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

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25

26 **Running title:** ‘Pretty good yield’ in fisheries

27

28 **Abstract-**

29 Pretty Good Yield (PGY) is a sustainable fish yield corresponding to obtaining no less than a specified large
30 percentage of the Maximum Sustainable Yield (MSY). We investigated 19 European fish stocks to test the
31 hypothesis that 95% PGY yield range is inherently precautionary with respect to impairing recruitment. An F_{MSY}
32 range was calculated for each stock as the range of fishing mortalities (F) that lead to an average catch of at
33 least 95% of MSY in the long term simulations. Further, a precautionary reference point for each stock ($F_{P.05}$)
34 was defined as the F resulting in a 5% probability of the spawning stock biomass falling below an agreed
35 biomass limit below which recruitment is impaired (B_{lim}) in long-term simulations. For the majority of the stocks
36 analysed, the upper bound of the F_{MSY} range exceeded the estimated $F_{P.05}$. However, larger fish species had
37 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).

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

79 F_{MSY} and estimated maximum precautionary fishing mortalities are likely to respond differently to life history
80 traits such as somatic growth, natural mortality (M), maturation and the shape and variability of the stock

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

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

103 precautionary limits to F can be made for different species, linking estimated reference points to life history
104 characteristics and fisheries selection patterns through a meta-analysis.

105 **Methods**

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

110

111 **Precautionary criteria**

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

118

119 **F_{MSY} ranges**

120 F_{MSY} ranges were defined as the range of F s that leads to median landings of no less than 95% of MSY (EU 2014,
121 Figure 1). Landings rather than catches were used as the metric for yield to avoid a situation where total
122 catches were maximised at the cost of landings (i.e. the increase in catch is composed mainly of undersized

123 fish). The F in the simulations included discards for those stocks where discards were included in the
124 assessment. The mean of the simulated predicted yield can have undesirable properties when yield
125 distributions are highly skewed (i.e., with extended tails in the distribution). The median is often considered to
126 be more robust to these issues, and in cases where the distribution is unimodal and with short tails, mean and
127 median values are generally similar. We defined MSY as the peak of the median landings when plotted against
128 different values of F , with F_{MSY} being the F value which corresponds to that peak. Estimated F ranges were
129 based on a fixed F .

130

131 **Selecting the shape of S-R relationships**

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

144

145 **Implementation of stochasticity**

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

160

161 **Estimation of assessment/advice error**

162 The advice error was parameterised by two metrics, the conditional standard deviation in the log domain (σ_c)
163 and the autocorrelation described as an AR(1) process (ϕ). The advice error in any year y was defined as the
164 difference between the F estimated in the most recent assessment based on the catch recorded for year y and
165 the F in year y that was forecast in year $y-1$. Hence, predicted catch levels include all error sources for which
166 the advisory process is considered to be responsible, i.e., error in estimation of the stock and the short term

167 forecast. We use the magnitude of the observed catch and exclude the elements of implementation error
168 associated with choosing a TAC, which is the role of managers, and the control and enforcement aspects of
169 ensuring conformity of realized catch with the TAC. Further details are given in the online supplementary
170 material.

171

172 Data

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

183

184 Software

185 The Eqsim (stochastic equilibrium reference point) R library (ICES, 2013b) was used to estimate MSY reference
186 points based on the equilibrium distribution of stochastic projections

187 (<https://github.com/einarhjorleifsson/msy>, accessed September 2nd 2015) for all stocks but one; Western horse
188 mackerel, *Trachurus trachurus*. For western horse mackerel, an MSE framework was used instead (Kell *et al.*,
189 2007), which follows similar principles, but allows more detailed modelling of uncertainties as required for
190 stocks with occasional very large recruitment spikes. The basis of the main parameters, the precautionary
191 criteria F_{MSY} and associated ranges, and the elements included in the simulated stochasticity provided by the
192 Eqsim software, are described in the sections above. The Eqsim software incorporates assessment/advice error
193 introduced by the short-term forecast and implementation through a two-parameter error function, which is
194 applied directly on the target F . B_{lim} is given as input parameters in the simulations. The main function calls
195 used for fitting of S-R relationships and equilibrium simulations are shown in the Online Supplementary
196 Material.

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

201

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

203 As input to the meta-analyses, a number of stock specific factors were either estimated or obtained from the
204 appropriate literature (Table 2): age at 50% maturity, age at 50% selection (i.e. age at 50% of the maximum
205 fishing mortality at age), natural mortality (M) and asymptotic length (L_{∞}). To ensure comparability with the
206 yield predictions used to derive F_{MSY} , only the latest 10 years of data were used. All data were included in a
207 generalized linear model (McCullough and Nelder, 1989) assuming normally distributed residuals and a linear

208 effect of all factors. The model was reduced using backward selection (F-test). Residuals were subsequently
209 tested for normal distribution (Kolmogorov-Smirnov test) and for correlation between the stock specific factors
210 to indicate if there may be issues with co-linearity.

211

212 **Results**

213 Stock recruitment relationships

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

224

225 Exploitation age and maturity

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

228 50% selection to the fishery which was less than half the age at 50% maturity: North Sea plaice (*Pleuronectes*
 229 *platessa*) and western horse mackerel. Another three stocks, North Sea cod, North Sea saithe (*Polachius virens*)
 230 and Eastern channel plaice, had an age at 50% selection between 50 and 75% of the age at 50% maturity.
 231 Hence, these five stocks are entering the fishery before they reach the age of 50% maturation. Three stocks
 232 were not selected to the fishery until they reached an age of 125% of the age of 50% maturation and hence
 233 they were allowed to spawn before experiencing substantial fishing mortalities: North Sea herring (*Clupea*
 234 *harengus*), central Baltic herring and Western Baltic cod.

235

236 F_{MSY} ranges and precautionary limits to F

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

$$239 \quad F_{P,05} = 0.210^{(0.060)} + 0.0034^{(0.0008)} L_{\infty} \quad (r^2=0.59)$$

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

241 F_{MSY} was significantly related to age at 50% selection and M ($P < 0.05$ in both cases). Inspection of the
 242 relationship with age at 50% selection ($A_{50\%sel}$) revealed a saturating response (initial rapid increase followed by
 243 a flattening of the curve at high age at 50% selection) and so the analysis was repeated using the natural log of
 244 $A_{50\%sel}$ as the independent variable. This factor had a slightly lower significance level ($P = 0.0024$, Figure 5). The
 245 final relationship estimated was

$$246 \quad F_{MSY} = 0.150^{(0.041)} + 0.114^{(0.036)} \ln(A_{50\%sel}) + 0.167^{(0.074)} M$$

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

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

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

258

$$259 \quad \frac{F_{MSYLower} - F_{MSY}}{F_{MSY}} = -0.259^{(0.031)} - 0.0012^{(0.0004)} L_\infty, r^2=0.31$$

260

$$261 \quad \frac{F_{MSYUpper} - F_{MSY}}{F_{MSY}} = 0.241^{(0.073)} + 0.0025^{(0.0010)} L_\infty, r^2=0.28$$

262

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

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

268 None of the models had residuals that deviated significantly from a normal distribution ($P>0.1500$) with the
 269 exception of the model of $F_{MSYlower}$ relative to F_{MSY} ($P=0.0160$). Two pairs of independent variables exhibited
 270 high correlation (i.e. collinearity): age at 50% maturity and age at 50% selection (correlation=0.70), and
 271 asymptotic length and age at 50% maturity (correlation=0.54). Among these, age at 50% selection and
 272 asymptotic length occurred in the final models. M was not significantly correlated to any of the other variables
 273 ($P>0.05$). On average, the ranges were 0.67 and 1.4 times F_{MSY} for $F_{MSYlower}$ and $F_{MSYupper}$, respectively. These
 274 ranges corresponded to average spawning stock biomasses of 1.44 and 0.76 times B_{MSY} , respectively,
 275 corresponding to a 1.9 times higher spawning biomass on average when fishing at $F_{MSYlower}$ than when fishing at
 276 $F_{MSYupper}$. The average biomass when fishing at F_{MSY} exceeded the defined $B_{MSYtrigger}$ (the biomass reference point
 277 that triggers a cautious response within the ICES MSY framework) in all cases. With the exception of Central
 278 Baltic herring, the average biomass at $F_{MSYupper}$ was also above $B_{MSYtrigger}$.

279 Discussion

280 The fishing mortality which a stock can sustain without impairing recruitment is a result of the stock
 281 recruitment relationship and the subsequent survival, individual growth, maturation and the selection pattern
 282 in the fishery. Considerations of the risk of impairing recruitment must be retained even under MSY
 283 management as it is not inherent in the MSY concept that the probability of obtaining a spawning stock that
 284 result in a slightly lower average recruitment is negligible when fishing at F_{MSY} . The practical consequence of
 285 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
 286 below precautionary limits of F . Although defining ranges such that no more than 5% of MSY is lost seems to
 287 imply minor changes to the stock, the flatness of the yield curves meant between 34% and 40% difference, on

288 average, between F_{MSY} and $F_{MSYlower}$, and F_{MSY} and $F_{MSYupper}$, respectively, substantially more than the 5%
 289 difference in yield.

290 Species with a smaller asymptotic length had values of $F_{MSYupper}$ that exceeded the $F_{P.05}$ limit such that the
 291 estimated F_{MSY} range was not inherently precautionary (Figure 4). This corresponds to the observation that
 292 small, fast growing species are more frequently depleted than larger, slow-growing species (Pinsky *et al.*, 2011;
 293 2015). The higher sensitivity of small pelagics has previously been suggested to be a result of the increase in
 294 catchability of these species with declining abundance (Beverton, 1990). However, this does not explain why
 295 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).

296 In stocks with high asymptotic length, cohorts can contribute substantially to the spawning stock for a long
 297 period after the age at first capture as losses to predation and fishing are compensated by individual weight
 298 gain, thereby providing a lower sensitivity of the spawning stock biomass to occasional years of poor
 299 recruitment. Stocks with lower weight gain after recruitment to the fishery lack this ability and as a result are
 300 more sensitive to fishing pressure. The fishing mortality at which MSY is attained on average is the fishing
 301 mortality where the gains of incrementally increasing fishing exactly equal the losses. Asymptotic length, and
 302 the von Bertalanffy K are highly correlated parameters (Gislason *et al.*, 2010) and K influences the contribution
 303 of individual cohorts to the spawning stock biomass. Consider two stocks with constant recruitment, identical
 304 selection patterns, maturity ogives, natural mortalities at age and fishing mortalities, where stock numbers
 305 decay exponentially and growth is described by the von Bertalanffy equation. One of these stocks is
 306 characterised by a higher von Bertalanffy K than the other. In the event that one year class disappears (e.g. a
 307 poor recruitment year) the effect on the spawning stock is greater on the species with large K (such as sprat,
 308 herring and sole) than species with a lower K (such as plaice, saithe and cod). If maturity at age, natural
 309 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

310 ages (1, 2, 3, 4+) and $F=0.3$ on fully recruited ages, the spawning stock biomass will decrease by 15% if the age
 311 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
 312 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
 313 high for the stock with low weight gains at recruitment.

314 F_{MSY} was generally precautionary for the examined Northern European fish species (81% of the 19 stocks
 315 investigated), whereas $F_{MSYupper}$ was generally not (44% of all stocks had $F_{MSYupper} < F_{P.05}$), though species with
 316 greater asymptotic length were more likely to have estimates of $F_{MSYupper}$ which were precautionary (i.e.
 317 $F_{MSYupper} < F_{P.05}$). Fishing at either end of the ranges of F_{MSY} corresponded to substantial changes in the average
 318 spawning stock biomass. Relative to the B_{MSY} , average spawning biomass was increased by 44% and decreased
 319 by 24% when fishing at the lower and upper ends of the ranges of F_{MSY} , respectively. Zhou *et al.* (2012)
 320 speculated that the relationship between M and F_{MSY} may be explained by the inclusion of M which is often
 321 calculated from an assumed relationship between M and K or L_{∞} . They speculate that K and/or L_{∞} may in fact
 322 be the reliable predictors of F_{MSY} . Interestingly, M and L_{∞} were not significantly correlated in our subset of
 323 stocks, and the results indicate that while F_{MSY} is not linked to asymptotic size, M retains a small positive effect.

324 Stocks that recruited late to the fishery (i.e. higher age at 50% selection) had higher F_{MSY} values than those that
 325 recruited early. This result supports the common assumption that minimizing capture of juveniles avoids
 326 growth overfishing and imparts greater resilience to the stock. Relatively subtle changes in fisheries size/age
 327 selection profiles can produce substantial differences in MSY and F_{MSY} (Scott and Sampson, 2011). Froese *et al.*
 328 (2014) suggest that many European fish stocks are fished at sizes smaller than the length at first maturity. The
 329 age at 50% selection to the fishery was on average 94% of the age at 50% maturity in our data. However, this
 330 number covered a wide range of values for individual stocks, with examples of individual small as well as large
 331 bodied stocks having age at 50% selection both substantially above and below the age at 50% maturity.

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

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

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

- 348 • If the species has a small asymptotic size (less than approx. 20 cm), it is unlikely that F_{MSY} is
349 precautionary
- 350 • If the species has a medium asymptotic size (below approx. 50 cm), it is unlikely that the range of
351 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.

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488 **Tables**

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

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

herring								
Bothnian Sea herring	<i>Clupea harengus</i> (Clupeidae)	Subdivision 30	30.0	ICES 2014c	0.15	NA	316 000	HE
North Sea herring	<i>Clupea harengus</i> (Clupeidae)	Division IV	30.0	ICES 2014d	0.27	800 000	NA	R, BH
Western Baltic sole	<i>Solea solea</i> (Soleidae)	Division IIIa and Subdivisions 22–24	39.0	ICES 2014c	0.32	1 200	2 000	R, HE ²
North Sea sole	<i>Solea solea</i> (Soleidae)	Division IV	39.0	ICES 2015b	0.22	25 000	35 000	HE ³
Eastern channel sole	<i>Solea solea</i> (Soleidae)	Division VIId	39.0	ICES 2014e	0.29	NA	8 000	HE
Western horse mackerel	<i>Trachurus trachurus</i> (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	<i>Melanogrammus aeglefinus</i> (Gadidae)	Division IV, IIIa and VIa	63.5	ICES 2014e	0.35	63 000	88 000	R, HE
NE Arctic haddock	<i>Melanogrammus aeglefinus</i> (Gadidae)	Division I and II	63.5	ICES 2014g	0.35	50 000	80 000	HE
North Sea plaice	<i>Pleuronectes platessa</i> (Pleuronectidae)	Division IV	70.0	ICES 2014e	0.25	160 000	230 000	R, BH, HE
Eastern channel plaice	<i>Pleuronectes platessa</i> (Pleuronectidae)	Division VIIId	70.0	ICES 2015c	0.27	NA	NA	R, HE
North Sea saithe	<i>Pollachius virens</i> (Gadidae)	Division IV, IIIa and VI	107.0	ICES 2014e	0.30	106 000	200 000	R, HE
NE Arctic saithe	<i>Pollachius virens</i> (Gadidae)	Division I and II	107.0	ICES 2014g	0.32	136 000	220 000	R, BH, HE
Western Baltic cod	<i>Gadus morhua</i> (Gadidae)	Subdivisions 22–24	132.0	ICES 2015d	0.26	26 000	37 400	HE

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

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

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

³Only 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

⁴The 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.

500 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).

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502

503 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
 504 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

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

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508 Figure legends

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

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

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

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

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

525 Figure 6. F_{MSY} (solid line), $F_{MSYLower}$ ($\bigcirc$), $F_{MSYUpper}$ ($\blacklozenge$) and $F_{P.05}$ ($\blacktriangle$) of all stocks as a function of the F_{MSY} estimated
526 for each stock. Each point represents the values of one stock. Hatched lines are regression lines of $F_{MSYUpper}$ and
527 $F_{MSYLower}$.

528 **Figures**

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530 Fig. 1.

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533 Fig. 2.

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Fig. 3.

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Fig. 4.

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545 Fig. 5.

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549 Fig 6.

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1 Online Supplementary Material

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

3 A summary of guidelines for good practice in the selection of stock-recruitment (S-R) relationships used for
4 estimation of F_{MSY} and precautionary limits to fishing mortality derived from discussions in ICES (2014a) is given
5 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.	<p>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.</p> <p>Serial autocorrelation in recruitment (or recruitment deviations from the model) may also influence the results (see the horse mackerel example below).</p>
Constant recruitment at all values of SSB are estimated.	<p>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.</p>
Recruitment appears to increase with SSB for all values of SSB observed.	<p>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.</p>

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).

6 Estimation of assessment/advice error

7 The estimated realized catch and annual values of F (F_{yr}) for the previous 10 years were taken from the most
8 recent assessments. The annual ICES advice sheets issued in previous years were consulted to determine the
9 F_{ya} that would have been advised to obtain the estimated realized catch. Linear interpolation was used where
10 the appropriate catch was not available in the catch option table. For North Sea cod, the assessment changed
11 considerably over the last few years, making historic comparisons meaningless, and an MSE analysis was
12 recently conducted for this stock (De Oliveira, 2013). In this case, the intended F (F_{ya}) was compared with the
13 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 ,
14 was calculated as $\ln(F_{yr}/F_{ya})$, and the standard deviation σ_m of the log deviations gave the marginal distribution.
15 The conditional standard deviation, σ_c , was calculated as $\sigma_m \sqrt{1-\phi^2}$, where ϕ is the autocorrelation of the
16 AR(1) process. σ_c and ϕ were the input parameters for Eqsim.

17

18 Main function calls used for fitting of stock recruit relationships and equilibrium 19 simulation

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

24

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

26 method = "Buckland", id.sr = NULL, remove.years = NULL, delta = 1.3,

27 nburn = 10000)

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

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

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

38 References

39 Buckland, S.T.Burnham, K.P., and Augustin, N. H. (1997) Model selection: an integral part of inference.
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