ICES Journal of Marine Science

ICES Journal of Marine Science (2019), 76(4), 787–793. doi:10.1093/icesjms/fsy190

Food for Thought

Stock collapse or stock recovery? Contrasting perceptions of a depleted cod stock

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Cook, R. M. Stock collapse or stock recovery? Contrasting perceptions of a depleted cod stock. – ICES Journal of Marine Science, 76: 787–793.

Received 17 October 2018; revised 14 November 2018; accepted 20 November 2018; advance access publication 23 January 2019.

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

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

Introduction

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

While these assessment models may be the best available, it is widely understood that their estimates of fishing mortality (F) and spawning stock biomass will be subject to uncertainty, and perhaps more importantly, are conditioned on many necessary assumptions that may in reality be incorrect resulting in bias. These include the way fishery selectivity changes with age and time, the relationship between survey indices and abundance, natural mortality and the stock-recruitment relationship. In particular, the function that describes fishery selectivity by age or size can be critical in the assessment (Punt *et al.*, 2014). In recognition of these issues ICES has adopted a system of periodic benchmark assessments where detailed analysis of a wide range of biological and fishery data is reviewed, a range of assessment methods tested, and a preferred model identified for future routine annual assessments (ICES, 2013a). This procedure should help understand the range of uncertainty and the importance of conditioning assumptions. The focus of benchmark assessments, in common with most annual stock assessments, is stock specific and frequently relies on model goodness-of-fit criteria and internal consistency based on retrospective analysis (Mohn, 1999). The output is usually a single model that provides an historical reconstruction of the stock with estimates of status relative to management reference points. Scientific advice to management tends, therefore, to be conditioned on a "best model" with a qualitative description of major uncertainties beyond the estimation error derived from the best model.

While the "best model" approach has its attractions on the grounds of simplicity, it nevertheless carries with it risks since it may imply a narrower range of uncertainty about the assessment than is actually the case. Other plausible interpretations of the data may be possible which can give a perspective quite different from the best model, even where these are less likely. This problem is illustrated here with the assessment of cod (*Gadus morhua*) in the west of Scotland (ICES Division 6a), which was last benchmarked in 2012 (ICES, 2012). Successive assessments have shown the stock to be all but collapsed having declined from over 40 000 t in 1981 to 1400 t in 2006 (ICES, 2017). Despite a slow but small increase to 2400 t in 2017, the stock remains well below the SSB limit reference point (B_{lim}) of 14 000 t (ICES, 2017). Furthermore, the estimated fishing mortality remains high at close to $F = 1$ despite several years of advice for zero catch and the imposition of a cod recovery plan by the European Union (EU, 2008). What makes the assessment of this stock unusual is that it contrasts with other demersal stocks in the same fishery such as haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*), and with adjacent stocks of cod in the North Sea (ICES Subarea 4 and Division 3a) and the Irish Sea (ICES Division 7a) all of which show declining fishing mortality rates and recovering biomass (ICES, 2013b, 2018a). Since cod, haddock and whiting in 6a are all taken by the same vessels in a mixed fishery, it might be expected that trends in fishing mortality would be similar. Furthermore, since cod in the Irish Sea and North Sea are subject to the same cod recovery plan as cod in 6a, some comparable trends in F might be anticipated. There has also been a marked decline in fishing activity in the area (STECF, 2014), which might be expected to lead to lower fishing mortality rates. There is, therefore, information external to the target stock that appears inconsistent with the 6a cod assessment results.

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

Data

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

(1) Total catch numbers at age 1983–2017 (the sum of landings and discards), ages 1–6.

(2) ScoGFS-WIBTS Q1 survey 1985–2010, ages 1–6.

(3) UK-SCOWCGFS-Q1 survey 2011–2018, ages 1–6.

(4) ScoGFS-WIBTS-Q4: survey 1996–2009, ages 1–6.

(5) UK-SCOWCGFS-Q4: 2011–2017, ages 1–6.

(6) IRGFS-WIBTS-Q4: 2003–2017, ages 1–4.

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

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

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

Material and methods

An exploratory stock assessment model is used for analysis, which has similarities to, but is simpler than the TSA assessment model used by ICES (Fryer, 2002). The principal model equations are set out in Tables 2–5, which describe the population model, the observation equations, observation error distributions and prior distributions on the parameters. It is a conventional age structured population model where total mortality, *Z*, is split between fishing mortality, F, which is dynamic, and natural mortality, *M*, which is fixed. These mortalities reduce the number of the fish, *N*, at the start of the year according to Equation (T2.1). Total mortality is the sum of fishing mortality and natural mortality (T2.2). Fishing mortality is separable into an age effect and a year effect (T2.3) and these follow a random walk through time (T2.4 and T2.5). The observed catch is derived from the Baranov equation with a multiplier that accounts for unreported catch (T3.1). The survey indices, required to calibrate the model, are assumed to be proportional to the population in the sea (T3.2). Observed quantities are assumed to be measured with lognormal sampling error (Table 4). Priors on the parameters are either uniform or log uniform (Table 5).

The model was fitted to the data using Bayesian methods in the R package "rstan" (Stan Development Team, 2016). The base

Table 1. Fishing effort data expressed as kilowatt days for fleets fishing in ICES Division 6a.

year	TR1 (Scotland)	TR2 (Scotland)	EU regulated gears	EU unregulated gears
2000	7 453	5 065	–	–
2001	8 523	4 903	–	–
2002	7 566	4 797	–	–
2003	5 723	5 761	21 812 003	16 785 425
2004	4 502	5 334	19 331 955	22 340 494
2005	2 635	4 587	16 182 914	18 073 811
2006	2 100	4 381	14 418 703	15 707 334
2007	1 986	4 694	15 126 642	14 590 850
2008	1 990	4 809	14 321 504	13 014 656
2009	2 229	4 525	14 295 597	12 084 271
2010	2 361	3 787	11 467 342	11 278 121
2011	2 101	3 570	9 384 270	12 242 937
2012	2 132	4 408	9 618 309	12 960 359
2013	2 243	3 759	8 849 672	13 854 958
2014	1 979	3 669	–	–
2015	2 423	3 515	–	–
2016	2 488	3 783	–	–

Note that the Scottish data are included in the EU effort.

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 >1.
T2.4	$f_y = f_{y-1}\varepsilon^f_y$	Annual fishing mortality follows a random walk with lognormal process error.
T2.5	$s_{a,y} = s_{a,y-1}\varepsilon^s_{a,y}$	Selectivity follows a random walk with lognormal process error.

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.

Table 4. Observation error distributions.

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

Table 5. Prior distributions on the parameters.

T5.1	$log(N_{1,y}) \sim uniform(3, 20)$ $\log(N_{a,1}) \sim uniform(3, 20)$	Initial populations are drawn from log uniform distributions.
T5.2	$f_1 \sim uniform(0, 2)$ $\sigma^f \sim uniform(0, 1)$	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	$s_{a,1} \sim \mathrm{uniform}(0, 2)$ $\sigma^s \sim \mathrm{uniform}(0, 1)$	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	$\log(q_{a,k}) \sim \mathrm{uniform}(-20, 3)$	Log survey catchability is drawn from a uniform distribution.
T5.5	$\sigma^c_a \sim$uniform(0,2)	Measurement error on the catch is drawn from a uniform distribution.
T5.6	$\sigma^I_{a,k} \sim$uniform(0,2)	Measurement error on the survey indices are drawn from a uniform distribution.
T5.7	$p_y \sim \mathrm{uniform}(0,\ \ 1)$	Misreporting factor is drawn from a uniform distribution.

case model was fitted assuming a selectivity reference age of 4, i.e. selectivity for age 4 was set to 1. The misreporting factor was fixed at 1 except for years 1996–2005 where it was freely estimated. This corresponds to the period when misreporting was considered significant (ICES, 2018b). In addition, a retrospective analysis was performed by successively leaving out data from the terminal year as a test of model consistency (Mohn, 1999).

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

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

Results

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

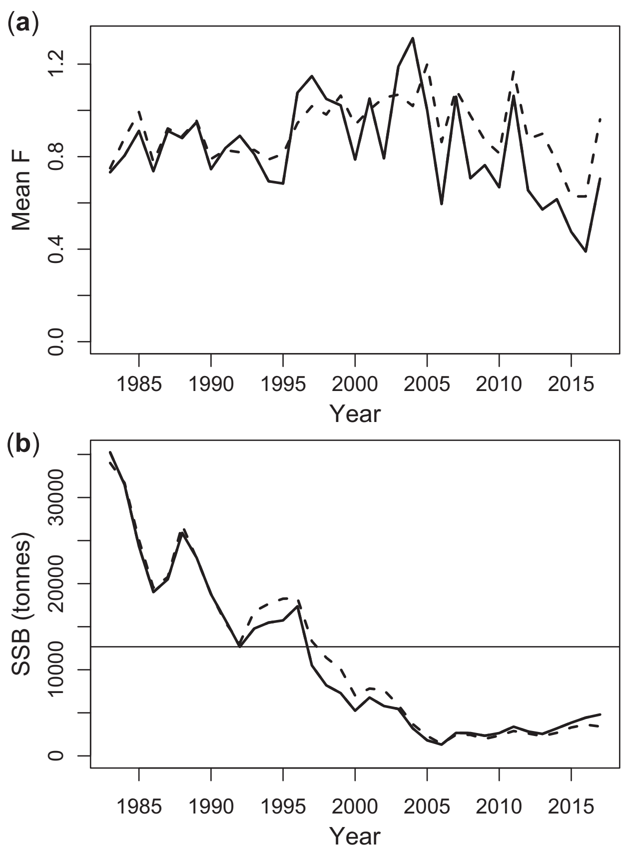

Figure 1. Trends in (a) mean fishing mortality and (b) spawning stock biomass from the ICES assessment (dashed line) and the flat topped selectivity case (solid line). The solid horizontal line in (b) is the ICES estimate of B_{lim}.

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

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

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

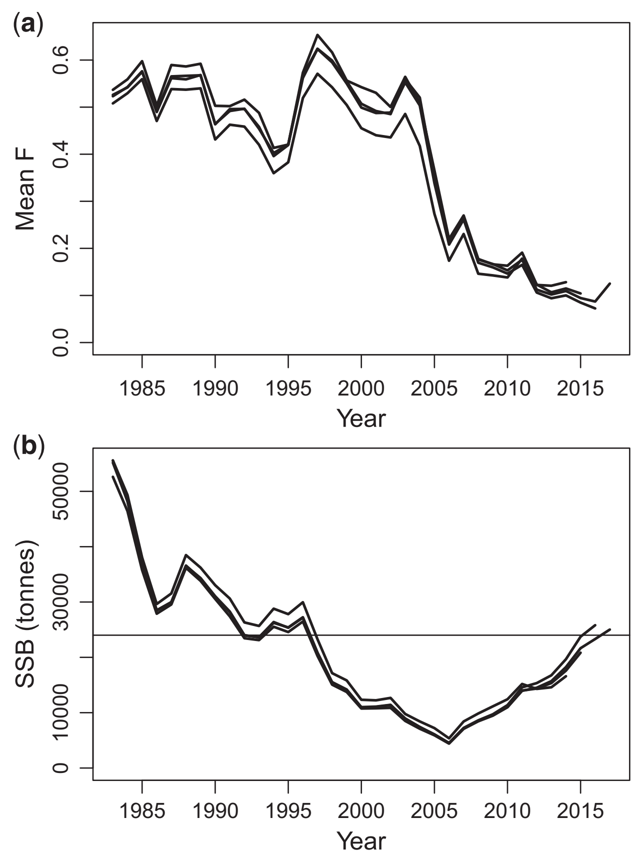

Figure 2. Trends in (a) mean fishing mortality and (b) spawning stock biomass from the base case. Each line shows the result for successive retrospective runs. The horizontal line in (b) shows the value of the 1992 biomass and is the equivalent of the value for B_{lim} in the ICES assessment.

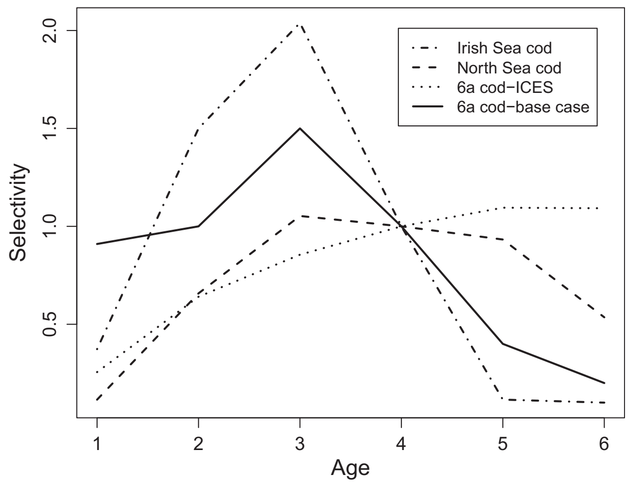

Figure 3. Selection patterns for three cod stocks around the British Isles in 2017. In each case selectivity is scaled relative to age 4. The selection pattern from the ICES 6a cod assessment (dotted line; ICES, 2018b) can be compared with the base case (solid line). The ICES model allows small deviations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

Table 6. Summary of multiple regression analysis of fishing mortality from the base case on fleet effort data.

	Estimate	SE	*t* value	*p*
Scottish fleet effort				
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				
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				

A similar analysis using the ICES estimates of F gave no significant slopes.

Discussion

The results of the ICES assessment are closely mirrored in the selectivity case and make the assumption that the selection pattern is flat above age 4. In this scenario, fishing mortality is high and the SSB is well below B_{lim} with little sign of recovery. Relaxing the asymptotic selectivity assumption offers a different interpretation of stock development with a sharp decline in F and recovering SSB. The base case trend in F can be explained by documented changes in effort both by the Scottish fleets that account for 65% of the landings and the total effort of the EU regulated fleets. Furthermore, unlike the ICES assessment, the changes in F are consistent with stocks taken in the same fishery and adjacent cod stocks that have been subject to the EU cod recovery plan. It suggests the base case configuration is at least as plausible as the ICES assessment.

The principal factor leading to the difference between the ICES assessment and the base case appears to be the conditioning selectivity assumption. The flat topped selectivity in the ICES

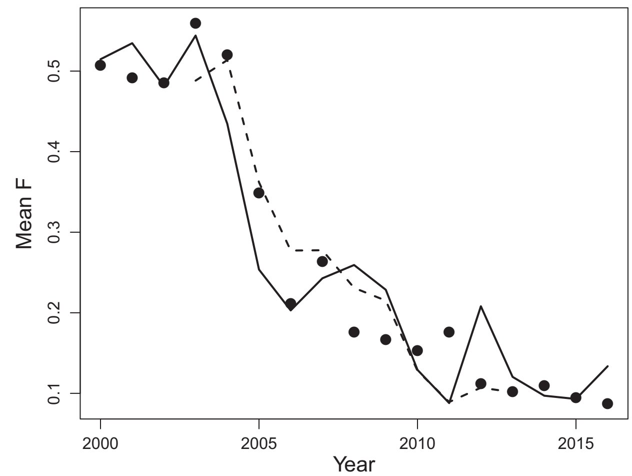

Figure 4. Predicted fishing mortality from effort data in Division 6a. Dots show the values estimated from the base case, solid line shows fitted values from the Scottish fleet effort data and the dotted line shows fitted values from the EU fleet data.

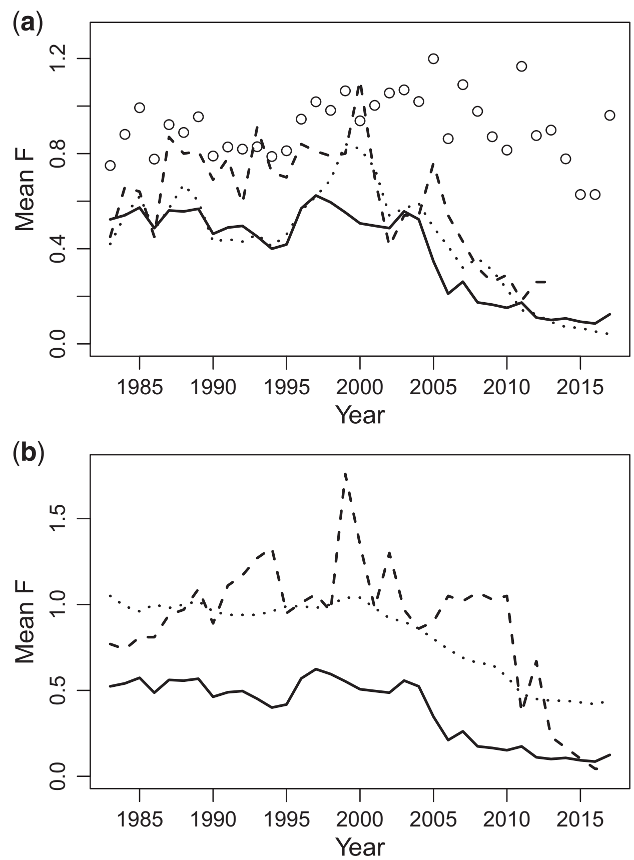

Figure 5. Trends in fishing mortality rate for various stocks. (a) F trends in 6a cod estimated from the base case (solid line), 6a haddock (dashed line) and 6a whiting (dotted line). The open circles are the ICES values for 6a cod. (b) F trends in 6a cod estimated from the base case (solid line), Irish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

assessment causes the model to interpret the low observed catches at older ages as the result of a high mortality acting on a small population. In contrast, the base case suggests the selection pattern is "dome-shaped" where older fish have lower selectivity. Hence this model explains the low catches as a lower fishing mortality acting on a larger population in the sea.

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

There may be other factors that contribute to the estimated dome-shaped selectivity. These include area misreporting, which is known to occur and the possible presence to two sub-populations (ICES, 2018b) that may be differentially exploited. These factors can affect the age compositions in the recorded catches and result in the apparent domed selection pattern.

The difference between the ICES assessment and the base case has significant implications for management. If the ICES assessment is correct and F really is above F_{lim}, management has been ineffective in controlling fishing mortality and the zero catches advised by ICES for many years have been unsuccessful. To explain the persistently high values of F in the presence of large reductions in fishing activity ($\sim$60% for the EU regulated fleet) requires that the vulnerability of cod to capture has increased substantially. This could occur if the remaining stock is concentrated in areas of optimal habitat that are easily located by exploiting fleets (Blanchard *et al.*, 2005). Management in this scenario should therefore focus on identifying and protecting those areas where fish have concentrated since catch and effort restrictions have clearly failed. If the base case scenario is closer to the truth, then effort controls appear to have been successful in reducing fishing mortality rate to a low level and there has been some improvement to the SSB as a result of higher survival. While the SSB is close to the limit reference point, the low fishing mortality rate offers the best chance of recovery and management needs to focus more on ensuring that effort remains low. Trying to implement a zero catch regime in this scenario, whilst other stocks in the same fishery are still available, is of less value since the cod catch restrictions act as a choke species (Schrope, 2010) simply resulting in high and wasteful discard rates. This problem is exacerbated by the Landing Obligation (EU, 2013) that requires all fish caught to be landed and adds to the operational difficulties of the fishery.

Other assessments for this stock have considered alternative assumptions about survey catchability and natural mortality, as well as seal predation (Cook *et al.*, 2015; Trijoulet *et al.*, 2018). These indicate that fishing mortality has declined with some recovery in the SSB. They also highlight the need to consider predation in recovery scenarios (Cook and Trijoulet, 2016). While such analyses make additional assumptions, particularly about seal predation, they are credible interpretations of the data and they emphasize the need for a more comprehensive assimilation of the available information in the formulation of advice to managers.

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

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

Acknowledgements

This study was part funded by MASTS through the Scottish Funding Council (grant reference 349 HR09011). I am grateful to Mike Heath for comments on an earlier version of the article.

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Handling editor: Shijie Zhou