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Total number of authors:
12

Published in:
ICES Journal of Marine Science

Link to article, DOI:
10.1093/icesjms/fsw111

Publication date:
2017

Document Version
Peer reviewed version

Citation (APA):
Rindorf, A., Cardinale, M., Shephard, S., De Oliveira, J. A. A., Hjorleifsson, E., Kempf, A., Luzenczyk, A., Millar, C., Miller, D. C. M., Needle, C. L., Simmonds, J., & Vinther, M. (2017). Fishing for MSY: using “pretty good yield” ranges without impairing recruitment. *ICES Journal of Marine Science*, *74*(2), 525-534. https://doi.org/10.1093/icesjms/fsw111

Fishing for MSY: can 'pretty good yield' ranges be used without impairing recruitment?

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Running title: 'Pretty good yield' in fisheries

Abstract-

Pretty Good Yield (PGY) is a sustainable fish yield corresponding to obtaining no less than a specified large percentage of the Maximum Sustainable Yield (MSY). We investigated 19 European fish stocks to test the hypothesis that 95% PGY yield range is inherently precautionary with respect to impairing recruitment. An F_{MSY} range was calculated for each stock as the range of fishing mortalities (F) that lead to an average catch of at least 95% of MSY in the long term simulations. Further, a precautionary reference point for each stock ($F_{P.05}$) was defined as the F resulting in a 5% probability of the spawning stock biomass falling below an agreed biomass limit below which recruitment is impaired (B_{lim}) in long-term simulations. For the majority of the stocks analysed, the upper bound of the F_{MSY} range exceeded the estimated $F_{P.05}$. However, larger fish species had higher precautionary limits to fishing mortality, and species with larger asymptotic length were less likely to have F_{MSY} ranges impairing recruitment. Our study shows that fishing at F_{MSY} generally is precautionary with respect to impairing recruitment for highly exploited teleost species in Northern European waters whereas the upper part of the range providing 95% of MSY is not necessarily precautionary for small and medium sized teleosts.

Key words: F_{MSY} ranges, Maximum Sustainable Yield, impaired recruitment, Pretty Good Yield

Introduction

The 2002 Johannesburg World Summit on Sustainable Development established a global imperative to manage fish stocks and fisheries according to the concept of Maximum Sustainable Yield (MSY) and the MSY principle was subsequently written into the US Magnuson-Stevens Fishery Conservation and Management Act (2007), the EU Common Fisheries Policy (CFP)(EU, 2013) and other fisheries legislation worldwide. MSY is defined as the largest yield that can be taken on a continuous basis from a stock under normal environmental conditions. F_{MSY} is the fishing mortality for which average yield is equal to MSY. Using these criteria, exploitation at MSY does not give the largest sustained *constant* yield, but the largest sustainable *average* yield, allowing variation among years due to variability in stock size. Exploitation at or below F_{MSY} while ensuring long-term sustainability, are commonly accepted fisheries objectives and many current management regimes have been built around this framework (Worm *et al.,* 2009; Dichmont *et al.,* 2010; ICES, 2014a).

Due to the frequent occurrence of 'flat top curves' in the relationship between fishing mortality and yield, Hilborn (2010) suggested using the F range delivering 80% of the maximum sustainable yield to provide 'pretty good yield'. This range allows for considerable flexibility, albeit at a cost of lower spawning stock biomass when using the part of the range above F_{MSY} (Hilborn, 2010; Smith *et al*., 2011; Mesnil, 2012, Figure 1). In a single species fishery, there would be no apparent benefit of using the range above F_{MSY}, as this would entail a higher fishing effort and hence a higher cost with no added yield and a resulting lower stock size (Figure 1), a higher dependence of stock and yield on recruiting year classes, increased variability on catch opportunities, and smaller fish on average (Froese *et al.,* 2011). However, in mixed fisheries, where the catch of one stock is accompanied by unavoidable catch of another stock, it is often difficult to reconcile fishing mortalities on different stocks (Hilborn *et al*., 2012; Rindorf *et al*., 2016). In this case, an approach for maximizing long term yield could be to attempt to use target fishing mortalities within a pretty good yield range providing, for example, 95% of MSY on average. Advice on such ranges was requested by the European Commission in 2014 and subsequently incorporated in analyses supporting the development of Multiannual management plans (EU, 2014: ICES, 2014a; STECF, 2015). However, for F_{MSY} ranges to be acceptable as the basis for management decisions in the ICES area all values of F within the defined range should be strictly precautionary with respect to impairing recruitment (ICES, 2014a, 2015a; 2015e). If not, a management strategy implementing these ranges will be in violation of the precautionary principle for the exploitation of natural resources (UN 1992). The precautionarity of different levels of fishing mortalities is determined by biological factors such as the stock reproductive capacity and management aspects, such as agreed stock reference points. Therefore, it does not necessarily follow that F_{MSY} or F_{MSY} ranges are precautionary with respect to stock biomass reference points defined to avoid impaired recruitment.

F_{MSY} and estimated maximum precautionary fishing mortalities are likely to respond differently to life history traits such as somatic growth, natural mortality (M), maturation and the shape and variability of the stock recruitment relationship as well as anthropogenic factors such as the selection pattern exhibited in the fishery. Zhou *et al.* (2012) identified a strong positive relationship between F_{MSY} and M in a meta-analysis of 245 fish species, but speculated that this relationship may be explained by the inclusion of M into the assessment models used to estimate F_{MSY}, which leads to correlation, possibly reflecting measurement error in the M estimates used (e.g., MacCall, 2009) as not all stocks use estimated natural mortalities. They suggest that K and/or L_∞ may in fact be the reliable predictors of F_{MSY}. Further, relatively subtle changes in fisheries size/age selection profiles can produce substantial differences in MSY and F_{MSY} (Scott and Sampson, 2011). Small bodied fish tend to have a higher natural mortality than larger bodied fish (Gislason *et al.*, 2010), and thereby presumably higher F_{MSY} values. They are often perceived as being more resilient to fishing (Beverton, 1990) compared to the frequently overfished larger bodied fish (Myers and Worm, 2003). However, including larger datasets, Pinsky *et al*. (2011, 2015) showed that small, fast growing species are more frequently depleted than larger, slow-growing species, indicating that small bodied species may in fact be more sensitive to exploitation than previously considered. It is unclear from the present literature how the combined effects of life history characteristics and fisheries selection patterns act on the relationship between F_{MSY} and precautionary limits to F.

In this study, we estimated (i) ranges of F_{MSY} compatible with obtaining 95% of the maximum average landings in the long term, and (ii) precautionary limits to fishing mortality aiming to ensure that recruitment is not impaired. We compared these estimates to determine whether F ranges corresponding to 95% of MSY are generally precautionary and hence can be used for giving sustainable fisheries advice in the context of MSY without further investigation of precautionarity. We investigated 19 North East Atlantic and Baltic stocks, including stocks with highly erratic S-R relationships and stocks where recruitment appears to increase or decrease monotonically as stock size increases and discuss whether general expectations about F_{MSY} ranges and precautionary limits to F can be made for different species, linking estimated reference points to life history characteristics and fisheries selection patterns through a meta-analysis.

Methods

The estimates of F_{MSY}, F_{MSY} ranges and precautionary limits to F depend heavily on the methodologies, assumptions, and data used to estimate them. In order to minimise any variation in our meta-analysis caused by differences in methods, common definitions and methods were agreed in a dedicated workshop before the onset of the analyses (ICES, 2014a).

Precautionary criteria

The precautionary limit to fishing mortality ($F_{P.05}$) was defined as the fishing mortality resulting in a 5% probability of the spawning stock biomass falling below an agreed lower limit, B_{lim}, in each year in long term simulations with a fixed F. B_{lim} is the spawning stock biomass below which impaired recruitment is expected. This reference point has been estimated following standardised guidance (ICES, 2003) by dedicated ICES expert groups based on the spawning stock biomass and recruitment pairs observed historically (see Table 1 for references).

F_{MSY} ranges

F_{MSY} ranges were defined as the range of Fs that leads to median landings of no less than 95% of MSY (EU 2014, Figure 1). Landings rather than catches were used as the metric for yield to avoid a situation where total catches were maximised at the cost of landings (i.e. the increase in catch is composed mainly of undersized fish). The F in the simulations included discards for those stocks where discards were included in the assessment. The mean of the simulated predicted yield can have undesirable properties when yield distributions are highly skewed (i.e., with extended tails in the distribution). The median is often considered to be more robust to these issues, and in cases where the distribution is unimodal and with short tails, mean and median values are generally similar. We defined MSY as the peak of the median landings when plotted against different values of F, with F_{MSY} being the F value which corresponds to that peak. Estimated F ranges were based on a fixed F.

Selecting the shape of S-R relationships

The stock recruitment (S-R) relationship is crucial in the estimation of F_{MSY}, F_{MSY} ranges, and the probability of the SSB falling below precautionary biomass reference points (Mace, 1994; Williams and Shertzer, 2003). Therefore, guidelines for best practice in the estimation of S-R relationships were developed prior to the analysis (Supplementary material). Three different S-R relationships were investigated: Ricker (Ricker, 1954), Beverton-Holt (Beverton and Holt, 1957) and hockey stick (O'Brien *et al.,* 2003; also known as segmented regression)(Figure 2). The method follows the procedure of Simmonds *et al.* (2011) with the contribution of each of the S-R models to the stock specific S-R relationship defined by applying multiple models using smooth AIC weights (Buckland *et al.,* 1997) in order to assign a weight to each of the S-R model types. Recruitments were re-sampled from their predictive distribution, which was based on parametric models fitted to the full time series provided unless substantial changes in recruitment occurred and were thought to be the result of factors unrelated to stock abundance in which case a shorter (but always greater than 10 years) period was used. Random deviations from the S-R model were the same for each target F.

Implementation of stochasticity

Stochastic simulations were carried out projecting 1000 populations for 150 years including both process and observation errors over a range of constant F exploitation rates. Variability in biological parameters such as growth, maturation and natural mortality (M) were included in a random bootstrap approach and inter-annual variability in recruitment was derived from stochastic draws from functional forms of the S-R curves as discussed above. Autocorrelation in recruitment, growth, maturation and natural mortality or correlations between these parameters was not considered in the analysis apart from autocorrelation in recruitment for western horse mackerel, where this seemed to be an intricate feature of the stock. In the estimation of the probability of obtaining a spawning stock biomass below the biomass limit reference points, it is necessary to include realistic estimates of uncertainty in the advised catch. This uncertainty was estimated from a comparison of the recent historic advised F (or catch forecast) and the resulting fishing mortality taken from the most recent assessment, or alternatively from a comparison of intended and realised F in the advisory year from a Management Strategy Evaluation (MSE) analysis (De Oliveira 2013). There are several ways to implement stochasticity, process and estimation uncertainty, and correlated errors in the simulations. For examples, see Kell *et al.* (2005), ICES (2013a) and Punt *et al.* (2015).

Estimation of assessment/advice error

The advice error was parameterised by two metrics, the conditional standard deviation in the log domain (σ_c) and the autocorrelation described as an AR(1) process (ϕ). The advice error in any year *y* was defined as the difference between the F estimated in the most recent assessment based on the catch recorded for year *y* and the F in year *y* that was forecast in year *y*-1. Hence, predicted catch levels include all error sources for which the advisory process is considered to be responsible, i.e., error in estimation of the stock and the short term forecast. We use the magnitude of the observed catch and exclude the elements of implementation error associated with choosing a TAC, which is the role of managers, and the control and enforcement aspects of ensuring conformity of realized catch with the TAC. Further details are given in the online supplementary material.

Data

A total of 19 stocks were selected for the analysis (Table 1), aiming to encompass species of differing stock-recruitment relationships, natural mortalities and asymptotic lengths, and covering different geographical areas of the North East Atlantic (Figure 3). Input data for weight at age in the stock and in the catches, maturity at age, natural mortality and selection patterns were derived as the last 10 years of available data taken from relevant ICES working group reports (see Table 1 for references). This period seemed to provide a reasonable balance between following trends in the parameters and avoiding tracking noise except for Atlantic cod (*Gadus morhua*) in the North Sea, where a 5 year period was used because recent trends were detected. Precautionary limits to F could only be defined when a B_{lim} was agreed for the stock. Estimates of Von Bertalanffy asymptotic size (L_∞) and K were derived from Gislason *et al.* (2010). Estimates of M were derived from relevant stock assessments (see Table 1).

Software

The Eqsim (stochastic equilibrium reference point) R library (ICES, 2013b) was used to estimate MSY reference points based on the equilibrium distribution of stochastic projections (https://github.com/einarhjorleifsson/msy, accessed September 2nd 2015) for all stocks but one; Western horse mackerel, *Trachurus trachurus*. For western horse mackerel, an MSE framework was used instead (Kell *et al*., 2007), which follows similar principles, but allows more detailed modelling of uncertainties as required for stocks with occasional very large recruitment spikes. The basis of the main parameters, the precautionary criteria F_{MSY} and associated ranges, and the elements included in the simulated stochasticity provided by the Eqsim software, are described in the sections above. The Eqsim software incorporates assessment/advice error introduced by the short-term forecast and implementation through a two-parameter error function, which is applied directly on the target F. B_{lim} is given as input parameters in the simulations. The main function calls used for fitting of S-R relationships and equilibrium simulations are shown in the Online Supplementary Material.

All results were screened to ensure that they were plausible according to expert knowledge. In a few cases, the program was unable to estimate hockey stick break points in accordance with estimates from other models and in these cases, models with fixed breakpoints equal to that estimated in FLR (Kell *et al*., 2007) were used to avoid the problem.

Meta-analyses of the estimated precautionary reference points, F_{MSY} and F_{MSY} ranges

As input to the meta-analyses, a number of stock specific factors were either estimated or obtained from the appropriate literature (Table 2): age at 50% maturity, age at 50% selection (i.e. age at 50% of the maximum fishing mortality at age), natural mortality (M) and asymptotic length (L_∞). To ensure comparability with the yield predictions used to derive F_{MSY}, only the latest 10 years of data were used. All data were included in a generalized linear model (McCullaugh and Nelder, 1989) assuming normally distributed residuals and a linear effect of all factors. The model was reduced using backward selection (F-test). Residuals were subsequently tested for normal distribution (Kolmogorov-Smirnov test) and for correlation between the stock specific factors to indicate if there may be issues with co-linearity.

Results

Stock recruitment relationships

All variants of stock recruitment relationships were used across the 19 study stocks (Table 1). All common sole (*Solea solea*) stocks showed monotonic decreases in recruitment with increasing biomass. In these cases, the Ricker S-R was excluded as this had the maximum to the far left in the range of observed biomasses. This procedure avoids predictions where fishing the stock at substantially higher Fishing mortalities than previously observed leads to increased yield. For North Sea cod, the Beverton- and Holt and the Ricker S-R curves showed an almost linear increase through the observed spawning stock biomass and recruitment pairs, and consequently the peak of the estimated Ricker curve was well beyond the highest spawning stock biomass observed. A segmented regression curve was therefore fitted for this stock. In both cases, this avoids a strong influence on results of the shape of the stock recruitment relationship at levels of spawning biomass which have not been observed historically.

Exploitation age and maturity

On average, fish were 50% selected to the fishery (i.e. age at 50% selection) when they reached an age which corresponded to 94% (standard deviation=10%) of the age of 50% maturity. Two stocks experienced an age at

50% selection to the fishery which was less than half the age at 50% maturity: North Sea plaice (*Pleuronectes platessa*) and western horse mackerel. Another three stocks, North Sea cod, North Sea saithe (*Polachius virens*) and Eastern channel plaice, had an age at 50% selection between 50 and 75% of the age at 50% maturity. Hence, these five stocks are entering the fishery before they reach the age of 50% maturation. Three stocks were not selected to the fishery until they reached an age of 125% of the age of 50% maturation and hence they were allowed to spawn before experiencing substantial fishing mortalities: North Sea herring (*Clupea harengus*), central Baltic herring and Western Baltic cod.

F_{MSY} ranges and precautionary limits to F

F_{MSY} ranges and precautionary limits to fishing mortality ($F_{P.05}$) are shown in Table 3 for all stocks. $F_{P.05}$ was significantly correlated to L_∞ (correlations>0.71, Figure 4). The reduced model included only asymptotic length:

$$F_{P.05} = 0.210^{(0.060)} + 0.0034^{(0.0008)} L_\infty \qquad (r^2=0.59)$$

No other factors had a significant effect on $F_{P.05}$.

F_{MSY} was significantly related to age at 50% selection and M ($P<0.05$ in both cases). Inspection of the relationship with age at 50% selection ($A_{50\%sel}$) revealed a saturating response (initial rapid increase followed by a flattening of the curve at high age at 50% selection) and so the analysis was repeated using the natural log of $A_{50\%sel}$ as the independent variable. This factor had a slightly lower significance level ($P=0.0024$, Figure 5). The final relationship estimated was

$$F_{MSY} = 0.150^{(0.041)} + 0.114^{(0.036)} ln(A_{50\%sel}) + 0.167^{(0.074)} M$$

where values in parentheses denote standard error of the parameters (r^2=0.46). There was no significant relationship between L_∞ or age at 50% maturity and F_{MSY} (P>0.05).

Natural mortalities of five of the stocks were derived from dedicated multispecies models (ICES 2011, 2014b) whereas the other estimates appeared more roughly estimated (values equal to 0.1, 0.2 or 0.5). We therefore investigated whether the effect of natural mortality remained significant when including only stocks with multispecies estimates of natural mortality. The effect of M on F_{MSY} remained the same order of magnitude but was no longer significant as the number of observations became very low (value=0.222, P=0.1429, n=5).

Results are seen as a function of F_{MSY} in Figure 6. The relative size of the range around F_{MSY} did not vary significantly with F_{MSY} (P=0.4510). Instead, both lower and upper limits relative to F_{MSY} varied significantly with asymptotic length, increasing the range with increasing asymptotic length (P=0.0133 and 0.0196 for lower and upper, respectively):

$$\frac{F_{MSYLower}-F_{MSY}}{F_{MSY}} = -0.259^{(0.031)} - 0.0012^{(0.0004)}L_\infty,\ r^2=0.31$$

$$\frac{F_{MSYUpper}-F_{MSY}}{F_{MSY}} = 0.241^{(0.073)} + 0.0025^{(0.0010)}L_\infty,\ r^2=0.28$$

Because of these relationships, $F_{MSYUpper}$ can only be expected to be precautionary for species with high asymptotic size (Figure 4). There were indications based on the linear models that F_{MSY} exceeds precautionary F for stocks with low L_∞ (<19 cm) (Figure 4). This indication was supported by the observation for Baltic sprat

(*Sprattus sprattus*, L_∞=16 cm,) where $F_{MSY}>F_{P.05}$. Furthermore, for stocks with L_∞ in the range of 19 to 47cm, F values in the range from F_{MSY} to $F_{MSYupper}$ were generally not precautionary.

None of the models had residuals that deviated significantly from a normal distribution (P>0.1500) with the exception of the model of $F_{MSYlower}$ relative to F_{MSY} (P=0.0160). Two pairs of independent variables exhibited high correlation (i.e. collinearity): age at 50% maturity and age at 50% selection (correlation=0.70), and asymptotic length and age at 50% maturity (correlation=0.54). Among these, age at 50% selection and asymptotic length occurred in the final models. M was not significantly correlated to any of the other variables (P>0.05). On average, the ranges were 0.67 and 1.4 times F_{MSY} for $F_{MSYlower}$ and $F_{MSYupper}$, respectively. These ranges corresponded to average spawning stock biomasses of 1.44 and 0.76 times B_{MSY}, respectively, corresponding to a 1.9 times higher spawning biomass on average when fishing at $F_{MSYlower}$ than when fishing at $F_{MSYupper}$. The average biomass when fishing at F_{MSY} exceeded the defined $B_{MSYtrigger}$ (the biomass reference point that triggers a cautious response within the ICES MSY framework) in all cases. With the exception of Central Baltic herring, the average biomass at $F_{MSYupper}$ was also above $B_{MSYtrigger}$.

Discussion

The fishing mortality which a stock can sustain without impairing recruitment is a result of the stock recruitment relationship and the subsequent survival, individual growth, maturation and the selection pattern in the fishery. Considerations of the risk of impairing recruitment must be retained even under MSY management as it is not inherent in the MSY concept that the probability of obtaining a spawning stock that result in a slightly lower average recruitment is negligible when fishing at F_{MSY}. The practical consequence of increased $F_{P.05}$ with L_∞, but no change in F_{MSY}, is that species with larger L_∞ are likely to have an $F_{MSYupper}$ that falls below precautionary limits of F. Although defining ranges such that no more than 5% of MSY is lost seems to imply minor changes to the stock, the flatness of the yield curves meant between 34% and 40% difference, on average, between F_{MSY} and $F_{MSYlower}$, and F_{MSY} and $F_{MSYupper}$, respectively, substantially more than the 5% difference in yield.

Species with a smaller asymptotic length had values of $F_{MSYupper}$ that exceeded the $F_{P.05}$ limit such that the estimated F_{MSY} range was not inherently precautionary (Figure 4). This corresponds to the observation that small, fast growing species are more frequently depleted than larger, slow-growing species (Pinsky *et al.*, 2011; 2015). The higher sensitivity of small pelagics has previously been suggested to be a result of the increase in catchability of these species with declining abundance (Beverton, 1990). However, this does not explain why similar low $F_{P.05}$ values are found for sole stocks in this study or that $F_{MSY} > F_{P.05}$ for sea scallops (Hart 2013).

In stocks with high asymptotic length, cohorts can contribute substantially to the spawning stock for a long period after the age at first capture as losses to predation and fishing are compensated by individual weight gain, thereby providing a lower sensitivity of the spawning stock biomass to occasional years of poor recruitment. Stocks with lower weight gain after recruitment to the fishery lack this ability and as a result are more sensitive to fishing pressure. The fishing mortality at which MSY is attained on average is the fishing mortality where the gains of incrementally increasing fishing exactly equal the losses. Asymptotic length, and the von Bertalanffy *K* are highly correlated parameters (Gislason *et al.*, 2010) and *K* influences the contribution of individual cohorts to the spawning stock biomass. Consider two stocks with constant recruitment, identical selection patterns, maturity ogives, natural mortalities at age and fishing mortalities, where stock numbers decay exponentially and growth is described by the von Bertalanffy equation. One of these stocks is characterised by a higher von Bertalanffy *K* than the other. In the event that one year class disappears (e.g. a poor recruitment year) the effect on the spawning stock is greater on the species with large *K* (such as sprat, herring and sole) than species with a lower *K* (such as plaice, saithe and cod). If maturity at age, natural mortality at age and selectivity at age is defined as (0.1, 0.5, 0.9, 1), (0.8, 0.5, 0.2, 0.2) and (0.1, 0.5, 0.9, 1) for ages (1, 2, 3, 4+) and F=0.3 on fully recruited ages, the spawning stock biomass will decrease by 15% if the age 3 group is missing due to a recruitment failure in a stock with *K*=0.2 (e.g. cod) whereas the decrease is 25% in a stock with *K*=0.65 (e.g. sprat). If two subsequent cohorts fail, the decrease is as high as 20 and 39%, i.e. twice as high for the stock with low weight gains at recruitment.

F_{MSY} was generally precautionary for the examined Northern European fish species (81% of the 19 stocks investigated), whereas $F_{MSYupper}$ was generally not (44% of all stocks had $F_{MSYupper}<F_{P.05}$), though species with greater asymptotic length were more likely to have estimates of $F_{MSYupper}$ which were precautionary (i.e. $F_{MSYupper}<F_{P.05}$). Fishing at either end of the ranges of F_{MSY} corresponded to substantial changes in the average spawning stock biomass. Relative to the B_{MSY}, average spawning biomass was increased by 44% and decreased by 24% when fishing at the lower and upper ends of the ranges of F_{MSY}, respectively. Zhou *et al.* (2012) speculated that the relationship between M and F_{MSY} may be explained by the inclusion of M which is often calculated from an assumed relationship between M and K or L_∞. They speculate that K and/or L_∞ may in fact be the reliable predictors of F_{MSY}. Interestingly, M and L_∞ were not significantly correlated in our subset of stocks, and the results indicate that while F_{MSY} is not linked to asymptotic size, M retains a small positive effect.

Stocks that recruited late to the fishery (i.e. higher age at 50% selection) had higher F_{MSY} values than those that recruited early. This result supports the common assumption that minimizing capture of juveniles avoids growth overfishing and imparts greater resilience to the stock. Relatively subtle changes in fisheries size/age selection profiles can produce substantial differences in MSY and F_{MSY} (Scott and Sampson, 2011). Froese *et al.* (2014) suggest that many European fish stocks are fished at sizes smaller than the length at first maturity. The age at 50% selection to the fishery was on average 94% of the age at 50% maturity in our data. However, this number covered a wide range of values for individual stocks, with examples of individual small as well as large bodied stocks having age at 50% selection both substantially above and below the age at 50% maturity.

Furthermore, neither $F_{P.05}$ nor F_{MSY} were related to age at 50% maturity. Presumably, other factors are affecting the relationship to the point where it cannot be concluded that fishing the stock after age at 50% maturity is inherently precautionary.

Four stocks were identified as particularly sensitive to recruitment assumptions: Baltic sprat, North Sea saithe, North Sea cod and North Sea herring. Baltic sprat shows high recent recruitment supporting F_{MSY} values which would not be precautionary if earlier climatic conditions are considered. North Sea saithe, North Sea cod and North Sea herring show decreased recent recruitment success and it should be considered to update F_{MSY} values regularly in the coming years. A continued monitoring of recruitment success together with an increased focus on the precautionarity of management for stocks like these are required to ensure future sustainability.

Based on our results, we conclude that F_{MSY} ranges are consistent with precautionary principles in some cases. The relationships with asymptotic length and age at 50% selection can be used as rules of thumb before investigating whether there is a potential to implement 'Pretty good yield' ranges without jeopardising precautionarity. As our meta-analysis was conducted on data from stocks that have sustained fishing for a long time, we do not recommend transferring the conclusions on precautionarity of ranges for large teleosts to e.g. elasmobranchs and other less productive species. However, for teleosts, the conclusions can be summarised in the following four points:

- If the species has a small asymptotic size (less than approx. 20 cm), it is unlikely that F_{MSY} is precautionary
- If the species has a medium asymptotic size (below approx. 50 cm), it is unlikely that the range of values between F_{MSY} and $F_{MSYupper}$ are precautionary

- If the species has a large asymptotic size (above approx. 50 cm), it is likely that the range of values between F_{MSY} and $F_{MSYupper}$ are precautionary, and a further investigation can be performed to confirm this.
- 95% of MSY can on average be attained between 0.67 and 1.4 times F_{MSY}, but the upper part of the range should not be used without a detailed investigation of precautionary considerations.

Acknowledgements

The authors thank the participants of the Joint ICES-MYFISH Workshop to consider the basis for FMSY ranges for all stocks for contributing to the development of the general guidelines and the discussion of results. The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007–2013) under grant agreement MYFISH number 289257 (AR, AK, SS, MV).

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Tables

Table 1. List of stocks analysed. S-R models are Ricker (R), Beverton-Holt (BH) and hockey stick with estimated (HE) or fixed (HF) breakpoints (See Figure 2 for an example). Areas referred to are shown in Figure 3 and further details on the rationale for choosing specific models are given in the online supplementary material.

					Current reference levels			
Stock	Species	Area	L_∞ (cm)	Source of data	F_{MSY}	B_{lim} (t)	MSY $B_{trigger}$ (t)	S-R model(s)
Baltic sprat	*Sprattus sprattus*, (Clupeidae)	Subdivisions 22–32	16.0	ICES 2014c	0.29	410 000	570 000	R, HE[1]
Western Baltic herring	*Clupea harengus* (Clupeidae)	IIIa and Subdivisions 22–24	30.0	ICES 2014c	0.28	90 000	110 000	R, BH, HE
Central Baltic herring	*Clupea harengus* (Clupeidae)	Subdivisions 25–29 and 32	30.0	ICES 2014c	0.26	430 000	600 000	HE
Gulf of Riga	*Clupea harengus* (Clupeidae)	Subdivision 28.1	30.0	ICES 2014c	0.35	NA	60 000	HE

herring								
Bothnian Sea herring	*Clupea harengus* (Clupeidae)	Subdivision 30	30.0	ICES 2014c	0.15	NA	316 000	HE
North Sea herring	*Clupea harengus* (Clupeidae)	Division IV	30.0	ICES 2014d	0.27	800 000	NA	R, BH
Western Baltic sole	*Solea solea* (Soleidae)	Division IIIa and Subdivisions 22–24	39.0	ICES 2014c	0.32	1 200	2 000	R, HE[2]
North Sea sole	*Solea solea* (Soleidae)	Division IV	39.0	ICES 2015b	0.22	25 000	35 000	HE[3]
Eastern channel sole	*Solea solea* (Soleidae)	Division VIId	39.0	ICES 2014e	0.29	NA	8 000	HE
Western horse mackerel	*Trachurus trachurus* (Carangidae)	Division IIa, IVa, Vb, VIa, VIIa-c, e-k, and VIII	43.4	ICES 2014f	0.13	NA	634 577	HF[4]

Northern Shelf haddock	*Melanogrammus aeglefinus* (Gadidae)	Division IV, IIIa and VIa	63.5	ICES 2014e	0.35	63 000	88 000	R, HE
NE Arctic haddock	*Melanogrammus aeglefinus* (Gadidae)	Division I and II	63.5	ICES 2014g	0.35	50 000	80 000	HE
North Sea plaice	*Pleuronectes platessa* (Pleuronectidae)	Division IV	70.0	ICES 2014e	0.25	160 000	230 000	R, BH, HE
Eastern channel plaice	*Pleuronectes platessa* (Pleuronectidae)	Division VIId	70.0	ICES 2015c	0.27	NA	NA	R, HE
North Sea saithe	*Pollachius virens* (Gadidae)	Division IV, IIIa and VI	107.0	ICES 2014e	0.30	106 000	200 000	R, HE
NE Arctic saithe	*Pollachius virens* (Gadidae)	Division I and II	107.0	ICES 2014g	0.32	136 000	220 000	R, BH, HE
Western Baltic cod	*Gadus morhua* (Gadidae)	Subdivisions 22–24	132.0	ICES 2015d	0.26	26 000	37 400	HE

North Sea cod	*Gadus morhua* (Gadidae)	Division IV, VIId and IIIa	132.0	ICES 2015e	0.19	70 000	150 000	HE[3]
NE Arctic cod	*Gadus morhua* (Gadidae)	Division I and II	132.0	ICES 2014g	0.40	220 000	460 000	R, BH, HE

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[1] Only the time series from 1992-2013 was used as there was evidence of a shift in recruitment per SSB in 1992

[2] Only the time series from 1992-2013 was used as there was evidence of a shift in recruitment per SSB in 1992

[3] Only hockey stick was used as the Ricker curve appeared driven by a few low recruitments and it was unclear whether these low recruitments were connected to SSB

[4] The breakpoint was fixed at the lowest SSB because the highest recruitment events occurred at the lowest SSBs. Furthermore, recruitment spikes were modelled as a separate process.

Table 2. Estimation methods used for stock specific factors analysed.

Factor	Estimation method
Age at 50% maturity	Linear interpolation to estimate the age at 50% maturity from average proportion mature of the age below and above 50% proportion mature.
Age at 50% selection	Linear interpolation to estimate the age at 50% of maximum F from average F of the age below and above 50% of maximum F at age. If the selection pattern is dome shaped, the lowest of the two estimates is used.
Natural mortality M	Average M before reaching age at 50% selection
Asymptotic length (L_∞)	L_∞ of all species were derived from Gislason et al. (2008).

Table 3. Estimates of F_{MSY} ranges and precautionary limits to F. $F_{P.05}$ is the F resulting in a 5% probability of SSB falling below B_{lim} in any year.

Stock	F_{MSY}	$F_{MSYLower}$	$F_{MSYUpper}$	$F_{P.05}$
Baltic sprat	0.26	0.19	0.34	0.21
Western Baltic herring	0.32	0.23	0.41	0.46
Central Baltic herring	0.23	0.16	0.31	0.22
Gulf of Riga herring*	0.32	0.24	0.38	
Bothnian Sea herring*	0.12	0.09	0.13	
North Sea herring	0.33	0.24	0.44	0.35
Western Baltic sole	0.22	0.17	0.26	0.23
North Sea sole	0.20	0.11	0.37	0.38
Eastern channel sole	0.30	0.16	0.43	0.39
Western horse mackerel*	0.095	0.075	0.115	
Northern Shelf haddock	0.37	0.25	0.52	0.51
NE Arctic Haddock	0.41	0.25	0.57	0.40
North Sea plaice	0.19	0.13	0.27	0.48
Eastern channel plaice	0.30	0.20	0.43	0.52

North Sea saithe	0.32	0.20	0.43	0.39
NE Arctic Saithe	0.26	0.15	0.42	0.38
Western Baltic cod	0.26	0.15	0.45	0.57
North Sea cod	0.32	0.22	0.49	0.86
NE Arctic cod	0.45	0.25	0.68	0.80

[*] B_{lim} is not defined for this stock and hence $F_{P.05}$ cannot be estimated.

Figure legends

Figure 1. Example of a curve showing the median yield and average spawning stock biomass as a function of fishing mortality. The location of F_{MSY}, $F_{MSYLower}$ and $F_{MSYUpper}$ are indicated in the right figure, with the latter two corresponding to 95% of the peak of the median landings curve. B_{lim}, the biomass at which recruitment is impaired is indicated on the left figure together with $F_{P.05}$, the fishing mortality leading to a 5% risk of falling below B_{lim}. Units are standardised to a scale of 0-100. Note that $F_{P.05}$ cannot be deducted from the left plot alone.

Figure 2. Examples of the S-R relationship fitted in the study (Central Baltic herring (*Clupea harengus*)). Red dots: observed recruitment; solid black line: Beverton and Holt; dashed black line: Ricker; dotted black line: hockey stick. The yellow and blue lines represent the combination of the three S-R curves and the 95% interval of the observations, respectively.

Figure 3. Geographic location of ICES divisions used to define fish stocks in Table 1. Modified after ICES (www.ices.dk).

Figure 4. $F_{P.05}$ (▲, broken line), F_{MSY} (◇, solid line) $F_{MSYUpper}$ and $F_{MSYLower}$ (dotted lines) as a function of L_∞. Points are observed values of F_{MSY} and $F_{P.05}$ (stocks without $F_{P.05}$ estimates are excluded from the plot), lines are regression lines.

Figure 5. F_{MSY} as a function of ln(age at 50% selection). Line is a regression line.

Figure 6. F_{MSY} (solid line), $F_{MSYLower}$ (○), $F_{MSYUpper}$ (◇) and $F_{P.05}$ (▲) of all stocks as a function of the F_{MSY} estimated for each stock. Each point represents the values of one stock. Hatched lines are regression lines of $F_{MSYUpper}$ and $F_{MSYLower}$.

Figures

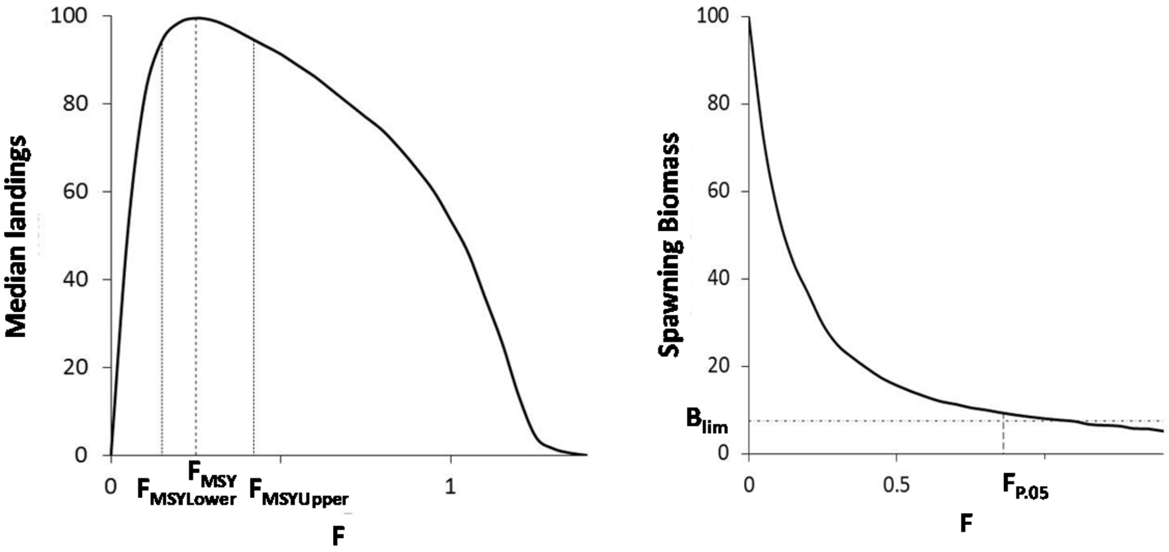

Fig. 1.

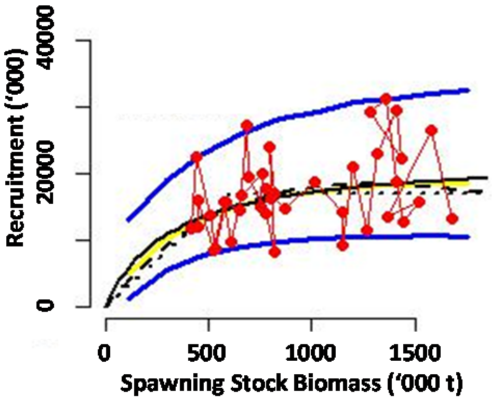
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Fig. 2.

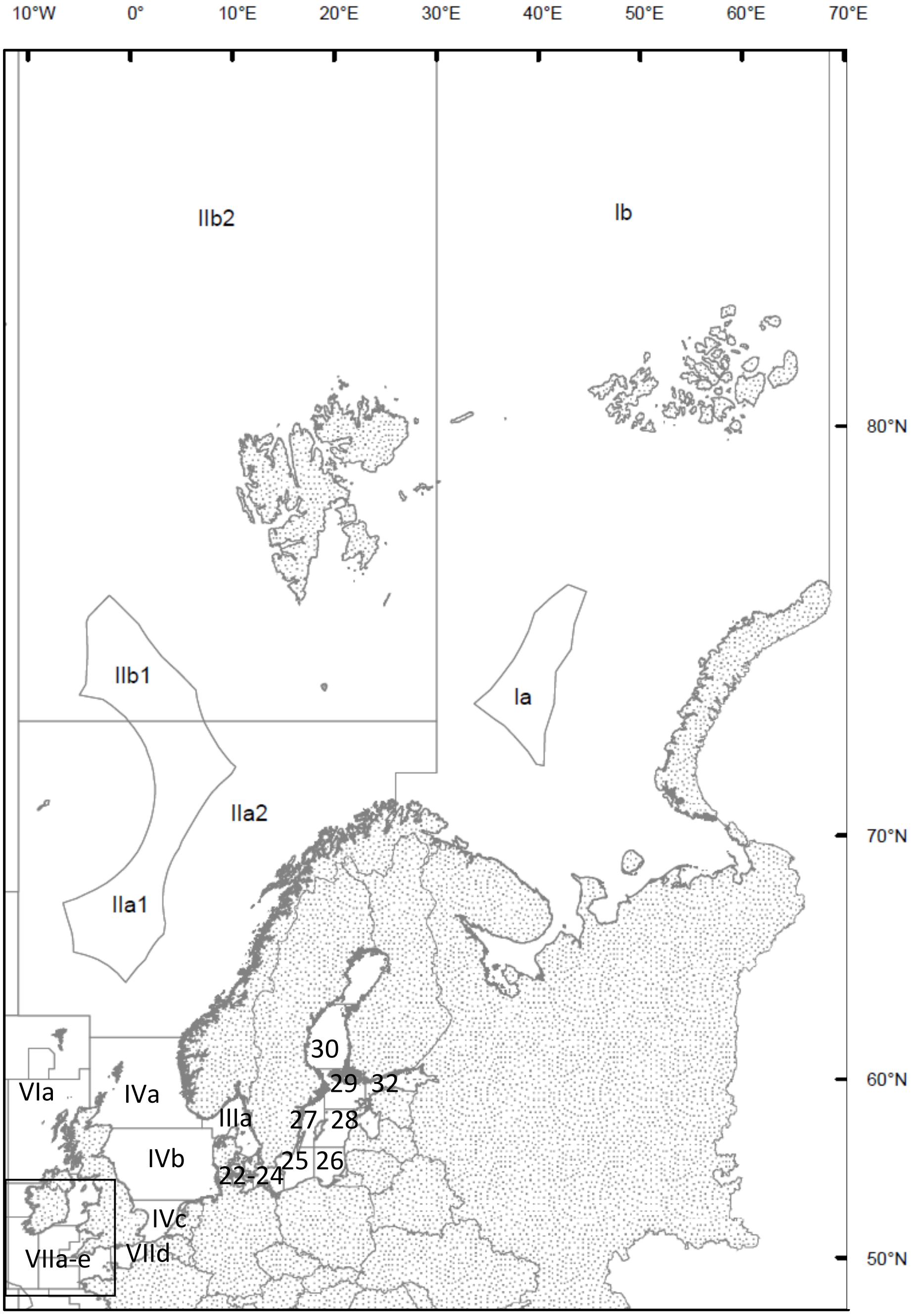
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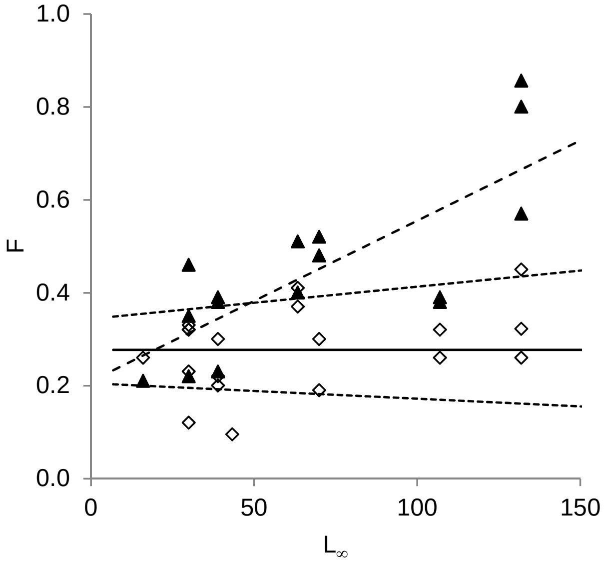
Fig. 3.

540



541 Fig. 4.

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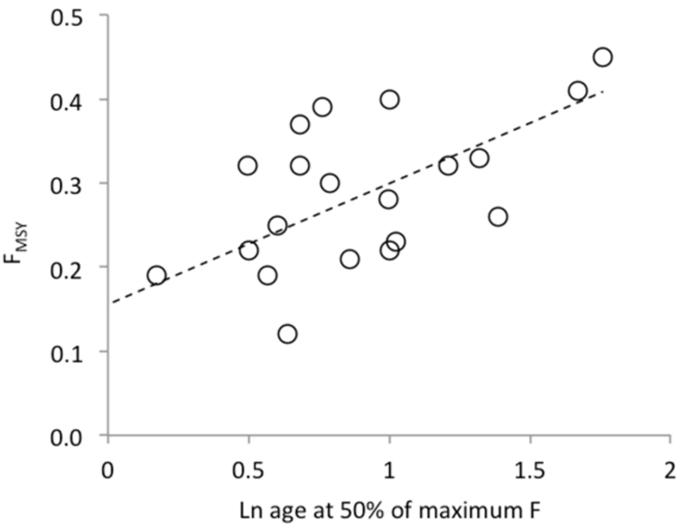

Fig. 5.

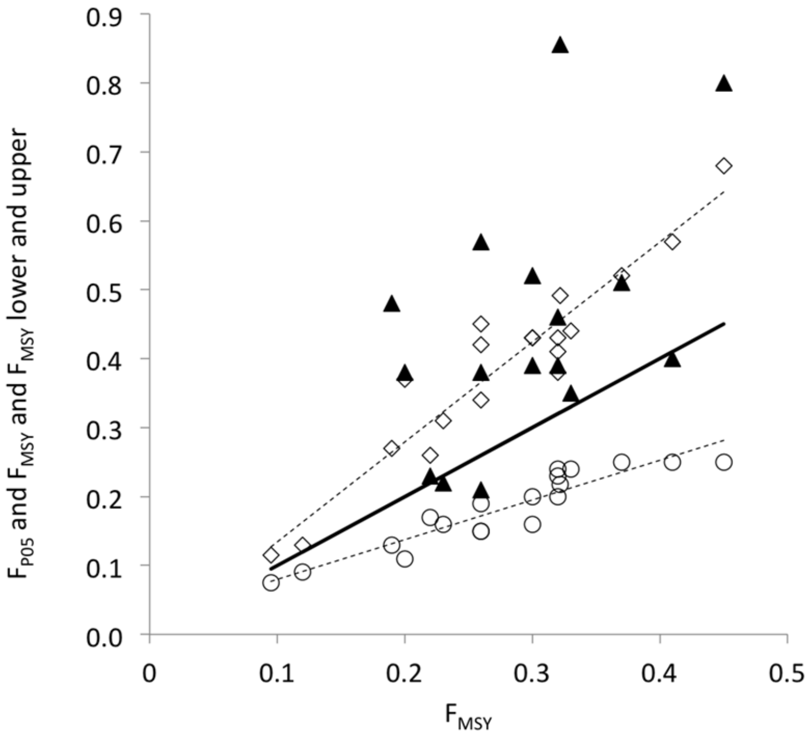

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Fig 6.

Online Supplementary Material

Guidelines for good practice in the selection of stock-recruitment (S-R) relationships

A summary of guidelines for good practice in the selection of stock-recruitment (S-R) relationships used for estimation of F_{MSY} and precautionary limits to fishing mortality derived from discussions in ICES (2014a) is given in the below table.

Scenario	Recommended action
There is clear evidence that a specific S-R relationship is the correct model.	In this case, the estimation of reference points should be based on that specific S-R relationship and no other S-R relationships should be included.
It is unclear which S-R relationship provides the best fit to data, i.e., several models show similar fits to data.	Use more than one S-R relationship of different shapes and weigh the results of simulations from the different options. A method to consistently weigh the results is described below under 'Eqsim'.
Individual points are highly influential in the S-R relationship.	Examine the validity of the highly influential data points. If they are considered valid, then retain them in the analysis; the use of a hockey stick or the Cadigan (Cadigan 2012) method with bootstrap observations may provide a robust option incorporating the uncertainty associated with the function. If the recruitment series show a few very high spikes, a distribution of the spikes can be

	added (see below).
Prolonged shifts in recruitment success that are unrelated to SSB, are suspected.	Unless strong evidence exists that a consistent change has occurred, the full time series of stock and recruitment should be used. Be careful not to mistake periodicity in recruitment success induced by e.g., cyclic climate conditions for prolonged shifts. Serial autocorrelation in recruitment (or recruitment deviations from the model) may also influence the results (see the horse mackerel example below).
Constant recruitment at all values of SSB are estimated.	Such relationships should not be included in the estimation. The predicted recruitment should be assumed to decrease significantly below the lowest observed stock size. For example, a hockey stick relationship with the lowest observed stock size as the forced breakpoint can be used.
Recruitment appears to increase with SSB for all values of SSB observed.	In these cases, F_{MSY} tends to be estimated at very low values as it is assumed in predictions that recruitment is an ever-increasing function of SSB. This seems highly unlikely. To avoid such unrealistic predictions, a hockey stick relationship can be used. The breakpoint of the hockey stick should be at the average of all observed stock sizes.

Recruitment appears to decrease with SSB for all values of SSB observed.	This usually results in a Ricker curve fitting the points with the descending limb of the function. Hence, maximum recruitment is predicted to occur at unknown stock sizes (well) below the minimum observed. The interpretation that recruitment will increase as S decreases to values well below the lowest observed seems highly risky. To avoid such predictions, a hockey stick relationship with a breakpoint at the lowest observed stock size can be used.
Recruitment has occasional very high values (spasmodic recruitment).	This type of S-R relationship is incorporated in the method used for western horse mackerel (Table 1). Removing the extreme points from the analysis for this stock led to lower suggested F_{MSY} and $F_{P.05}$ (F corresponding to 5% probability of $SSB<B_{lim}$) values than when the occasional high recruitments were included. Instead, a mixture of statistical distributions, including spikes, can be used. As a minimum, it is recommended to investigate the sensitivity of the results to the occurrence of occasional very large recruitments.
Predicted average recruitment at F_{MSY} is substantially higher than the maximum observed.	Predictions of average recruitment at F_{MSY} that are far greater than the maximum observed should be investigated thoroughly. Often, this results from estimating S-R functions using monotonically increasing observed S-R values. In this case, a hockey stick can be used (see explanation above).

Estimation of assessment/advice error

The estimated realized catch and annual values of F (F_{yr}) for the previous 10 years were taken from the most recent assessments. The annual ICES advice sheets issued in previous years were consulted to determine the F_{ya} that would have been advised to obtain the estimated realized catch. Linear interpolation was used where the appropriate catch was not available in the catch option table. For North Sea cod, the assessment changed considerably over the last few years, making historic comparisons meaningless, and an MSE analysis was recently conducted for this stock (De Oliveira, 2013). In this case, the intended F (F_{ya}) was compared with the realised F in the advice year (F_{yr}). For both approaches used to calculate F_{yr} and F_{ya}, the deviation in year *y*, d_y, was calculated as $\ln(F_{yr}/F_{ya})$, and the standard deviation σ_m of the log deviations gave the marginal distribution. The conditional standard deviation, σ_c, was calculated as $\sigma_m \sqrt{(1-\phi^2)}$, where ϕ is the autocorrelation of the AR(1) process. σ_c and ϕ were the input parameters for Eqsim.

Main function calls used for fitting of stock recruit relationships and equilibrium simulation

The specific calls to the routines used and the meaning of the variables can be found at https://github.com/einarhjorleifsson/msy/tree/master/man (accessed September 2nd 2015). The main function calls used for fitting of stock recruit relationships and equilibrium simulation using the Eqsim (stochastic equilibrium reference point) software were:

```
eqsr_fit <- function (stk, nsamp = 5000, models = c("ricker", "segreg", "bevholt"),
```

```
    method = "Buckland", id.sr = NULL, remove.years = NULL, delta = 1.3,
    nburn = 10000)
```

Where stk is an FLR stock object (Kell *et al*. 2007) giving SSB and recruitment; nsamp is the number of stock recruit draws to determine the median and 90% intervals simulated; models provides for 3 standard models, though alternative equations can also be fitted. The models are weighted by the method based on Buckland et al. (1997).

```
Eqsim_run <- function (fit, bio.years = c(2004, 2013), bio.const = FALSE, sel.years = c(2004, 2013), sel.const =
FALSE, Fscan = seq(0,1.2, len = 61), Fcv = 0, Fphi = 0, Blim, Bpa, recruitment.trim = c(3,
      -3), Btrigger = 0, Nrun = 200, process.error = TRUE,verbose = TRUE, extreme.trim=c(0,0))
```

The fitted S-R object (fit) is then combined with biological parameters drawn randomly (bio.const=FALSE) or as an average from a recent period (bio.years typically 10 years 2004-2013). Similarly selection in the fishery is drawn randomly (sel.const=FALSE) or as an average from a recent period (sel.years eg. 10 years 2004-2013).

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