

- 1 Stock collapse or stock recovery? Contrasting perceptions of a depleted cod stock
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10 Abstract

11 ICES assessments of cod (*Gadus morhua*) in the west of Scotland (ICES Division 6a) suggest the
12 biomass has collapsed and that fishing mortality rate (F) has remained high. By contrast, other stocks
13 in the same fishery, and adjacent cod stocks all show marked declines in fishing mortality and some
14 recovery of the biomass. The perception of the status of 6a cod appears to be dependent on the
15 assumption that the fishery exploitation pattern is flat topped. An assessment that allows the
16 exploitation to take a domed shape produces results that suggest a marked decline in fishing
17 mortality rate and that the spawning stock biomass has recovered to the minimum biomass
18 reference point, B_{lim} . The reduction in F is consistent with substantial reductions in fishing effort and
19 shows a similar pattern to stocks taken within the same fishery. The management implications
20 arising from the two assessments differ substantially. The analysis indicates that benchmark
21 assessments need to test assessment model conditioning assumptions more widely and that
22 management advice needs to consider a more comprehensive range of information about the stock
23 and fishery.

24

25 Keywords: Stock collapse, stock recovery, cod, selectivity pattern, assessment uncertainty,
26 management advice.

27 Introduction

28 Fishery managers need to be able to judge stock status in relation to reference points so that
29 appropriate interventions can be made and also to assess the success of previous management
30 measures. This requires stock assessments that are reliable and robust. For a great many stocks
31 worldwide, the desired assessment approach is to use statistical catch at age models that can
32 provide detailed estimates of fishing mortality rate and spawning stock biomass. In the ICES area, for
33 example, common choices for stock assessment are SAM (Nielsen and Berg, 2014), XSA (Shepherd
34 1999) and TSA (Gudmundsson, 1994, Fryer, 2002). Such models make use of data from the age
35 structure of the commercial catches and estimates of relative abundance from research vessel
36 surveys. The methods have been widely tested (Deroba et al 2015) and may perform well when
37 tested with simulated data.

38 While these assessment models may be the best available, it is widely understood that their
39 estimates of fishing mortality (F) and spawning stock biomass (SSB) will be subject to uncertainty,
40 and perhaps more importantly, are conditioned on many necessary assumptions that may in reality
41 be incorrect resulting in bias. These include the way fishery selectivity changes with age and time,
42 the relationship between survey indices and abundance, natural mortality and the stock-recruitment
43 relationship. In particular, the function that describes fishery selectivity by age or size can be critical
44 in the assessment (Punt et al 2014). In recognition of these issues ICES has adopted a system of
45 periodic benchmark assessments where detailed analysis of a wide range of biological and fishery
46 data is reviewed, a range of assessment methods tested, and a preferred model identified for future
47 routine annual assessments (ICES 2013a). This procedure should help understand the range of
48 uncertainty and the importance of conditioning assumptions. The focus of benchmark assessments,
49 in common with most annual stock assessments, is stock specific and frequently relies on model
50 goodness-of-fit criteria and internal consistency based on retrospective analysis (Mohn, 1999). The
51 output is usually a single model that provides an historical reconstruction of the stock with estimates

52 of status relative to management reference points. Scientific advice to management tends,
53 therefore, to be conditioned on a “best model” with a qualitative description of major uncertainties
54 beyond the estimation error derived from the best model.

55 While the “best model” approach has its attractions on the grounds of simplicity, it nevertheless
56 carries with it risks since it may imply a narrower range of uncertainty about the assessment than is
57 actually the case. Other plausible interpretations of the data may be possible which can give a
58 perspective quite different from the best model, even where these are less likely. This problem is
59 illustrated here with the assessment of cod (*Gadus morhua*) in the west of Scotland (ICES Division
60 6a) which was last benchmarked in 2012 (ICES, 2012). Successive assessments have shown the stock
61 to be all but collapsed having declined from over 40000t in 1981 to 1400t in 2006 (ICES 2017).
62 Despite a slow but small increase to 2400t in 2017, the stock remains well below the SSB limit
63 reference point (B_{lim}) of 14000t (ICES 2017). Furthermore, the estimated fishing mortality remains
64 high at close to $F=1$ despite several years of advice for zero catch and the imposition of a cod
65 recovery plan by the European Union (EU 2008). What makes the assessment of this stock unusual is
66 that it contrasts with other demersal stocks in the same fishery such as haddock (*Melanogrammus*
67 *aeglefinus*) and whiting (*Merlangius merlangus*), and with adjacent stocks of cod in the North Sea
68 (ICES Subarea 4 and Division 3a) and the Irish Sea (ICES Division 7a) all of which show declining
69 fishing mortality rates and recovering biomass (ICES 2013b, ICES 2018a). Since cod, haddock and
70 whiting in 6a are all taken by the same vessels in a mixed fishery, it might be expected that trends in
71 fishing mortality would be similar. Furthermore since cod in the Irish Sea and North Sea are subject
72 to the same cod recovery plan as cod in 6a, some comparable trends in F might be anticipated.
73 There has also been a marked decline in fishing activity in the area (STECF, 2014) which might be
74 expected to lead to lower fishing mortality rates. There is, therefore, information external to the
75 target stock that appears inconsistent with the 6a cod assessment results.

76 To investigate the robustness of the estimated 6a cod trends a simple assessment model is
77 described that can reproduce the ICES assessment results and allows investigation of alternative
78 conditioning assumptions. It can be shown that it is possible to obtain contrasting results more
79 consistent with other information from the fishery and which have important consequences for
80 management. It illustrates the need to look beyond the target stock alone in order to understand
81 the full range of assessment sensitivity and to conduct more thorough exploration of the range of
82 uncertainty.

83 Data

84 Stock assessment input data for cod in 6a were taken from the relevant ICES assessment working
85 group (ICES 2018b). They consist of numbers at age data for landings and discards, survey indices
86 and biological data on natural mortality, maturity and growth. The data used in the assessment
87 model described below were as follows:

- 88 1. Total catch numbers at age 1983-2017 (the sum of landings and discards), ages 1-6.
- 89 2. ScoGFS-WIBTS Q1 survey 1985-2010 ages 1-6.
- 90 3. UK-SCOWCGFS-Q1survey 2011-2018, ages 1-6
- 91 4. ScoGFS-WIBTS-Q4: survey 1996-2009, ages 1-6
- 92 5. UK-SCOWCGFS-Q42011-2017, ages 1-6
- 93 6. IRGFS-WIBTS-Q4 2003-2017, ages 1-4

94 The five surveys (2-6) are groundfish surveys (GFS) conducted by the UK, Scotland (SCO) and Ireland
95 (IR) in quarters 1 (Q1) and 4 (Q4). For surveys 2 and 4, these form part of the International bottom
96 trawl survey in western waters (WIBTS). The standard ICES assessment only uses surveys 2 and 3.
97 These are consecutive surveys with no overlap which makes the estimation of survey catchability
98 uncertain, especially as the time series of the UK-SCOWCGFS-Q1 is very short. For this reason both
99 the quarter 1 and quarter 4 surveys are included. The IRGFS-WIBTS-Q4 survey overlaps the other

100 surveys in time and therefore provides intercalibration information to assist in the estimation of
101 catchability.

102 Stock summary data for cod in the North Sea, Irish Sea, and whiting in 6a, were taken from ICES
103 advice (ICES 2018a). In the case of haddock in 6a, data were taken from ICES (2013b) as the stock
104 was merged with the North Sea stock in 2014 and separate assessment data are not available
105 thereafter. ICES stock summary data for cod in 6a were taken from ICES (2017) as the advice in 2018
106 was based on the same assessment as the previous year.

107 Fishing effort expressed, as kilowatt-days were available. This represents vessel engine power
108 multiplied by days at sea. Effort data for regulated Scottish fleets in Division 6a between 2000 and
109 2016 were taken from Scottish sea fish statistical tables (Anon 2017). These include the TR1 fleet
110 which includes mainly trawlers targeting roundfish with a mesh size of 100mm or more and the TR2
111 fleet targeting mainly *Nephrops norvegicus* with a mesh size of 80mm or more. Here “regulated”
112 refers to fleets subject to effort control in the EU cod recovery plan (EU 2008). Total fishing effort for
113 all EU fleets fishing in 6a between 2003 and 2014 was taken from STECF (2014). The latter are
114 partitioned between regulated and unregulated fleets. The effort data are given in Table 1.

115 Methods

116 An exploratory stock assessment model is used for analysis which has similarities to, but is simpler
117 than the TSA assessment model used by ICES (Fryer, 2002). The principal model equations are set
118 out in Tables 2-5 which describe the population model, the observation equations, observation error
119 distributions and prior distributions on the parameters. It is a conventional age structured
120 population model where total mortality, Z , is split between fishing mortality, F , which is dynamic,
121 and natural mortality, M , which is fixed. These mortalities reduce the number of the fish, N , at the
122 start of the year according to equation T2.1. Total mortality is the sum of fishing mortality and
123 natural mortality (T2.2). Fishing mortality is separable into an age effect and a year effect (T2.3) and
124 these follow a random walk through time (T2.4 and T2.5). The observed catch is derived from the

125 Baranov equation with a multiplier that accounts for unreported catch (T3.1). The survey indices,
126 required to calibrate the model, are assumed to be proportional to the population in the sea (T3.2).
127 Observed quantities are assumed to be measured with lognormal sampling error (Table 4). Priors on
128 the parameters are either uniform or log uniform (Table 5).

129 The model was fitted to the data using Bayesian methods in the R package “rstan” (The Stan
130 Development Team, 2016). The base case model was fitted assuming a selectivity reference age of 4,
131 i.e. selectivity for age 4 was set to 1. The misreporting factor was fixed at 1 except for years 1996-
132 2005 where it was freely estimated. This corresponds to the period when misreporting was
133 considered significant (ICES 2018b). In addition, a retrospective analysis was performed by
134 successively leaving out data from the terminal year as a test of model consistency (Mohn, 1999).

135 The ICES assessment assumes that the selection pattern is flat from age 4 and older (ICES 2012) but
136 allows small annual deviations from this pattern. In order to implement a similar configuration, the
137 model was re-run with selectivity from age 4 onwards set to 1 and is referred to as the “selectivity
138 case”.

139 Fishing mortality estimated from the base case was regressed against effort data using time series
140 multiple regression (Hyndman and Khandakar, 2008) to establish whether effort can explain changes
141 in fishing mortality. For the Scottish data, F was regressed against TR1 and TR2 effort data, while for
142 the EU data F was regressed against regulated and unregulated effort.

143 Results

144 Figure 1 shows the trend in F and SSB estimated from the ICES assessment and the selectivity case
145 described above. Fishing mortality is high with slight tendency to decline in recent years. SSB has
146 declined sharply and remains at a low value. The selectivity case model and the ICES assessment
147 show close agreement.

148 In the base case model, where selectivity is not constrained to be flat topped, fishing mortality
149 shows a marked decline, while there is a modest recovery of the SSB (Figure 2). In this case the
150 estimated selection pattern is dome shaped (Figure 3) and has a qualitatively similar shape to cod
151 stocks in the Irish Sea and North Sea, all with peak selection at age 3. ICES defines B_{lim} , the minimum
152 biomass limit, as the 1992 SSB value. The estimate from the base case for the 2017 SSB is close to
153 this value (Figure 2b) unlike the ICES assessment that estimates it as only 18% of B_{lim} (Figure 1b). The
154 retrospective analysis indicates that the model is internally consistent. Further details of the base
155 case model output are given in Supplementary material.

156 Results of multiple regression of F from the base case on fishing effort is shown in Table 6. For
157 Scottish gears both the TR1 and TR2 fleets have highly significant slopes. The total EU effort shows a
158 highly significant slope with regulated gears but with a weakly significant slope for unregulated
159 gears. The fitted F values from the regressions are shown in Figure 4.

160 The base case estimates of F show trends that are consistent with the two other target species in the
161 mixed demersal fishery (Figure 5a). There is similarity both in trend and scale, especially with
162 whiting. The adjacent cod stocks which were also subject to the cod recovery plan also show a
163 similarity with the base case (Figure 5b).

164 Discussion

165 The results of the ICES assessment are closely mirrored in the selectivity case and make the
166 assumption that the selection pattern is flat above age 4. In this scenario, fishing mortality is high
167 and the SSB is well below B_{lim} with little sign of recovery. Relaxing the asymptotic selectivity
168 assumption offers a different interpretation of stock development with a sharp decline in F and
169 recovering SSB. The base case trend in F can be explained by documented changes in effort both by
170 the Scottish fleets that account for 65% of the landings and the total effort of the EU regulated
171 fleets. Furthermore, unlike the ICES assessment, the changes in F are consistent with stocks taken in

172 the same fishery and adjacent cod stocks that have been subject to the EU cod recovery plan. It
173 suggests the base case configuration is at least as plausible as the ICES assessment.

174 The principal factor leading to the difference between the ICES assessment and the base case
175 appears to be the conditioning selectivity assumption. The flat topped selectivity in the ICES
176 assessment causes the model to interpret the low observed catches at older ages as the result of a
177 high mortality acting on a small population. In contrast, the base case suggests the selection pattern
178 is “dome-shaped” where older fish have lower selectivity. Hence this model explains the low catches
179 as a lower fishing mortality acting on a larger population in the sea.

180 The choice of flat topped selection is based on observations from early assessments that used XSA in
181 1997 (ICES 1997). Trawl codend selectivity may be expected to be asymptotic and is the
182 conventional assumption for trawl gear selectivity models (MacLennan, 1992). However, whole
183 fishery selectivity will be an aggregate of a variety of differing gears whose selection characteristics
184 differ. Spatial effects in the distribution of both the target stock and the exploiting fleets will also
185 affect selectivity and may result in dome shaped responses (Waterhouse et al 2014). In the case of
186 6a cod, the two most important fleets are the TR1 and TR2 fleets. In 2016 the TR1 fleet accounted
187 for 95% of the landings and 63% of the discards while the TR2 fleet contributed only 0.95% of
188 landings but a high fraction (31%) of the discards (ICES 2017). Approximately half the total catch
189 comprises discards which indicates that the TR2 fleet makes an important contribution to whole
190 fishery selectivity even though its landings are small. The TR2 fleet uses a smaller mesh size and
191 operates closer inshore where younger cod are more abundant (Wright, 2005) so that this may
192 manifest itself as higher selection at younger ages in the whole fishery. This does not, of course,
193 establish that the selection pattern is dome shaped but it does indicate that non-asymptotic
194 selection is credible and accords with the adjacent cod stocks.

195 There may be other factors that contribute to the estimated dome-shaped selectivity. These include
196 area misreporting which is known to occur and the possible presence to two sub-populations (ICES

197 2018b) that may be differentially exploited. These factors can affect the age compositions in the
198 recorded catches and result in the apparent domed selection pattern.

199 The difference between the ICES assessment and the base case has significant implications for
200 management. If the ICES assessment is correct and F really is above F_{lim} , management has been
201 ineffective in controlling fishing mortality and the zero catches advised by ICES for many years have
202 been unsuccessful. To explain the persistently high values of F in the presence of large reductions in
203 fishing activity (approximately 60% for the EU regulated fleet) requires that the vulnerability of cod
204 to capture has increased substantially. This could occur if the remaining stock is concentrated in
205 areas of optimal habitat that are easily located by exploiting fleets (Blanchard et al 2005).

206 Management in this scenario should therefore focus on identifying and protecting those areas where
207 fish have concentrated since catch and effort restrictions have clearly failed. If the base case
208 scenario is closer to the truth, then effort controls appear to have been successful in reducing fishing
209 mortality rate to a low level and there has been some improvement to the SSB as a result of higher
210 survival. While the SSB is close to the limit reference point, the low fishing mortality rate offers the
211 best chance of recovery and management needs to focus more on ensuring that effort remains low.
212 Trying to implement a zero catch regime in this scenario, whilst other stocks in the same fishery are
213 still available, is of less value since the cod catch restrictions act as a choke species (Schrope, 2010)
214 simply resulting in high and wasteful discard rates. This problem is exacerbated by the Landing
215 Obligation (EU, 2013) that requires all fish caught to be landed and adds to the operational
216 difficulties of the fishery.

217 Other assessments for this stock have considered alternative assumptions about survey catchability
218 and natural mortality, as well as seal predation (Cook et al, 2015; Trijoulet et al, 2018). These
219 indicate that fishing mortality has declined with some recovery in the SSB. They also highlight the
220 need to consider predation in recovery scenarios (Cook and Trijoulet, 2016). While such analyses
221 make additional assumptions, particularly about seal predation, they are credible interpretations of

222 the data and they emphasize the need for a more comprehensive assimilation of the available
223 information in the formulation of advice to managers.

224 This analysis shows that an apparently minor but plausible change to one conditioning assumption in
225 a stock assessment model can have major implications for management. It demonstrates the need
226 to explore, thoroughly, the range of uncertainty in the assessment and avoid dependence on a single
227 “best model” for scientific advice. It also illustrates the need to look beyond the target stock alone
228 and consider the wider context in which the fishery is operating to assess whether model results
229 accord with other relevant stocks and information about fleet activity. Reliance on statistical
230 measures of goodness-of-fit, while important, may not be sufficient to validate the model.

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301

302 Table 1. Fishing effort data expressed as kilowatt days for fleets fishing in ICES Division 6a. Note that the Scottish data are
 303 included in the EU effort.

year	TR1 (Scotland)	TR2 (Scotland)	EU regulated gears	EU unregulated gears
2000	7453	5065		304
2001	8523	4903		305
2002	7566	4797		306
2003	5723	5761	21812003	16785425
2004	4502	5334	19331955	22340494
2005	2635	4587	16182914	18073811
2006	2100	4381	14418703	15707334
2007	1986	4694	15126642	14590850
2008	1990	4809	14321504	13014656
2009	2229	4525	14295597	12084271
2010	2361	3787	11467342	11278121
2011	2101	3570	9384270	12242937
2012	2132	4408	9618309	12960359
2013	2243	3759	8849672	13854958
2014	1979	3669		
2015	2423	3515		
2016	2488	3783		

308

309

310 Table 2. Population model equations

T2.1	$N_{a,y} = N_{a-1,y-1} e^{-Z_{a-1,y-1}}$	The population N at age a and year y decays exponentially with total mortality Z .
T2.2	$Z_{a,y} = M_a + F_{a,y}$	The total mortality Z is partitioned between natural mortality M , and fishing mortality F .
T2.3	$F_{a,y} = s_{a,y} f_y$	Fishing mortality is separable into an age effect, s , and year effect, f . Selectivity, s , is set to 1 for a reference age in all years for identifiability. Note that relative selectivity can be greater than 1.
T2.4	$f_y = f_{y-1} \epsilon_y^f$	Annual fishing mortality follows a random walk with lognormal process error
T2.5	$s_{a,y} = s_{a,y-1} \epsilon_{a,y}^s$	Selectivity follows a random walk with lognormal process error

311

312 Table 3. Observation equations

T3.1	$C_{a,y} = p_y \frac{F_{a,y}}{Z_{a,y}} N_{a,y} (1 - e^{-Z_{a,y}})$	The observed catch, C , is calculated using the Baranov equation. The parameter p_y is a reporting factor to account for under-reported catch.
T3.2	$u_{a,y,k} = q_{a,k} N_{a,y} e^{-\pi_k Z_{a,y}}$	The survey indices are proportional to the population, where k indexes survey and π is the proportion of total mortality occurring before the survey.

313

314 Table 4. Observation error distributions.

T4.1	$C'_{a,y} \sim \text{lognormal}(\log(C_{a,y}), \sigma_a^c)$	The catch is observed with lognormal error, σ^c .
T4.2	$u'_{a,y,k} \sim \text{lognormal}(\log(u_{a,y,k}), \sigma_{a,k}^l)$	Survey indices are observed with lognormal error σ^l

315

316 Table 5. Prior distributions on the parameters.

T5.1	$\log(N_{1,y}) \sim \text{uniform}(3,20)$ $\log(N_{a,1}) \sim \text{uniform}(3,20)$	Initial populations are drawn from log uniform distributions
T5.2	$f_1 \sim \text{uniform}(0,2)$ $\sigma^f \sim \text{uniform}(0,1)$	Initial fishing mortality is drawn from a uniform distribution and the standard deviation of the process error on F is also drawn from a uniform distribution
T5.3	$s_{a,1} \sim \text{uniform}(0,2)$ $\sigma^s \sim \text{uniform}(0,1)$	Initial selectivity at age is drawn from a uniform distribution and the standard deviation of the process error on s is also drawn from a uniform distribution
T5.4	$\log(q_{a,k}) \sim \text{uniform}(-20,3)$	Log survey catchability is drawn from a uniform distribution
T5.5	$\sigma_a^c \sim \text{uniform}(0,2)$	Measurement error on the catch is drawn from a uniform distribution
T5.6	$\sigma_{a,k}^l \sim \text{uniform}(0,2)$	Measurement error on the survey indices are drawn from a uniform distribution.
T5.7	$p_y \sim \text{uniform}(0,1)$	Misreporting factor is drawn from a uniform distribution.

317

318

319 Table 6. Summary of multiple regression analysis of fishing mortality from the base case on fleet effort data. A similar
 320 analysis using the ICES estimates of F gave no significant slopes.

321

Scottish fleet effort

	Estimate	SE	t value	p
Intercept	-5.03E-01	1.11E-01	-4.526	0.000475
TR1	4.01E-05	8.22E-06	4.878	0.000244
TR2	1.42E-04	2.83E-05	5.015	0.000189

R-squared=0.90

EU fleet effort

	Estimate	SE	t value	p
Intercept	-3.55E-01	7.95E-02	-4.472	0.00208
Regulated	2.62E-08	5.90E-09	4.432	0.00219
Unregulated	1.63E-08	7.45E-09	2.183	0.06059

R-squared=0.91

326 Figure legends

327 Figure 1. Trends in (a) mean fishing mortality and (b) spawning stock biomass from the ICES
328 assessment (dashed line) and the flat topped selectivity case (solid line). The solid horizontal line in
329 (b) is the ICES estimate of B_{lim} .

330 Figure 2. Trends in (a) mean fishing mortality and (b) spawning stock biomass from the base case.
331 Each line shows the result for successive retrospective runs. The horizontal line in (b) shows the
332 value of the 1992 biomass and is the equivalent of the value for B_{lim} in the ICES assessment.

333 Figure 3. Selection patterns for three cod stocks around the British Isles in 2017. In each case
334 selectivity is scaled relative to age 4. The selection pattern from the ICES 6a cod assessment (dotted
335 line; ICES, 2018b) can be compared to the base case (solid line). The ICES model allows small
336 deviations from the flat exploitation pattern and hence the age 4 value is below the maximum. The
337 North Sea data are taken from ICES (2018c).

338 Figure 4. Predicted fishing mortality from effort data in Division 6a. Dots show the values estimated
339 from the base case, solid line shows fitted values from the Scottish fleet effort data and the dotted
340 line shows fitted values from the EU fleet data.

341 Figure 5. Trends in fishing mortality rate for various stocks. (a) F trends in 6a cod estimated from the
342 base case (solid line), 6a haddock (dashed line) and 6a whiting (dotted line). The open circles are the
343 ICES values for 6a cod. (b) F trends in 6a cod estimated from the base case (solid line), Irish Sea cod
344 (dashed line) and North Sea cod (dotted line). Correlations between the various time series are high
345 and given in the Supplementary Material Figure S14.

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