quota setting.

Cons:

- In a typical data-limited fishery, this would require balancing knowledge of the fishery, the life-history characteristics of the species, and political opinion on sustainable harvest. When set too generously, the rules incorrectly set high quotas at low population sizes

HCR 5: Survey data – derived HCR

(Apostolaki and Hillary 2009) describes several control rules. In terms of the available information and key variables one might have we consider the following:

- A set of measured indicators of the stock itself and the environment and ecosystem which it resides; $I = \{I_1, \ldots, I_k\}$. Some potential indicators could be the trend in mature/immature/exploitable stock biomass (either directly measured from survey data or from a stock assessment), mean weight, recruitment, total mortality, sea-surface temperature, and so on.
- A set of reference and/or target points (absolute/relative for use with the indicator set in assessing general 'status': $R = \{R_1, \ldots, R_l\}$. Reference points could be related to abundance levels, total mortality, mean weight or primary production levels.
- A set of auxiliary information about the stock and fishery of interest such as life-history information, economic parameters and constraints, trophic dependencies and so on. $A = \{A_1, \ldots, A_m\}$
- A set of parameters, θ, that can be used to mathematically define the HCR.
- The previous harvest actions: $H = \{H_1, \ldots, H_n\}$. These harvest actions cover any possible fishery actions such as catches, effort, capacity, mesh regulations and so on.

We can now express the dependence of a HCR, F, to the components described above in the following way:

$H_t = F(I, R, A, \theta, H_{past})$

But the CV for the observation error is known (preferable for each year). Management is affected via an annual TAC which is adapted year to year based upon temporal trends in observed SSB series. We assume that the new TAC is set as an adjusted back average of previous TAC. The adjustment is achieved through a multiplicative factor that indicates (weighted) time averaged growth in the survey SSB index.

$$TAC_{t+1} = \left(\frac{1}{N_{TAC}} \sum_{i=t-N_{TAC}+1}^{t} TAC_i\right) \propto_{t,}$$

Where N_{TAC} is the number of years over which we average previous TAC, and the TAC adjustment, $\propto_t$, is defined as:

$$\propto_t = \sum_{i=t-N_{SSB}+1}^{t} \omega_i \left(\frac{I_i^{SSB}}{I_{i-1}^{SSB}}\right)$$

N_{SSB} denotes the number of years over which we average the crude SSB growth/decline trend. The weightings, ω_t, sum to one and can be calculated in various ways as explained further below. If the survey index of the spawning stock has been consistently increasing/decreasing, then the TAC will increase/decrease.

Pros:

- Survey-based stock assessments have the potential to reduce bias associated with fishery-dependent data since they replace those data with data from surveys (use of information from surveys to validate the fishery dependent data and define the weight they will assign to them is another potential use of survey data but we will not touch on this here)
- They could be seen as an opportunity to look for HCR that can reduce the dependency of management plans on data, assumptions, and reference points that are difficult to define.

Cons:

- Our results indicated that the memory that we build into our HCR (i.e. using a multi-year indicator instead of single year one) can have a great impact on the performance of the HCR.
- An absolute TAC suitable for managing exploitation of the stock in following years cannot be derived. In this context, HCR derived from survey data are expected to provide information on future exploitation (e.g. TAC) only in relative terms. In this case, and if past TAC cannot be utilised in some way to inform the adoption of new catch quotas, there will necessarily be a period of adaptive management.

HCR 6: HCRs based on survey-derived information and TAC adjustment (Hillary 2009).

This paper contains the details on how the candidate harvest control rules, based on survey-derived information, can be characterized and implemented, and how the processes of management strategy evaluation and stock assessment can be included in the simulations. The author uses the North Sea herring as an example case.

HCR 6.1. using relative SSB trends (index)

The HCR essentially is a total allowable catch (TAC) adaptation scheme which changes the TAC from year to year, relative to the TAC from the year before and the status of the stock, given the information in the abundance indices of interest. The HCR can be parameterised as follows:

$$\Delta_{y-1} = \frac{I_{y-1}}{I_{y-2}}$$

$$\mathrm{TAC}_{y+1} = \Delta_{y-1} \times \mathrm{TAC}_y$$

where the delay effect of time y − 2 affecting the TAC in y + 1 is present because of the delay that is intrinsic to the observable effect of changing the TAC on the stock, for this particular management system. Here, I_y represents the trend in spawning stock biomass (relative or absolute) and can either be from a survey directly or have been estimated by a survey-based assessment method. The basic idea is that the TAC will increase if the spawning stock index is considered to be increasing and will be decreased if the spawning stock index is decreasing.

HCR 7: Fisheries dependent index HCR (Kell, Hillary et al. 2015).

An empirical HCR has been adopted for southern bluefin which sets the using data solely from a fisheries dependent index of adult abundance and a fisheries independent aerial survey of juveniles. The HCR is based on year-to-year changes and in the indices.

HCR 7.1. The first HCR is based on a single index

HCR 1: $TAC^1_{y+1} = TAC_y \times \begin{cases} 1 - k_1|\lambda|^{\gamma} & for \quad \lambda < 0 \\ 1 + k_2|\lambda|^{\gamma} & for \quad \lambda \geq 0 \end{cases}$

Where λ is the slope y the regression of lnB_y against year for the most recent n years, k_1 and k_2 are gain parameters. This HCR is in line with the HCRs described in section 1.5.

A variation of this HCR was analysed in (Hillary, Preece et al. 2016) . An adaptive rebuilding strategy for the depleted southern bluefin tuna stock. The management procedures adopted involves a HCR that fully specifies the TAC as a function of key indicators of stock status, adjusting the future harvest level every three years so as to meet the rebuilding targets agreed the Commission for the Conservation of Southern Bluefin tuna. In this paper the analysed HCR is as follows:

The harvest control rule has three components:

1. A trend-based effect whereby catch is increased or decreased based on the positive or negative trend in the log-scale adult biomass, ln B_y.

2. A target-based effect whereby catch is increased or decreased based on whether the adult biomass is above or below a threshold level.

3. A precautionary juvenile biomass term whereby catch will be strongly decreased for levels of juvenile biomass, J_y, below a threshold level set using historical estimates and permitted to increase weakly when above it.

The trend-based effect defines a candidate new catch limit (TAC) as follows:

$$\mathrm{TAC}^1_{y+1} = \mathrm{TAC}_y \times \begin{Bmatrix} 1 - k_1|\lambda|^{\gamma} & \lambda < 0 \\ 1 + k_2\lambda & \lambda \geq 0 \end{Bmatrix}$$

where λ is the slope in the regression of $\ln B_y$ for τ_B years (from years $y - \tau_B + 1$ to year y), k_1 and k_2 are gain parameters, and γ is an asymmetry parameter that permits stronger or weaker action for negative biomass trends depending on the value. The second TAC is defined as follows:

$$\mathrm{TAC}^2_{y+1} = 0.5 \times (\mathrm{TAC}_y + C^{\mathrm{targ}}_y \Delta^J_y)$$

where

$$C^{\mathrm{targ}}_y = \begin{Bmatrix} \delta\left[B_y/B^*\right]^{1-\varepsilon_b} & B_Y \geq B^* \\ \delta\left[B_y/B^*\right]^{1+\varepsilon_b} & B_Y < B^* \end{Bmatrix}$$

where ε_b represents the degree of asymmetry in the response to adult biomass levels above or below the target level B* which is set at a value close to the level of Japanese longline CPUE observed when the stock was at the interim rebuilding target in the early 1980s. The recruitment adjustment Δ_y^J is defined as follows:

$$\Delta_y^J = \begin{cases} [\bar{J}/\Psi]^{1-\varepsilon_J} & \bar{J} \geq \psi \\ [\bar{J}/\Psi]^{1+\varepsilon_J} & \bar{J} < \psi \end{cases}$$

and ε_J is also the degree of asymmetry in response to the current moving (arithmetic and of length τ_J) average juvenile biomass levels, $\bar{J}$, relative to the mean level of juvenile biomass, Ψ, seen for the years for which there are actual aerial survey data (1993–2011) and which are the lowest observed levels of historical juvenile abundance. The key control parameter is δ which is altered until the MP meets the tuning criteria [$PSSB_{2035} > 0.2*SSB_0$) = 0.7] for the reference set. The actual catch limit set by the MP when a decision is made is simply the average value of the two candidate catch limits

HCR 7.2 The second HCR uses both, a biomass and a juvenile index.

Where δ is the *target* catch; B * the *target* CPUE (i.e. the mean observed CPUE corresponding to some multiple of a biomass reference point such as $B0$ or $MMSY$) and $\bar{R}$ is the average recent juvenile biomass i.e. R is a "limit" level derived from the mean recruitment over a reference period; while $\varepsilon \bullet \in [0, 1]$ actions asymmetry so that increases in TAC do not occur at the same level as decreases.

$$TAC_{y+1} = 0.5 \times \left(TAC_y + C_y^{\text{targ}} \Delta_y^R\right),$$

$$TAC_{y+1}^2 = 0.5 \times \left(TAC_y + C_y^{\text{targ}} \Delta_y^R\right),$$

$$C_y^{\text{targ}} = \begin{cases} \delta \left[\dfrac{B_y}{B^*}\right]^{1-\varepsilon_b} & \text{for} \quad B_y \geq B^* \\ \delta \left[\dfrac{B_y}{B^*}\right]^{1+\varepsilon_b} & \text{for} \quad B_y < B^* \end{cases},$$

$$\Delta_y^R = \begin{cases} \left[\dfrac{\bar{R}}{\mathcal{R}}\right]^{1-\varepsilon_r} & \text{for} \quad \bar{R} \geq \mathcal{R} \\ \left[\dfrac{\bar{R}}{\mathcal{R}}\right]^{1+\varepsilon_r} & \text{for} \quad \bar{R} < \mathcal{R} \end{cases}$$

HCR 8: HCR using length-based reference points and survey biomass indices[2] (Ernesto Jardim, Manuela Azevedo et al. 2015)

Two harvest control rule are developed. One uses survey information and the statistical characteristics of the biomass index, while the other uses catch length compositions and life history parameters. These HCRs were developed taking into account common indicators derived from fisheries monitoring programmes and in themselves define different levels of data limitation. Survey information is independent of the fishery and constitutes a direct observation of the trends in biomass.

[2] Note that this HCR cannot be implemented in FLBEIA.

The Harvest Control Rules take the form:

$C_{y+1} = C_{y-1} \cdot \alpha$

where *C* are catches in weight and *y* indexes years. Different forms for α, the catch multiplier, lead to alternative HCRs. Three rules were tested, one based on short term trends in surveys (used frequently by ICES to provide catch advice for data-limited stocks); an alternative that uses the confidence interval of the mean abundance of the survey, to take into account long term information; and a third that uses length-based reference points.

HCR 8.1. Harvest rule based on short term changes in abundance index.

The rule based on short term changes in abundance, here after referred to as HCR1, compares the two most recent index values with the three preceding values and takes the following form:

$$\alpha = \frac{\sum_{i=y-2}^{y-1} I_i/2}{\sum_{i=y-5}^{y-3} I_i/3},$$

where *I* refers to the stock biomass or abundance index and *i* indexes years.

HCR 8.2. Harvest rule based on on survey confidence intervals.

The rule based on survey confidence intervals, named HCR2, sets α as:

$$\alpha = \begin{cases} \alpha_l & \text{if } I_{y-1} < \mu_I + z_{low}\frac{\sigma_I}{\sqrt{n_I}} \\ 1 & \text{if } \mu_I + z_{low}\frac{\sigma_I}{\sqrt{n_I}} \leq I_{y-1} \leq \mu_I + z_{upp}\frac{\sigma_I}{\sqrt{n_I}} \\ \alpha_u & \text{if } I_{y-1} > \mu_I + z_{upp}\frac{\sigma_I}{\sqrt{n_I}}, \end{cases}$$

with μ_I the mean index abundance, σ_I the index's standard deviation, n_I the length of the index time-series, and z_x the z-statistic from the standard normal distribution for which $P[Z \leq z_x] = x$. z_{low} and z_{upp} define the confidence interval limits, which don't have to be symmetric, and α_l and α_u the catch multipliers when the index is outside the lower or upper confidence interval, respectively. Note that in this rule the length of the index increases with time, as new data becomes available, which in theory means that the precision of the index mean, μ_I, will increase with new data.

HCR 8.3. Harvest rule based on length-based reference points.

The rule based on length-based reference points, named HCR3, has the following form for α:

$$\alpha = \frac{L_{SQ}}{L_{F=M}}$$

where F is the fishing mortality rate, M the natural mortality rate,L refers to individual length, and L_{SQ} the status quo (current) mean length in the catch, which is given by:

$$L_{SQ} = \frac{\sum_{a=1}^{A} C_{a,y} L_a}{\sum_{a=1}^{A} C_{a,y}}$$

with a indexing ages. $L_{F=M}$ refers to the mean length in the catch that sets fishing mortality at the same level as natural mortality.

HCR1 and HCR2 can be used to provide catch advice if survey data exists, while HCR3 can be used in more severe data limited cases where only catch length compositions are available. If both information sources exist, combinations of these HCRs can be explored.

Pros:

- HCRs 2 and 3 showed better performance in terms of SSB recovery and biological risk for both exploitation scenarios.
- All HCRs drive most fisheries to levels of catches below MSY, although in the case of HCR1 it is due to low levels of biomass, while for HCR2 and HCR3 this effect is related to low levels of fishing mortality, which reflects the more precautionary approach of these rules. HCR2 seems to behave better, showing a lower number of very small catch/MSY ratios.

Cons:

- The results show that HCR1 is not able to recover the biomass in both scenarios and the rule resulted in a high biological risk for the majority of the stocks.
- HCR1, which was designed to provide status quo catch advice adjusted by the biomass index ratio, showed the poorest performance, decreasing or keeping SSB at low levels and catches mostly below the MSY target.
- A common feature of the stocks for which HCR3 showed a poor performance.

HCR 9: DI-CUSUM- HCRS (Pazhayamadom, Kelly et al. 2015).

This study examines whether a fish stock can be managed using cumulative sum (CUSUM) control charts if limited historical information is available for the fish stock. Decision Interval Cumulative Sum (DI-CUSUM) control chart was used to monitor two indices from a simulated fishery; the recruitment indicator and the large fish indicator (LFI). The fishery was subsequently managed using a harvest control rule (HCR) that triggered only when a significant deviation in the indicator trend was detected by the DI-CUSUM. The HCR was constructed using methods adopted from engineering process control (EPC) theory where the adjustment in total allowable catch was determined by estimating the size of the shift in the indicator time series. It was found that monitoring combined indicator of both recruitment and LFI was more successful in controlling the fishery irrespective of the initial state of the fish stock. The HCR was evaluated for stocks with three life history traits i.e. short, medium and long-lived species.

The DI-CUSUM is constructed by the cumulative sum of deviations of indicator observations from a reference point. To compute the DI-CUSUM, each observation in the indicator time series is first standardized (Z_i) using the control parameters such that,

$$Z_i = \left(X_i - \frac{\bar{X}}{\bar{\sigma}} \right)$$

where X_i is the i^{th} indicator observation, $\bar{X}$ is the control mean and $\bar{\sigma}$ is the control standard deviation. This procedure determines how far each indicator observation is from the control mean and has the advantage of monitoring a variety of indicators combined since the deviations are expressed in standard deviation units. In the next step, a cumulative sum of Z_i is computed such that the positive indicator deviations (when $Z_i > 0$) and negative deviations (when $Z_i < 0$) are treated independently by computing two separate CUSUMs for each of them. These are termed as the 'Upper DI-CUSUM' (θ_i^+) and 'Lower DI-CUSUM' (θ_i^-), respectively.

$$\theta_i^+ = \max(0, \theta_{i-1}^+ + Z_i - k) \quad \text{and} \quad \theta_i^- = \min(0, \theta_{i-1}^- + Z_i + k),$$

where 'k' is the allowance parameter, a threshold used for accommodating the common cause variability that may occur even when the state of the stock is in-control e.g. natural variability in recruitment. An out-of-control situation can be formally detected by DI-CUSUM using the 'control limit' (h). If the indicator is in an in-control state, all CUSUM observations will fall between h^+ and h^- and no management action is necessary. However, if the CUSUMs exceed these control limits, then the state of the stock is said to be in out-of-control state and a management action is required to bring the stock back to in-control. The out-of-control state of the stock can be mathematically expressed as:

$$\theta_i^+ > h^+ \quad \text{or} \quad \theta_i^- < h^-$$

The control mean ($\bar{X}$) should ideally represent an "in-control" situation of the fishery (equivalent to a reference point in a fisheries management context). In this paper they assumed that $\bar{X}$ is available for the fish stock and it corresponds to the indicator observation when the fishery is in equilibrium at 90% of the MSY. Previous studies have confirmed that this target is associated with long term yields for a wide range of stock sizes and are close to the optimal conservative level of harvest. The control standard deviation ($\bar{\sigma}$) for DI-CUSUM was updated every year by computing the standard deviation of all indicator observations obtained until the most recent year. A 'metric winsorization' procedure was used to remove the effect of extreme outliers in the indicator if any. A low allowance of k = 0.5 and h = 0.5 was used for monitoring the indicators in this study. However, the effects of using higher k or h limits were tested.

Once an out-of-control situation is detected, the next step is to estimate the shift that has occurred in the indicator. The advantage of this approach is that if such estimates are available, they can be used as a correction/adjustment factor for the control variable (TAC in this context) so that the next indicator observation will be closer to the control mean. Several methods are available for computing the adjustment factor ($\hat{E}_i$).

1. Taguchi's method (M1): $\hat{E}_i = Z_i$

2. Montgomery's method (M2):

$$\hat{E}_i = \begin{cases} \dfrac{\theta_i^+}{O_i^+} + k & \text{if } \theta_i^+ > h^+ \\ + & \\ \dfrac{\theta_i^-}{O_i^-} - k & \text{if } \theta_i^- < h^- \end{cases}$$

3. Grubbs' harmonic rule (M3):

$$\hat{E}_i = \begin{cases} \sum_{t=0}^{H_i^+ - 1} \dfrac{Z_{i-H_i^+ + 1}}{t+1} & \text{if } \theta_i^+ > h^+ \\ + & \\ \sum_{t=0}^{H_i^- - 1} \dfrac{Z_{i-H_i^- + 1}}{t+1} & \text{if } \theta_i^- < h^- \end{cases}$$

4. Using CUSUM observations (M4): $\hat{E}_i = (\theta_i^+ + \theta_i^-)$

In the present study, the fishery was managed using a HCR in the fourth phase of the simulation where the TAC was updated only if an out-of-control situation is signal led by the DI-CUSUM. This can be mathematically expressed as:

If $\left|\theta_i^{\pm}\right| > \left|h^{\pm}\right|$, then

$$TAC_{i+1} = TAC_j + \left(TAC_j \times \hat{E}_i\right)$$

else,

$$TAC_{i+1} = TAC_j,$$

where *j* is the year in which an in-control situation was last indicated by the DI-CUSUM. The $\hat{E}_i$ is an adjustment factor to compensate for the shift that has occurred in the observed indicator. The formulation implies that when an in-control situation is signal led by the DI-CUSUM, the TAC from the previous year will be followed. Since $\hat{E}_i$ is a multiplier that makes relative adjustments to the TAC, the range of TACs could be extremely high if a large DI-CUSUM signal appears in the control chart (e.g. in the event of a recruitment failure). Similarly, the EPC methods may generate inaccurate estimates if a false alarm is signal led by the DI-CUSUM. Hence, an annual restriction in the TAC update was necessary to avoid stock collapse or closure of the fishery. The TAC_{i+1} was restricted using TAC^R such that it never dropped below $TAC_i \times (1 - TAC^R)$ and never exceeded $TAC_i \times (1 + TAC^R)$. For example if $TAC^R = 30\%$, then TAC_{i+1} will remain between $TAC_i \times 0.7$ and $TAC_i \times 1.3$.

In this paper the fishery simulations, indicator monitoring, and the DI-CUSUM-HCR were carried out using codes written in the programming language R (R Core Team, 2013).

Pros:

- Results from the fishery simulations indicate that the DI-CUSUM-HCR was successful at regulating the state of the stock by sustaining the indicators at their respective control means.
- The harvest strategy adopted in the present study belongs to a conditional constant catch control rule where the catch is set constant unless removing that amount would keep the CUSUM away from a predetermined maximum. There are several advantages in this approach compared to other rules that are based on fishing mortality (F) or biomass (B). First, this is most suitable for managing fish stocks that have limited or poor data because estimating the "current" F or B will require more information from the stock. Secondly, a harvest control rule expressed as catch is much easier to develop support from the stakeholders because the "out-of-control" situations are visually transparent in DI-CUSUM. Thirdly, the problem of over-fishing can be best addressed by regulating catch, as this quantity is directly interpretable in economic terms.
- Harvesting a constant catch is more strategic and proactive, because a reduction or increase in TAC is not necessary unless there is sufficient evidence that indicates overfishing or economic inefficiency.
- The DI-CUSUM-HCR approach can be implemented even if no biological information (other than the indicators with their respective control means) is available for the fish stock.

Cons:

- Many authors have demonstrated the usefulness of DI-CUSUM as a fishery monitoring tool (Scandol, 2003,2005; Petitgas, 2009; Mesnil and Petitgas, 2009), but their performance in directly managing a fishery has not been demonstrated so far.
- Setting a catch control rule in DI-CUSUM-HCR also has limitations in that an inter-annual TAC restriction (TACR) is necessary to avoid boom-or-bust situations.
- The proposed scheme may result in a stock collapse, but this can be reduced substantially if the TAC in the initial year is set lower than the stock's historical catch records or alternatively below MSY if such information is available. This also implies that the DI-CUSUM-HCR can be applied in a developing fishery situation, particularly if the catch has been maintained historically low compared to MSY of the fish stock.

According to (Dowling, Dichmont et al. 2015), CUSUM methods are simple methods that could be used to detect trends in empirical stock status indicators and trigger management interventions. Dowling also explains a single or multiple indicator trigger framework- indicator used sequentially. There are other 'multiple indicator harvest strategy framework': Traffit lights monitoring system, multidimensional scaling (MDS) which is a statistical technique that combines a described set of indicators and provides a rapid framework to assess fishery sustainability (rapfish).

HCR 10: HCRs derived from survey indices (spawner biomass, year-class strength and total mortality) (Pomarede, Hillary et al. 2010)

The design and evaluation of survey-based management strategies is addressed in this article, using three case-study fisheries: North Sea herring, Bay of Biscay anchovy and North Sea cod. Time-series estimates from fish surveys and other fishery independent sources may provide better information than those based on fishery-dependent sources for managing a fishery, especially when the available fishery-dependent data are of poor quality.

In this paper several HCR, based on fishery independent data, were tested for three fish stocks: herring, anchovy and cod. In particular, basic validation of the management strategy (TAC), total mortality (Z-based) harvest control rules, SSB-based harvest control rules was analyzed. The following table shows HCRs tested.

Pros:

- Inter-annual variation in TAC was noticeably less in the case of the total mortality HCR and this particular effect seems at least in part driven by the presence of reference points in the total mortality HCR.
- The results of the analyses show that survey-based management, in conjunction with the use of management strategy evaluation in the management design phase, could provide a workable alternative to catch-based methods for fisheries management.
- Survey-based approach are no associated biases entrained in the data available for estimating stock status.

Cons:

- In the case of Anchovy, performance of all the HCRs was strongly driven by the initialisation of the operating model. The HCR which utilised information on both recruitment and SSB appeared much less sensitive to the initialisation assumptions.
- In terms of using the MSE process it is clear that using a survey-based approach does not remove the problems of a lack of understanding of key processes, in particular the spawner-recruitment dynamics.
- A Z-based HCR was also tested and proved to be a more conservative HCR – the size of the SSB increase was larger than that seen for the derived SSB trend HCRs and with an initial decrease in TAC followed by an eventual increase in TAC as the stock abundance increased.

Synthesis table

ID	HCR NAME	REFERENCE	CASE STUDY
HCR 1.1.	HCR 1.1. Simple approach (Index)	SEAFO	General explanation.
HCR 1.2.	Survey-based assessments indicate trends	SEAFO	General explanation.
HCR 1.3.	Data-poor stocks	SEAFO	Stocks with only landings data
HCR 1.4.	HCR based on index (CPUE or survey index)	SEAFO (Shelton and Miller 2009)	Greenland Halibut (NAFO): The indicator is the slope of Abundance Index
HCR 1.5.	HCR based on trends in the CPUE and survey CPUE.	SEAFO	Australian HCR for Spanner Crab
HCR 2	Tier based HCRs	(Smith, Smith et al. 2008)	Southern and Eastern Scalefish and Shark Fishery (SESSF)
HCR 3	CPUE based HCR (Tier 4)	(Little, Wayte et al. 2011)	Southern and Eastern Scalefish and Shark Fishery (SESSF)
HCR 4	HCRs using catch rate data.	(O'Neill, F. et al. 2010)	Australian spanner crab fishery.
HCR 5	Survey data – derived HCR	(Apostolaki and Hillary 2009)	Describes several control rules
HCR 6.1.	HCR using relative SSB trends (index)	(Hillary 2009)	North Sea herring
HCR 7.1.	The first HCR is based on a single index	(Kell, Hillary et al. 2015)	Southern bluefin
HCR 7.2	The second HCR uses both, a biomass and a juvenile index.	(Kell, Hillary et al. 2015)	Southern bluefin
HCR 8.1	Harvest rule based on short term changes in abundance index.	(Ernesto Jardim, Manuela Azevedo et al. 2015)	Applied to 50 stocks (pelagic, demersal, deepsea species and Nephrops)
HCR 8.2	Harvest rule based on on survey confidence intervals.	(Ernesto Jardim, Manuela Azevedo et al. 2015)	Applied to 50 stocks (pelagic, demersal, deepsea species and Nephrops)
HCR 8.3	Harvest rule based on length-based reference points.	(Ernesto Jardim, Manuela Azevedo et al. 2015)	Applied to 50 stocks (pelagic, demersal, deepsea species and Nephrops)
HCR 9	DI-CUSUM- HCRS	(Pazhayamadom, Kelly et al. 2015)	The HCR was evaluated for stocks with three life history traits i.e. short, medium and long-lived species.
HCR 10	HCRs derived from survey indices (spawner biomass, year-class strength and total mortality)	(Pomarede, Hillary et al. 2010)	North Sea herring, Bay of Biscay anchovy and North Sea cod.

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Table 1. Decision matrix for setting λ in quota calculation (1), with subscript u and I indicating upper and lover catch rate thresholds, and θ an average ration of fishery and survey catch rates from the last 2 years divides by their target.

Mean catch rates ($\bar{c}$) Survey (s)	Commercial fishery (f) $\bar{c}_f \leq \bar{c}_{f,\text{target},l}$	$\bar{c}_{f,\text{target},l} < \bar{c}_f < \bar{c}_{f,\text{target},u}$	$\bar{c}_f \geq \bar{c}_{f,\text{target},u}$
$\bar{c}_s \geq \bar{c}_{s,\text{target},u}$	1	1	θ_{halfup}
$\bar{c}_{s,\text{target},l} < \bar{c}_s < \bar{c}_{s,\text{target},u}$	1 or θ	1	1
$\bar{c}_s \leq \bar{c}_{s,\text{target},l}$	θ or 0	1 or θ	1

Matrix cell 2,1: if $\bar{c}_s < \bar{c}_{s,\text{target}}$, then $\lambda = \theta$, else $\lambda = 1$. Matrix cell 3,1: if $\theta \leq 0.5$, then $\lambda = 0$, else $\lambda = \theta$. Matrix cell 3,2: if $\bar{c}_f < \bar{c}_{f,\text{target}}$, then $\lambda = \theta$, else $\lambda = 1$. Matrix cell 1,3: $\lambda = \theta_{\text{halfup}} = (\theta - 1) / 2 + 1$.

Table 2. Harvest control rules for each case study. ey: divergence of an index relative to a reference point: North Sea Herring, North Sea cod, Bay of Biscay anchovy; Kp, Hl and KD: three control parameters of the HCR.

		Case study	K_P	K_I	K_D
No exploitation					
HCR_0: $TAC_{y+1} = 0$		Herring	0	0	0
		Anchovy	0	0	0
		Cod	0	0	0
Constant *TAC*					
HCR_1: $TAC_{y+1} = TAC_y$		Herring	1	0	0
		Anchovy	1	0	0
		Cod	1	0	0
SSB-based					
HCR_2:	$e_y = \log\left(\frac{S\hat{S}B_y}{S\hat{S}B_{y-1}}\right)$	Herring	1	0	0
		Anchovy	1	0	0
		Cod	0.48	0.069	0.84
		Cod	0.48	0.027	0.84
		Cod	0.4	0	0
HCR_3:	$e_y = \log\left(\alpha(\hat{A}_y)\frac{S\hat{S}B_y}{S\hat{S}B_{y-1}}\right)$	Anchovy	1	0	0
HCR_4:	$e_y = \min\left\{\max\left\{\log\left(\frac{S\hat{S}B_y}{S\hat{S}B_{y-1}}\right), \log 0.8\right\} \log 1.2\right\}$	Anchovy	1	0	0
HCR_5:	$e_y = \log\left(\frac{\overline{SSB}_y}{\overline{SSB}_{y-1}}\frac{\hat{R}_y}{\hat{R}_{y-1}}\right)$	Anchovy	1	0	0
Z-based					
HCR_6:	$e_y = \min\left\{\log\left(\frac{Z^{PA}_{[0,1]}}{\hat{Z}_{y-1,[0,1]}}\right), \log\left(\frac{Z^{PA}_{[2,6]}}{\hat{Z}_{y-1,[2,6]}}\right)\right\}$	Herring	1	0	0
HCR_7:	$e_y = \log\left(\frac{\hat{Z}_y}{\hat{Z}_{y-1}}\right)$	Cod			
HCR_8:	$e_y = \log\left(\frac{\bar{Z}_y}{\bar{Z}_{y-1}}\right)$	Cod	0.32	0.02	0
		Cod	0.35	0	0
		Cod	0.175	0	0