…intended for ToR c) Re-examine and update (if necessary) MSY and PA reference points according to ICES guidelines (see Technical document on reference points).

Environmental pressures and population dynamics of North Sea cod

By Henrik Sparholt

Institute of Macroecology, Evolution and Climate, Centre of Excellence, University of Copenhagen, Universitetsparken 15, Building 3, 2100 Copenhagen Ø, Denmark.

Abstract

The productivity of the North Sea cod has changed over time as shown in WKNSEA HS2 2021. This document analyses the possible reasons. This stock and the North Sea ecosystem are very data rich. We go through all the environmental pressures that are potential factors responsible for the changes. We conclude that it can be linked to climate change, variable predation by grey gurnards, and food competition of pre-recruit cod with pelagic stocks. On the post-recruit stage increased grey seal predation further reduces the cod productivity. A likely contributing factor is predation by herring and mackerel on pre-recruit cod.

Introduction

In WK Doc HS2 WKNSEA 2021 we fitted surplus production models (SPMs) and stock-recruitment models to the historical data of the stock and found indications of regime shifts based on these data alone in the late 1980s regarding the production of post-recruits and in the late 1990s regarding recruits. Tables 1 and 2 give the corresponding population dynamic and biological references parameters.

In the present analysis we look at the potential reasons for the regime shifts in environmental data. This is an area which have been heavily researched in the past so we will mainly compile what is known already to get an overview and compare and contract these. Our aim is to give our best view of what can be expected in the coming decade and what might be the trade-off between different management approaches.

Table 1. *North Sea cod. K, SSBmsy, and MSY based on surplus production models for different time periods. Pseudo-B_{lim} is taken as 15% SSB at F=0 (as used by NAFO (2004)) - in ICES SSB-currency. Biomass in '000' t. From WK Doc HS2 WKNSEA 2021.*

Time period	K carrying capacity. Total stock biomass	Bmsy Total stock biomass	SSB-msy	SSBmsy in ICES SSB-currency	Pseudo-Blim	MSY
1963-1987	1256	551	240	305	92	305
1988-1997	697	306	133	169	51	169
1998-2018	214	94	41	52	16	52
1998-2018 (IBTS based)	317	139	77	61	23	77

Table 2. *North Sea cod. Parameter estimates of the hockey-stick S-R model by time period. Based on minimum sum of square deviations in the log scale. The numbers in bracket are from S-R models with no breakpoint and 600 million recruits assumed to be the maximum number*. *From WK Doc HS2 WKNSEA 2021.*

	Slope, r, in No/kg SSB	**Maximum recruitment, b, in millions**	**Blim in '000't**
1963-1996	**6.13**	**878**	**143**
1997-2019	**4.05**	**185**	**46***

* This breakpoint could be much lower, as the data fits almost as well models with lower values all the way down to almost zero (see the Discussion section).

ICES (2020b) suggest, based on genetic studies, egg surveys, trawl surveys, tagging studies, meristic studies, and life history parameters, that the stock assessment should support advice for managing the genetically distinct Viking cod and Dogger cod populations, separately.

In the present study we still operate mainly with the concept of one stock, because we do not have long data series for the Viking cod and Dogger cod populations. However, we make considerations to the facts that the "one" stock probably consists of two stocks and that the Dogger stock probably is so depleted that it needs a separate management measure, like "no directed fishery for cod in the southern area".

Material, methods, and result

We will in the following consider the environmental aspects listed in Table 1.

The regime-shift in the late-1980s of reduced productivity of post-recruit cod

There are no indications of reduced growth of post-recruits since the late-1980s except maybe for the oldest age groups (Figure 1). Maybe the decrease in weight-at-age of older cod in recent years could be due to density dependent effects as there are substantially more of these age groups in the stock now that F is much lower. A decrease in F from about 1.0 in the 1980-2000 to about 0.5 in 2010-2020 means that the numbers of survivors from age 3 to age 9 increases by a factor of as much as 20. This in combination with the decreased spatial distribution due to the North Sea cod mainly consisting of the northern cod stock in recent years, make this hypothesis likely true.

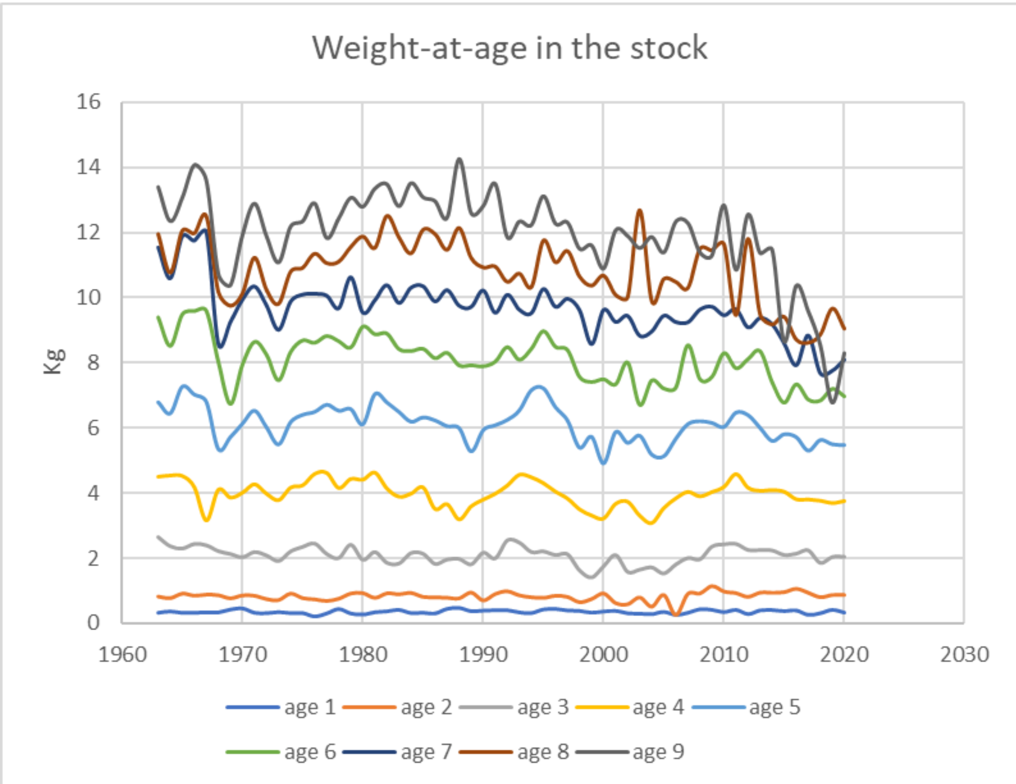


Figure 1. *North Sea cod. Weight-at-age (kg) in the stock. From WGNSSK 2020.*

Maturity-at-age of cod showed an increase from the late-1980s for the younger ages (Figure 2). Older ages are always almost 100% mature. The increase was gradual and peaked in 2005-2015. The reason for the increased maturity seems not to be related to any general increase in growth (see Figure 1). It is correlated to the high level of fishing mortality F from 1980 to 2000 and might be due to unintended selective fishing on non-maturing individuals within an age group. These are expected to growth faster as they do not need energy to produce gonads. This will leave relatively more mature individuals surviving and passing on their genes to a gradual increased proportional of the population. There seems to be a tendency to a reversal in recent years when F has gone down.

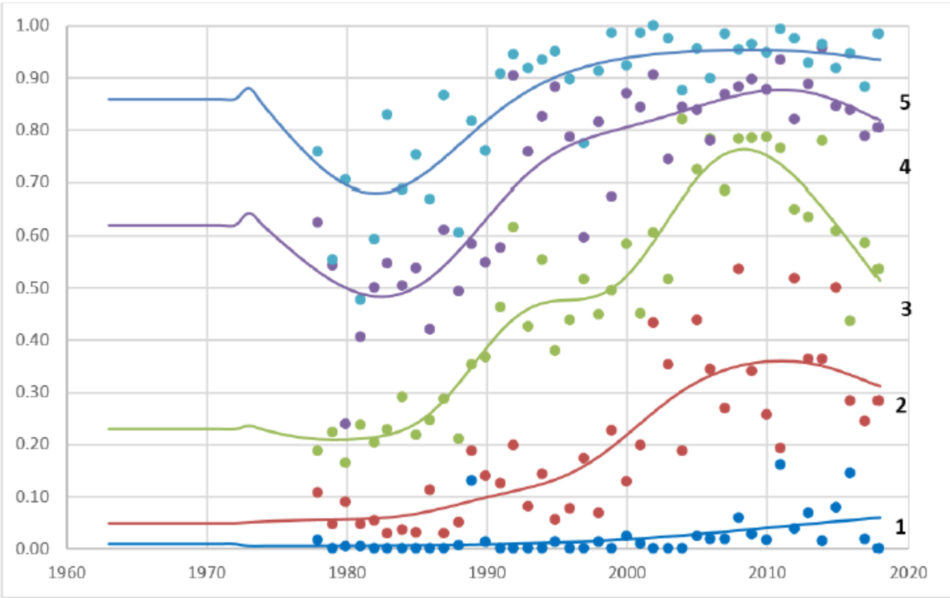


Figure 3.1.12. Cod in Subarea 4, Division 7.d and Subdivision 20: Annually varying maturity-at-age. Dots are the raw values estimated from IBTS–Q1 data while lines are the smoothed values that feed into the assessment. Values for 1963–1972 are the former constant maturity values used for cod.

Figure 2. *North Sea cod. Maturity by age and year. From WKNSMSE 2019.*

The hake stock is a potential food competitor to post-recruit cod and the hake stock has increased substantially in recent years (Figure 3). However, the increase happened around 2010 so cannot be responsible for the regime shift in the late 1980s but might be related to the decrease in growth of older cod recently because it is a food competitor.

Saithe, haddock, and whiting are also potential food competitors, but these stocks have collectively been at a rather stable level in the entire time-series from 1963-present (Figure 4). If anything, they have reduced in stock sizes in the late 1980s like cod. Maybe they are suffering from the same unknown factors as cod?

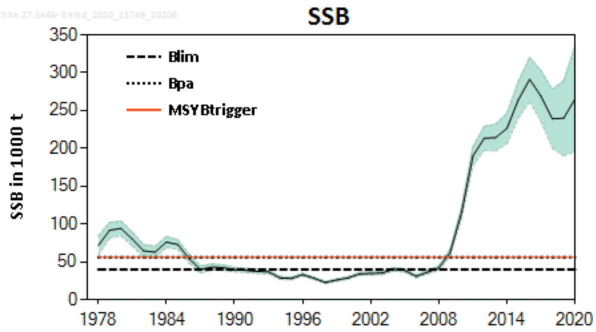


Figure 3. *Hake Northern stock. Spawning stock biomass by year. From ICES 2020. According to ICES 2017 (WGSAM):" When using CPUE per rectangle * number of rectangles in the survey area as index, it was estimated that 10- 15% of the hake stock in numbers were in the North Sea (WGSAM 2014) while the biomass percentage is much larger as the hake found in the North Sea in the second half of the year are larger than average".*

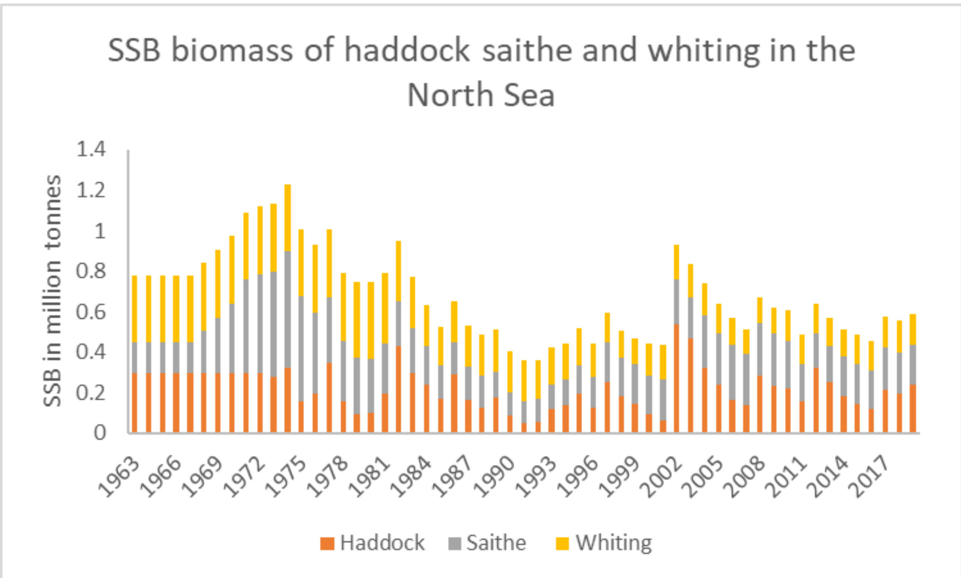


Figure 4. *Spawning stock biomass by year of haddock, saithe and whiting in the North Sea. From ICES 2020. For the years 1963-1970 for haddock, 1963-1965 for saithe and 1963-1976 for whiting SSB assumed similar to the 1971, 1966 and 1977 SSB respectively for haddock, saithe and whiting.*

Plaice is normally not regarded as a food competitor to cod, but when the stock has increased as tremendously as in recent years (Figure 5) maybe they could have a negative influence. However, the timing being around 2010 and thus not in line with a regime shift in the late 1980s. Plaice might, however, contribute at present to the low productivity of post-recruit cod.

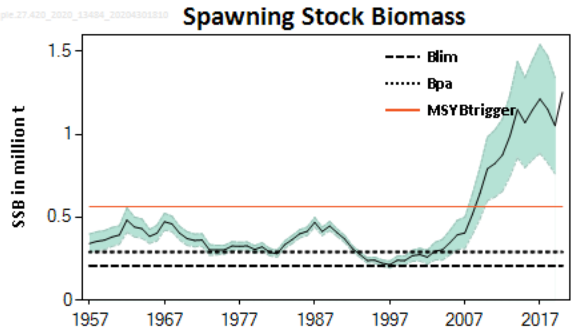


Figure 5. *Plaice in the North Sea. Spawning stock biomass by year. From ICES (2021).*

Predation mortality according to the standard North Sea multispecies keyrun from ICES (2021) show some increase for ages 2, 3 and 4 since mainly the late-1990s due to grey seal predation (Figure 6). For age 2 and 3 it is an increase of about 0.2 and 0.1 respectively and they are additive, so it will mean a reduction of about 25% in survivors. It will contribute to the observed reduction in productivity but are far from explaining all of it. For age 4 M2 is only increasing from 0.01 to 0.04 so this it is unlikely to be the cause on the observed regime shift.

The estimated harbour porpoise predation (according to the same multispecies keyrun) indicate an increase in M by around 0.4 for ages 1 and 2 together from pre-1989 to post-1998 (Figure 7). This this will reduce cod surviving to age 3 by about 33%. Harbour porpoise do not predate on cod age 3 or older.

Thus, seals and harbour porpoise together reduce the cod survivors to age 4 by 58%, everything else being equal. If not compensated by increased growth of the surviving cod, this will mean a reduction in MSY by the same percentage.

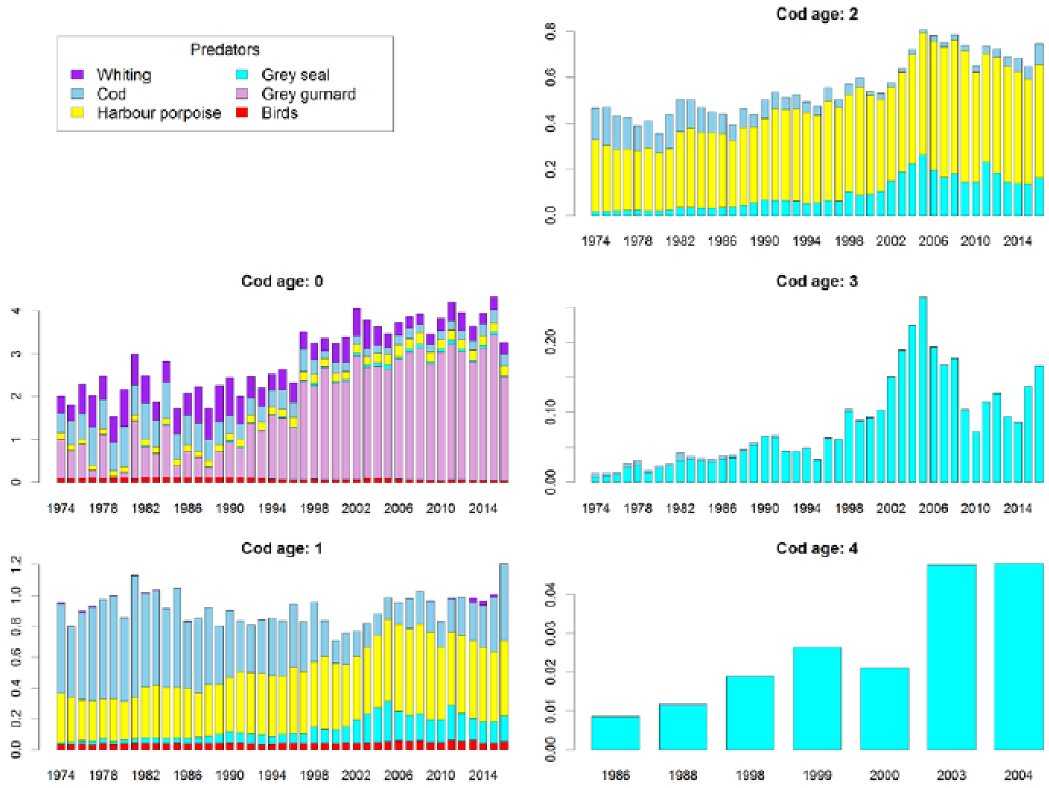


Figure 5.1.22. Annual predation mortality (M2) by prey species and age inflicted by predator species.

Figure 6. Predation on young cod by predator. The Y-axis is M2 – predation mortality. From ICES WGSAM 2017.

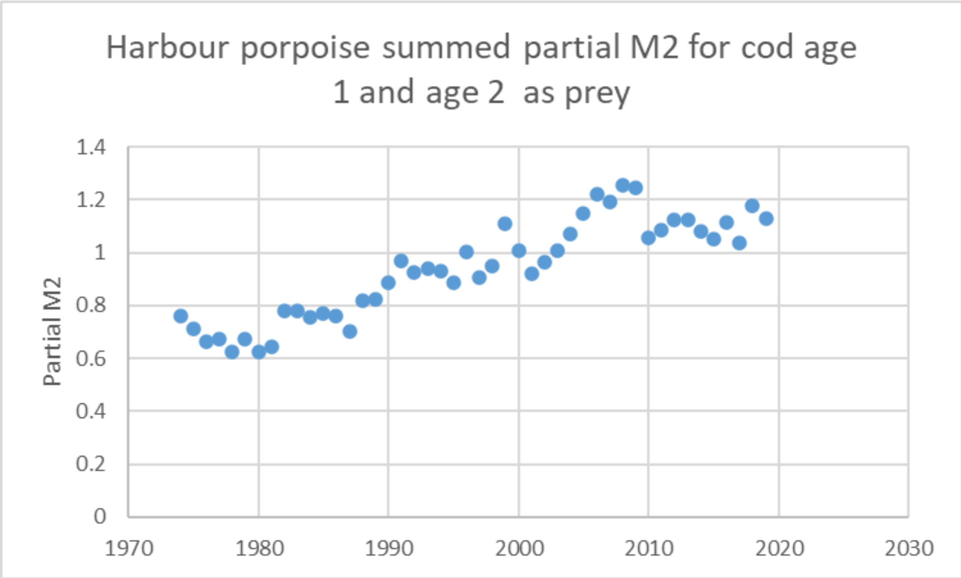


Figure 7. Partial M2 for cod ages 1 and 2 summed from predation by harbour porpoise. From ICES WGSAM 2020.

The regime-shift in the late-1990s of reduced productivity of both pre-recruit cod

A key to understand the population dynamic of cod in the North Sea is the sub-stock or real stock components of cod in the North Sea. The consensus among stock identification experts is that there are at least two separate stocks: a southern and a northern stock. They are reproductively separated. Thus, they should also be separated in ICES assessments is possible. Basic data need to be re-compiled first. This may take several years and might not cover the entire time series.

According to the IBTS the southern component has collapsed in recent years (Figure 8 and 9).

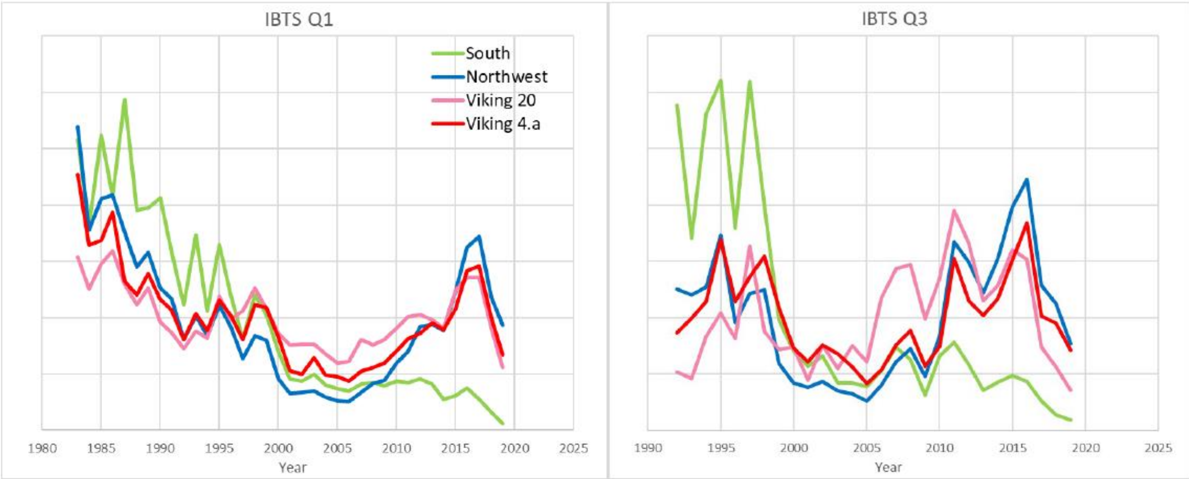


Figure 8. *North Sea cod. Biomass indices by subregion based on the IBTS quarter1 and 3 data. Relative scales, based on the NS IBTS Q1 and Q3 survey data. The biomass indices are derived by fitting a non-stationary Delta-GAM model (including ship effects) to numbers-at-age for the entire dataset, and integrating the fitted abundance surface over each of the subareas to obtain indices-at-age by area. These are then multiplied by smoothed weight-at-age estimates and summed to get the biomass indices. From ICES 2019.*

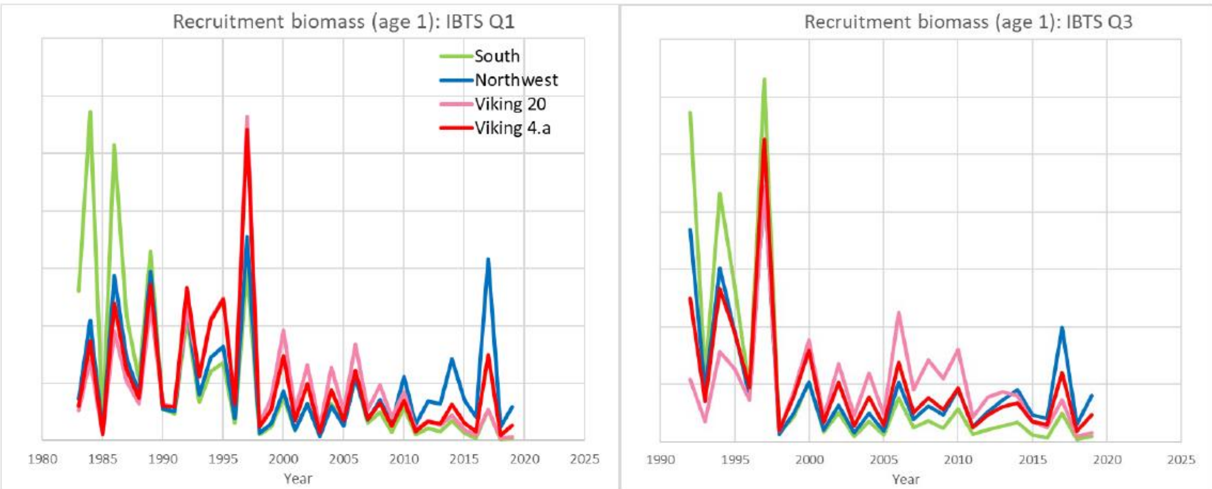


Figure 9. *Cod in the North Sea. Recruitment indices by subregion based on IBTS quarter1 and 3 data. From ICES 2019.*

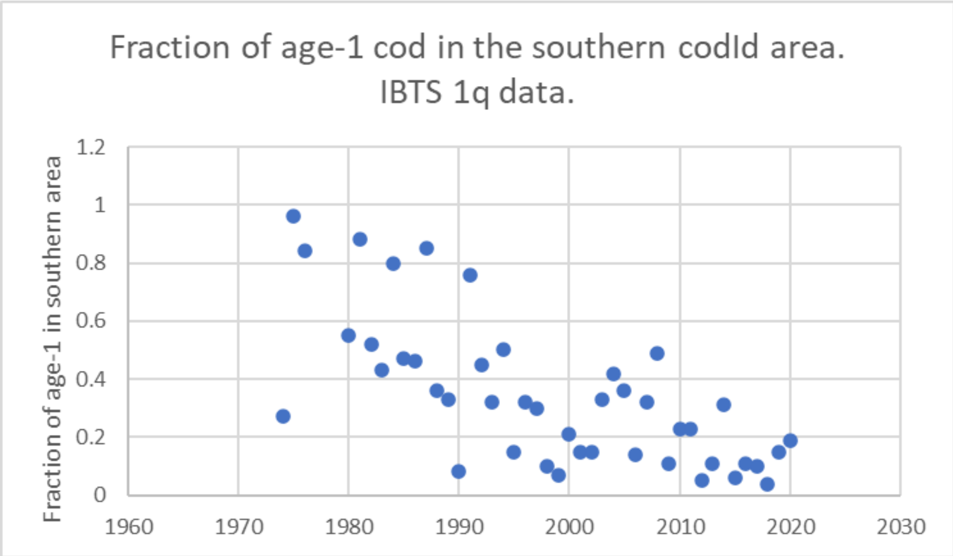


Figure 10. *Cod in the North Sea. Fraction of age-1 cod in the southern area compared to total North Sea stock of age-1 cod, based on IBTS quarter1 data. For 1974-87 the mean is 0.64, for 1988-96 0.36 and for 1997-2018 0.20. For the period 1974-1996 the ration of 0.57. Some years (1971-1973 and 1977-1979) omitted due to no coverage of Roundfish area RF8 andRF 9. RF10 not included because it was only covered by the survey since 2007. Weighted mean No/hr over RFs of mean No/hr by rectangle. The RFs that cover both the southern and northern cod area are split into two, and each part regarded as an RF in the calculations. The weight used was the size of the area with depths between 20m and 200m within each RF. From ICES DATRAS database 19 December 2020.*

The IBTS data back to 1971 (Figure 10) shows that for 1971-1980 the southern component constituted about 60% of the stock number of age-1 cod and for recent years only about 10%. Based on this figure there seems to a gradual regime-shift since 1980 and until 2015 in recruitment. The main contribution of recruitment to the North cod have changed over time and now comes from the northern component.

Climate change is an obvious candidate for the cause of the decreased productivity. Cod prefer cold water and is living close to its southern border in the North Sea and temperature in the North Sea has increased in the past decades (Figures 11-13). However, the precise mechanism is not known and another cold-water species, plaice, is booming. The further reduced size of the southern stock component might be due to climate change as temperatures in this area have approached the maximum limit cod stocks seems to tolerate according to a meta-analysis of cod stocks in the North Atlantic by Drinkwater (2005, or see Annex 4 for the main graphs). The northern components seem much less affected (Figures 8 and 9).

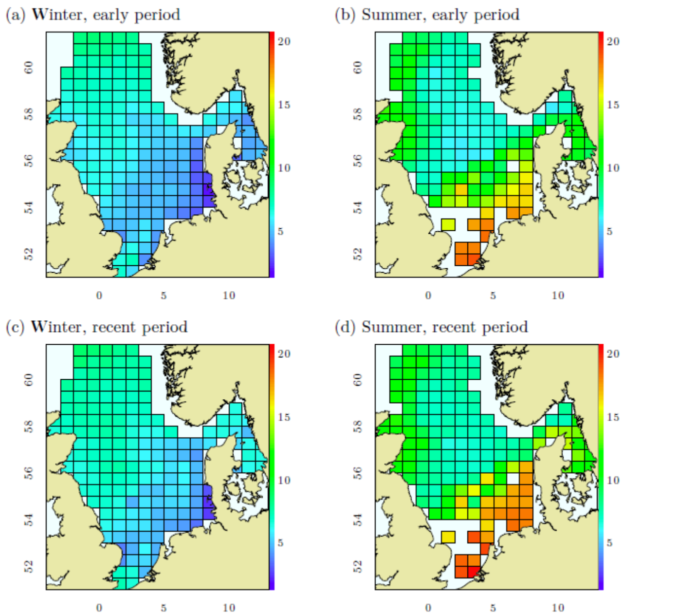


Figure S1: Temperature observation maps (in degree Celsius) for the early period (1991-1996), in (a) winter and in (b) summer and for the recent period (2007-2012) in (c) winter and in (d) summer.

Figure 11. *From Xochitl, et al. (2014).*

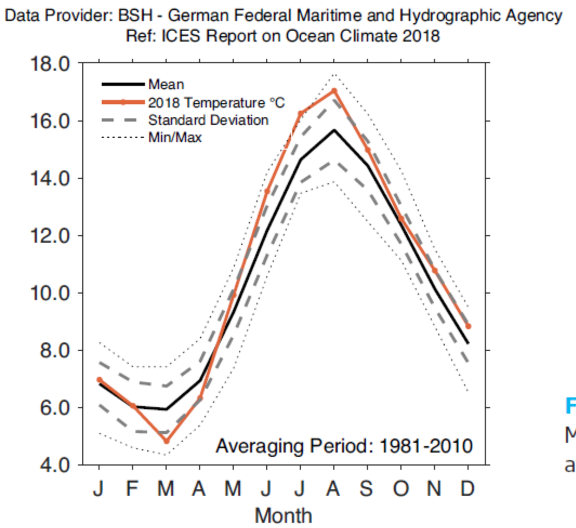


FIGURE 4.59.
Monthly means of area averaged North Sea SST.

Figure 12. *From Gonzáles-Pola et al (2019).*

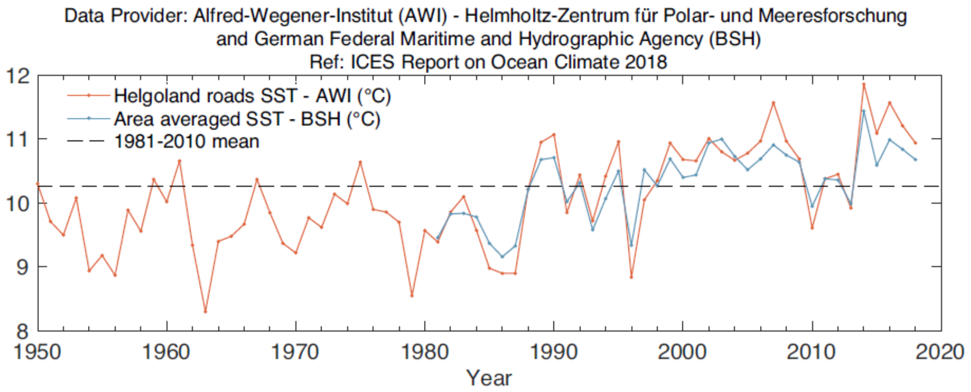


Figure 13. *Annual average temperature (SST) of the North Sea. From Gonzáles-Pola et al (2019).*

Another pressure that likely influence the productivity of North Sea cod are the food competition and predation by the booming pelagic stocks in the Northeast Atlantic (Figure 14). Herring in the North Sea might be predating on cod larvae (Speirs *et al.* 2010). Mackerel are likely to do the same. The timing of the increase fits well with the regime shift in recruitment at the late -1990s.

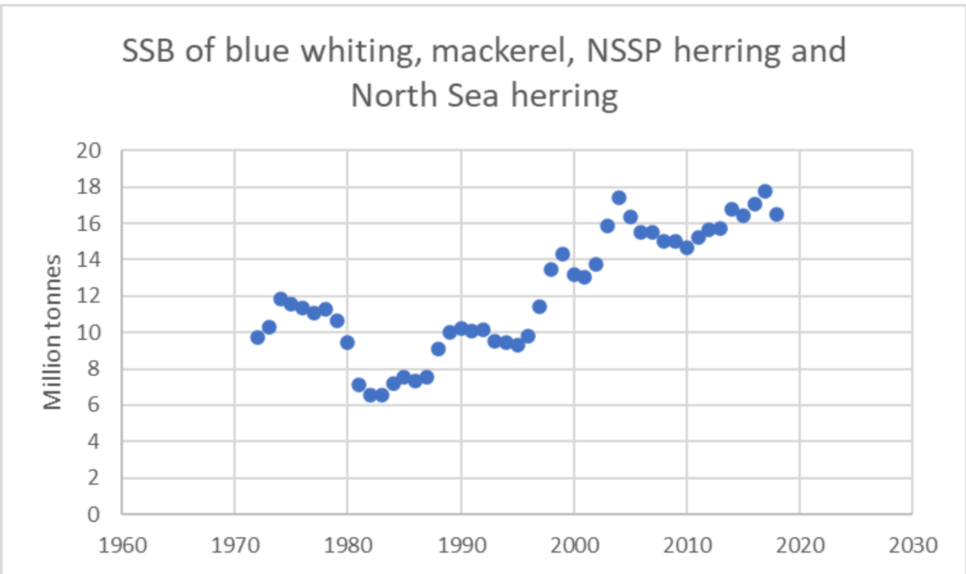


Figure 14. *The spawning stock biomass of the 4 major pelagic stocks in the Northeast Atlantic: mackerel, blue whiting, Norwegian Spring Spawning herring, and North Sea herring. Based on ICES (1986 and 2020), Toresen and Østved (2000), and Hamre (1978).*

The amount of zooplankton eaten by mackerel, NSS herring and blue whiting is substantial as shown in Figure 15 and increased by about 50% from before to after the late-1990s. Zooplankton biomass in the sea decreased in the same time (Figures 16 and 17). Mackerel and North Sea herring growth has reduced in recent years further supporting the notion of reduced zooplankton availability (ICES 2020b and ICES 2020c). There was a shift in *Calanus* species composition in the North Sea from *C. finmarkicus* to *C. helgolandicus* (Figure 18), which some authors links to decreased cod recruitment (Beaugrand *et al.* 2015), which probably again is linked to temperature changes so this could be one factor explaining the collapse of the southern stock.

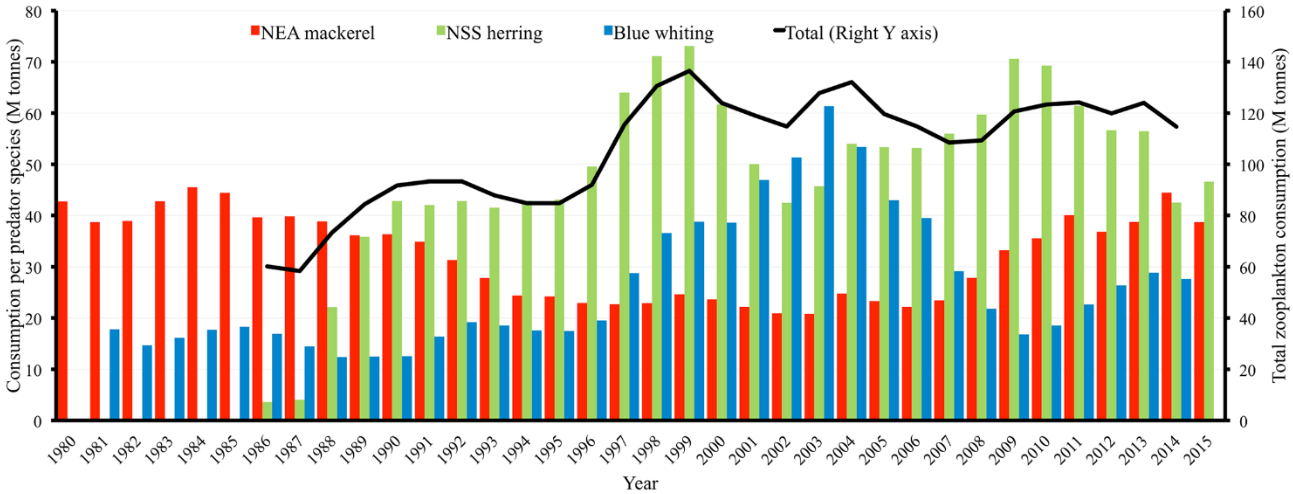


Figure 15. *Total zooplankton consumption by NEA mackerel, NSS herring and blue whiting, from 1980 to 2015. Estimates are based on the mean consumption values from 2005±2010, which were then extrapolated to the total fish biomass reported for different years by the assessment [9]. Black line represents the total consumption by the three species (note the different scale on the right vertical axis). From Bachille et al.* (2018).

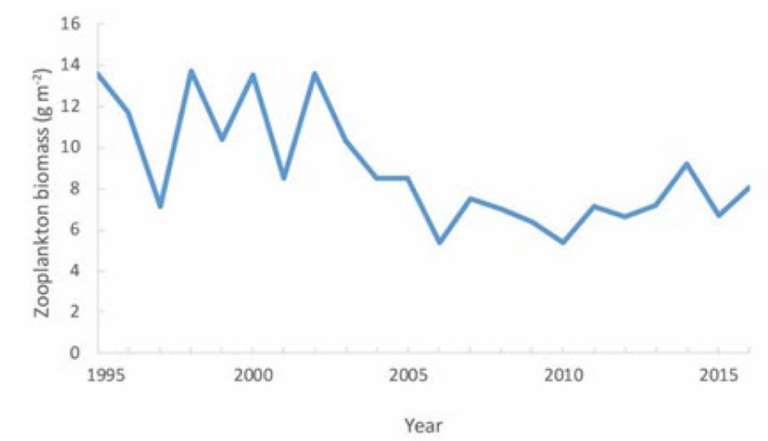


Figure 16. *indices of zooplankton dry weight (g m-2) sampled in May in and near the Norwegian Sea. From ICES (2019 and 2016).*

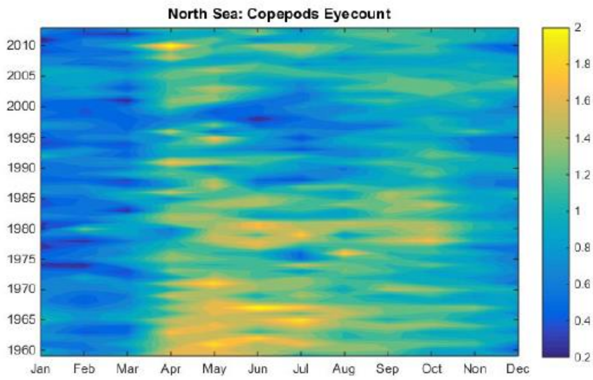


Figure 14 Long-term trends in copepod abundance from the Continuous Plankton Recorder (CPR) survey (log-mean abundance per cubic meter), aggregated for the Greater North Sea region 1958–2014 (data source: https://www.cprsurvey.org/).

Figure 17. *Long-term trends in copepod abundance in the North Sea from the CPR. From ICES (2019).*

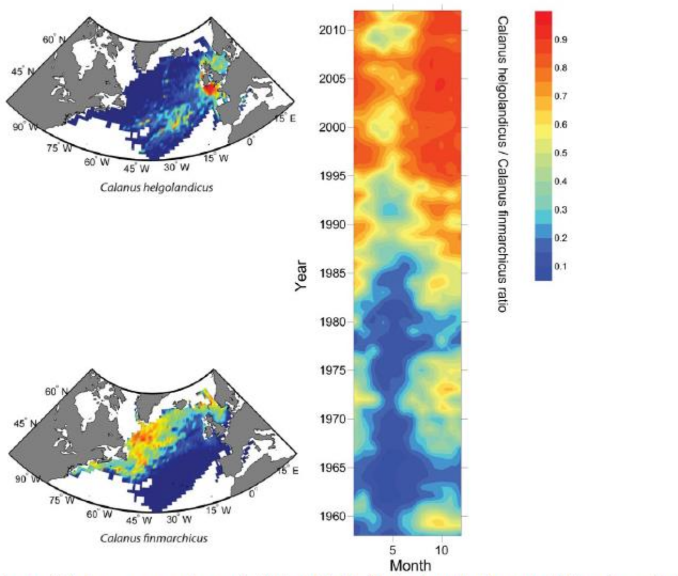


Figure 13 A simple ratio between a warm-water species (*Calanus helgolandicus*) and a cold-water species (*Calanus finmarchicus*) per month from 1958 to 2012 in the North Atlantic. Red values indicate a dominance of the warm-water species and blue values the dominance of the cold-water species.

Figure 18. *Change in Calanus species in the North Sea by year. From ICES (2019).*

Grey gurnards have been discovered due to intensive stomach sampling to be a fierce predator on pre-recruit cod. Figure 19 shows that the stock of grey gurnards increased in the North Sea in the late-1990s and multispecies modelling have made it possible to estimates the extra predation mortality from this increase (Figure 6). The total M2 for 0-group cod increased from around 2.0 before the late-1990 to around 3.0 after. Thus, also a likely contributor to the reduced recruitment of cod since the late-1990s.

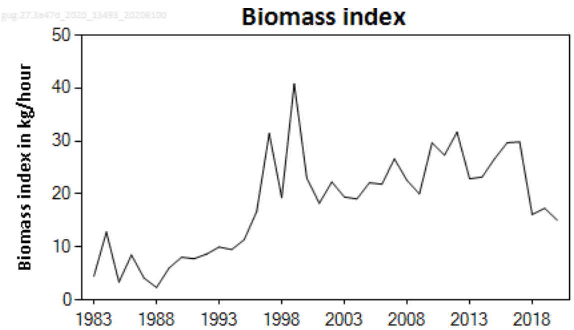


Figure 19. Grey gurnards in the North Sea. Stock biomass index based on IBTS research vessels surveys. From ICES 2020.

The key environmental pressures on the North Sea cod stock that have changed in recent decades are listed in Table 3.

Conclusion about key drivers of the regime shifts

There was no obvious key driver found for the regime shift in the late-1980s which was driven by reduced survival of post-recruits. However, the fact southern stock has decreased since that time means that post-recruit cod are distributed in a smaller area and this could be speculated to be a driver maybe via density dependent mechanisms on growth, maturity and increased diseases and parasites due to high cod densities in this area.

For pre-recruit productivity it seems obvious that the collapse of the southern stock is the main factor. Contributing is probably grey gurnards predation. Herring and mackerel food competition are likely also to contribute. Predation by herring and mackerel might contributes further, although direct observations of many pre-recruit cod in their stomachs are lacking.

There are also potential positive factors on the stock like increased temperature until a certain point means increased growth of cod. These are listed in Table 4.

Table 3. *North Sea cod. Negative environmental pressures on the cod stock in recent years and their possible effect on the carrying capacity, Fmsy, and shape of a SPM curve.*

Pressure	Effect on carrying capacity K	Effect on Fmsy	Effect on shape of the SPM curve
Increased grey gurnards predation on age-0 cod since and including 1997	No effect as K is more related to food competition and cannibalism	No effect as Fmsy is related to growth and survival of post recruits	Will shift the peak of the curve to the right towards a Schaefer model or beyond in terms of Bmsy/K getting larger than 0.5, because more spawners are needed to compensate for reduced R/SSB

Increased food competition with the pelagic stocks since 1998	No effect as K is more related to food competition and cannibalism	No effect as Fmsy is related to growth and survival of post recruits	Will shift the peak of the curve to the right towards a Schaefer model or beyond in terms of Bmsy/K getting larger than 0.5, because more spawners are needed to compensate for reduced R/SSB
Maybe predation on pelagic pre-recruit cod from herring and mackerel in May-August since 1998	No effect as K is more related to food competition and cannibalism	No effect as Fmsy is related to growth and survival of post recruits	Will shift the peak of the curve to the right towards a Schaefer model or beyond in terms of Bmsy/K getting larger than 0.5, because more spawners are needed to compensate for reduced R/SSB
Grey seals predation. This is estimated to give and extra natural mortality of 0.02 – 0.04 for cod ages above age 3.	No effect	A slightly reduced Fmsy by the same amount as the extra natural mortality 0.02 – 0.04	Probably a slight shift to the right of the peak of the SPM curve.
Southern areas too warm since 1996-1998	K will be smaller because of reduced space and food competition and cannibalism will be fiercer.	No effect as Fmsy is related to growth and survival of post recruits	No effects – the stock is just smaller but behaving as a normal cod stock in its restricted area
Predation by and food competition with hake since about 2010	K will be smaller due to food competition with large cod in north	No effect as Fmsy is related to growth and survival of post recruits	Will shift the peak of the curve to the right towards a Schaefer model or beyond in terms of Bmsy/K getting larger than 0.5, because more spawners are needed to compensate for reduced R/SSB
Maybe food competition with the booming plaice stock – since 2010	No effect on K because mainly influencing young cod	No effect as Fmsy is related to growth and survival of larger cod	Will shift the peak of the curve to the right towards a Schaefer model or beyond in terms of Bmsy/K getting larger than 0.5, because more spawners are needed

			to compensate for reduced R/SSB

Table 4.*North Sea cod. Positive or neutral environmental pressures on the cod stock in recent years.*

Pressure	Effect on K	Effect on Fmsy	Effect on shape of the MSP curve
Increased sea water temperature in the Northern area (assuming that the southern cod stock is gone)	No effect. All trophic levels have increased production.	Increase, due to better growth. According to Sparholt et al. (2020) a higher K and lower age-at-50% maturity are linked to a higher Fmsy.	Will shift the peak of the curve to the right towards a Schaefer model or beyond in terms of Bmsy/K getting larger than 0.5, because more spawners are needed to compensate for reduced R/SSB (Drinkwater 2006)
Smaller stocks of other demersal species – haddock, saithe, and whiting	K increases	Increase, due to better growth due to less competition.	Will shift the peak of the curve to the left towards a Schaefer model or beyond in terms of Bmsy/K getting smaller, because less spawners are needed due to increased R/SSB
Less cannibalism	No effect. Already accounted for in SPMs - but need to be included in age based MSE or Eqsim	No, effect. Already accounted for in SPMs - but need to be included in age based MSE or Eqsim	No effect. Already accounted for in SPMs - but need to be included in age based MSE or Eqsim

Discussion

It is still an open question how best to manage a fish stock which is suffering from the warming of the worlds' oceans. Should the fishery be closed for ever or can some exploitation be allowed? – that is a question for both managers and scientists to resolve together. In this paper we give our suggestion to the answer for the North Sea cod stock.

We use the well-known surplus production models (SPMs) to help us understand the issues. The SPM parameters: 1) carrying capacity K, 2) the relative productivity at Bmsy, i.e., Fmsy, and 3) the shape of the curve, n, are influenced to a varying degree on changes in the environmental factor influencing a fish stock.

The carrying capacity K will be influenced if the food availability of the adults is limited. This could be due to reduced geographical coverage as observed here when cod disappears from the southern North Sea. It could also be a result of the hugely increased plaice stock and food competition with that stock and the small- to medium-sized cod where overlap in diet is possible.

The productivity at Bmsy, i.e., MSY (and thus Fmsy which is MSY/Bmsy), will be influenced if predation on adult cod varies. This seems however, not to be the case to any large extent. Grey seal predation has increased a bit, but as shown in Figure 6, is only influencing natural mortality, M, to a small extent of age 4+ and therefore not likely to influence Fmsy substantially.

The shape of the curve, n, might change if, the pre-recruit cod (0-group cod) survival is impaired, e.g., by high predation from grey gurnards, food competition with the large pelagic stocks, and predation by the mackerel and herring. This would indicate a shift to the right of the top point because it will be beneficial for the stock to have a large adult stock to boost the number of pre-recruit cod produced and thus the recruitment (at say age 1), but of course the stock of adults should not be too large, so that food competition and cannibalism more than counter-act the improved recruitment. Also grey seal predation on age 2 and 3 should shift the peak of the curve to the right. However, as shown on WK Doc HS2 WKNSEA 2021, the observed production in the most recent two decades do not support that the shape of the curve has changed as expected, if anything it has changed in the other direction, but the data are probably too noisy to determine this with any useful certainty.

Conclusion.

The productivity of the North Sea cod has decreased in the past decades. There seems to be a regime shift in the late-1980s not in recruitment but in production by post-recruits. It seems to be resulting in increased natural mortality of post-recruits. There is a clear regime shift of recruitment in the late-1990s and the reduced productivity in the post-recruits from the previous period seem to continue. This regime shift seems to be cause by 1) collapse of the southern cod stock component likely caused by climate change, 2) increased food competition of pre-recruit cod with mackerel and herring, 3) increased grey gurnard predation on post-recruits, and 4) probably increased predation on cod larvae by mackerel and herring.

As the above pressures are expected to continue into the coming decade the North Sea cod stock will be in a reduced productivity regime for the same span of time.

If management continue with the current approach ignoring the new stock productivity situation and the split in stock structure, it is likely to result in a quick collapse of the southern stock and a foregone sustainable yield of the northern stock. It seems better to base the management on the "best available science" and to 1) accept the split into two stocks, 2) close the directed fishery on the southern stock component to slow down the collapse and increase the probability to save the stock, 3) manage the northern stock according to revised biological reference points, and 4) follow the situation closely the coming years with a view of revising the new reference points in 10 years' time unless there are clear indications before on new changes in the productivity of cod in the North Sea.

References.

Andersen, K. P., and Ursin, E. 1977. A multispecies extension to the Beverton and Holt theory of fishing, with accounts of phosphorus circulation and primary production. Meddelelser fra Danmarks Fiskeri- og Havundersøgelser, 7: 319–435.

Bachiller E, Utne KR, Jansen T, Huse G (2018) Bioenergetics modeling of the annual consumption of zooplankton by pelagic fish feeding in the Northeast Atlantic. PLOS ONE 13(1): e0190345. https://doi.org/10.1371/journal.pone.0190345.

Beaugrand G et al. 2015 Synchronous marine pelagic regime shifts in the Northern Hemisphere. Phil. Trans. R. Soc. B 370: 20130272. http://dx.doi.org/10.1098/rstb.2013.0272.

Collie, J. S., Gislason, H., and Vinther, M. 2003. Using AMOEBAs to display multispecies, multifleet fisheries advice. ICES Journal of Marine Science, 60: 709–720.

Froese, R., Garilao, C., Winker, H., Coro, G., Demirel, N., Tsikliras, A., Dimarchopoulou, D., et al. 2016. Exploitation and status of European stocks. Updated version. World Wide Web electronic publication, http://oceanrep.geomar.de/34476/.

Hamre J (1978) The effect of recent changes in the North Sea mackerel fishery on stock and yield. Rapp p-v Reun. (CIEM), 172: 197–210.

ICES 1986. Report of the Advisory Committee of Fisheries Management, 1985. ICES Cooperative Research Reports, CRR 137.

ICES. 2016. Final report of the Working Group on the Integrated Assessments of the Norwegian Sea (WGINOR), 7–11 December 2015, Reykjavik, Iceland. ICES CM 2015/SSGIEA:10. 149 pp. https://doi.org/10.17895/ices.pub.5727.

ICES 2018. Report of the Working Group on the Ecosystem Effects of Fishing Activities (WGECO). 12–19 April 2018, San Pedro del Pinatar, Spain. ICES CM 2018/ACOM:27. 65 pp.

ICES 2019. ICES Advisory Report 2019. http://ices.dk/sites/pub/Publication%20Reports/Advice/2019/2019/cod.27.47d20.pdf .

ICES. 2020a. Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK). ICES Scientific Reports. 2:61. 1140 pp. http://doi.org/10.17895/ices.pub.6092.

ICES. 2020b. Working Group on Widely Distributed Stocks (WGWIDE). ICES Scientific Reports. 2:82. 1019 pp. http://doi.org/10.17895/ices.pub.7475

ICES. 2020c. Herring Assessment Working Group for the Area South of 62° N (HAWG). ICES Scientific Reports. 2:60. 1151 pp. http://doi.org/10.17895/ices.pub.6105.

ICES. 2020d. Workshop on Stock Identification of North Sea Cod (WKNSCodID). ICES Scientific Reports. 2:89. 82 pp. http://doi.org/10.17895/ices.pub.7499.

ICES. 2021. Working Group on Multispecies Assessment Methods (WGSAM; outputs from 2020 meet-ing). ICES Scientific Reports. 3:10. 231 pp. https://doi.org/10.17895/ices.pub.7695.

González-Pola, C., Larsen, K. M. H., Fratantoni, P., and Beszczynska-Möller, A. (Eds.) 2019. ICES Report on Ocean Climate 2018. ICES Cooperative Research Report No. 349. 122 pp. https://doi.org/10.17895/ices.pub.5461.

Pedersen, Martin W., and Casper W. Berg. 2017. "A stochastic surplus production model in continuous time." *Fish and Fisheries* 18 (2): 226–43. https://doi.org/10.1111/faf.12174.

Sparholt, H., Bogstad, B., Christensen, V., Collie, J., van Gemert, R., Hilborn, R., Horbowy, J., et al. 2019. Report of the 1st working group meeting on optimization of fishing pressure in the Northeast Atlantic, Copenhagen, June 2017. NORDIC WORKING PAPERS http://dx.doi.org/10.6027/NA2019-904 NA2019:902, ISSN 2311-0562. https://www.norden.org/en/publication/report-1st-working-group-meeting-optimization-fishing-pressure-northeast-atlantic

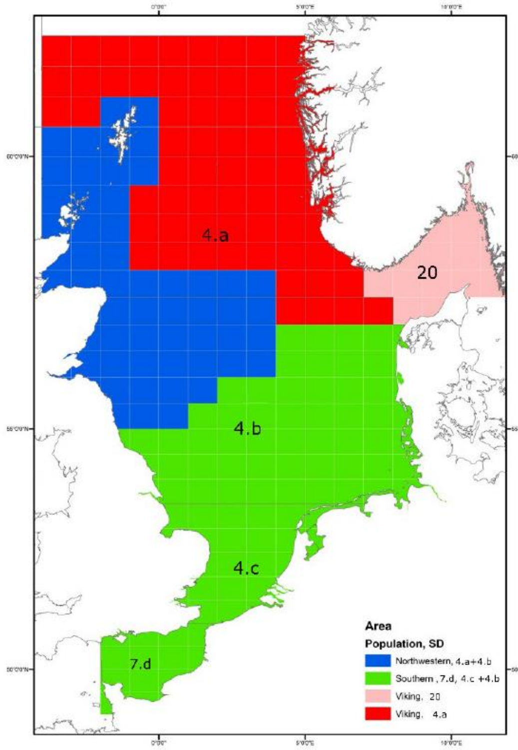
Sparholt, Henrik, Bjarte Bogstad, Villy Christensen, Jeremy Collie, Rob van Gemert, Ray Hilborn, Jan Horbowy, Daniel Howell, Michael C. Melnychuk, Søren Anker Pedersen, Claus Reedtz Sparrevohn, Gunnar Stefansson and Petur Steingrund. 2020. Estimating Fmsy from an ensemble of data sources to account for density-dependence in Northeast Atlantic fish stocks. ICES Journal of Marine Science. ICES Journal of Marine Science, doi:10.1093/icesjms/fsaa175.

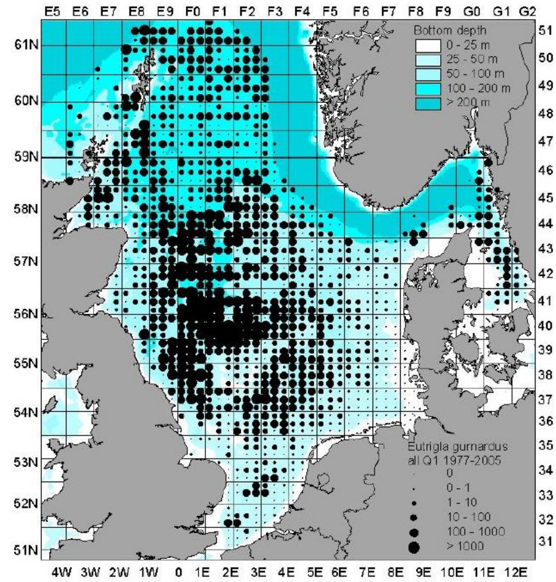
Speirs, D.C., Guirey, E.J., Gurney, W.S.C., and Heath, M.R. 2010. A length-structured partial ecosystem model for cod in the North Sea. Fisheries Research, 106: 474–494.

Toresen, R., Østved, J. (2000). Variation in abundance of Norwegian spring-spawning herring (Clupea harengus, Clupeidae) throughtout the 20th century and the influence of climatic variations. Fish and Fisheries 1, 231-256.

Annex 1. **Sub-areas of the North Sea defining the cod stocks or stock components and spatial distribution of grey gurnards.**

Right top panel grey gurnard distribution 1q. Right bottom panel grey gurnard distribution 3q. Left panel cod stock areas where the green area is the southern stock distribution area.





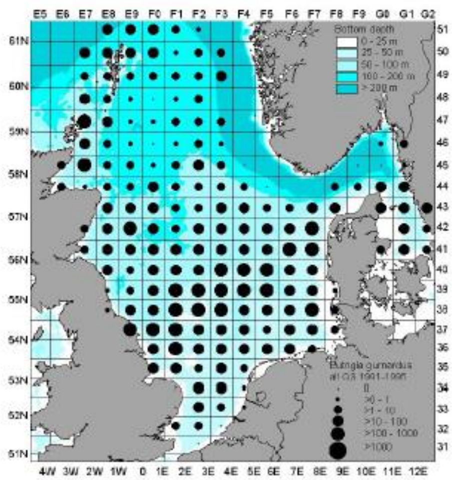


Figure 1. Average annual catch (number per fishing hour for all length classes combined) for E. *gurnardus* in the quarter 1 IBTS survey, 1977-2005.

Figure 2. Quarterly distribution of *E. gurnardus* (number per fishing hour, all length classes combined) based on the quarterly IBTS surveys, 1991-1995.

Cod in Subarea 4, Division 7.d, and Subdivision 20. Subregions used to derive area-specific biomass indices, based on NS IBTS Q1 and Q3 survey data.

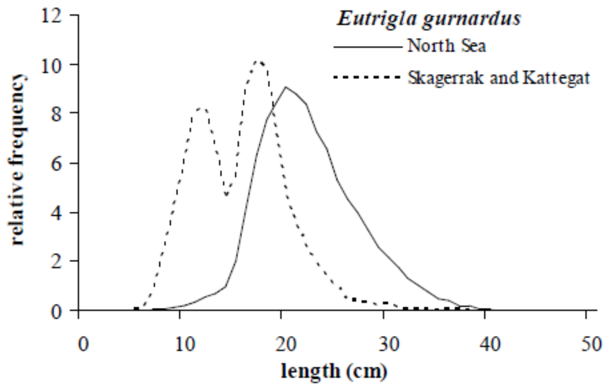


Figure 4. Length frequency distribution of *E. gurnardus* based on the quarter 1 IBTS, 1985–2005.

<u>Annex 2.</u> Naturel mortality for North Sea cod based on Multispecies model (ICES 2020 WGNNSK).

Cannibalism has reduced, but grey gurnard predation on 0-groups and grey seal and harbour porpoise predation on ages 1 and 2 cod increased.

	Age					
y	1	2	3	4	5	6
1963	1.100	0.643	0.213	0.2	0.2	0.2
1964	1.100	0.643	0.213	0.2	0.2	0.2
1965	1.100	0.643	0.213	0.2	0.2	0.2
1966	1.100	0.643	0.213	0.2	0.2	0.2
1967	1.100	0.643	0.213	0.2	0.2	0.2
1968	1.100	0.643	0.213	0.2	0.2	0.2
1969	1.100	0.643	0.213	0.2	0.2	0.2
1970	1.100	0.643	0.213	0.2	0.2	0.2
1971	1.100	0.643	0.213	0.2	0.2	0.2
1972	1.100	0.643	0.213	0.2	0.2	0.2
1973	1.100	0.643	0.213	0.2	0.2	0.2
1974	1.100	0.643	0.213	0.2	0.2	0.2
1975	1.113	0.638	0.216	0.2	0.2	0.2
1976	1.127	0.634	0.218	0.2	0.2	0.2
1977	1.141	0.631	0.221	0.2	0.2	0.2
1978	1.154	0.629	0.223	0.2	0.2	0.2
1979	1.164	0.629	0.225	0.2	0.2	0.2
1980	1.172	0.631	0.228	0.2	0.2	0.2
1981	1.175	0.635	0.230	0.2	0.2	0.2
1982	1.174	0.639	0.232	0.2	0.2	0.2
1983	1.168	0.643	0.234	0.2	0.2	0.2
1984	1.157	0.646	0.236	0.2	0.2	0.2
1985	1.143	0.650	0.238	0.2	0.2	0.2
1986	1.127	0.653	0.240	0.2	0.2	0.2
1987	1.111	0.657	0.242	0.2	0.2	0.2
1988	1.095	0.663	0.244	0.2	0.2	0.2
1989	1.082	0.670	0.246	0.2	0.2	0.2
1990	1.070	0.677	0.247	0.2	0.2	0.2
1991	1.061	0.685	0.249	0.2	0.2	0.2
1992	1.054	0.693	0.251	0.2	0.2	0.2
1993	1.048	0.700	0.255	0.2	0.2	0.2
1994	1.045	0.708	0.259	0.2	0.2	0.2
1995	1.042	0.717	0.265	0.2	0.2	0.2
1996	1.040	0.728	0.274	0.2	0.2	0.2
1997	1.037	0.740	0.284	0.2	0.2	0.2
1998	1.035	0.755	0.295	0.2	0.2	0.2
1999	1.033	0.771	0.308	0.2	0.2	0.2
2000	1.033	0.790	0.322	0.2	0.2	0.2
2001	1.038	0.811	0.335	0.2	0.2	0.2
2002	1.047	0.834	0.348	0.2	0.2	0.2
2003	1.061	0.857	0.359	0.2	0.2	0.2
2004	1.077	0.880	0.366	0.2	0.2	0.2
2005	1.094	0.899	0.369	0.2	0.2	0.2
2006	1.110	0.914	0.368	0.2	0.2	0.2
2007	1.125	0.924	0.363	0.2	0.2	0.2
2008	1.139	0.929	0.356	0.2	0.2	0.2
2009	1.151	0.929	0.348	0.2	0.2	0.2
2010	1.163	0.927	0.340	0.2	0.2	0.2
2011	1.177	0.923	0.333	0.2	0.2	0.2
2012	1.193	0.918	0.327	0.2	0.2	0.2
2013	1.212	0.912	0.324	0.2	0.2	0.2
2014	1.233	0.907	0.321	0.2	0.2	0.2
2015	1.256	0.902	0.320	0.2	0.2	0.2
2016	1.280	0.897	0.320	0.2	0.2	0.2
2017*	1.280	0.897	0.320	0.2	0.2	0.2
2018*	1.280	0.897	0.320	0.2	0.2	0.2
2019*	1.280	0.897	0.320	0.2	0.2	0.2

Annex 3. **Hake spatial and temporal distribution in the North Sea based on IBTS.**

From Cormon Xochitl, Loots Christophe, Vaz Sandrine, Vermard Youen, Marchal Paul (2014). Spatial interactions between saithe (*Pollachius virens*) and hake (*Merluccius merluccius*) in the North Sea. Ices Journal Of Marine Science, 71(6), 1342-1355. Publisher's official version:
https://doi.org/10.1093/icesjms/fsu120 , Open Access version :
https://archimer.ifremer.fr/doc/00200/31146/

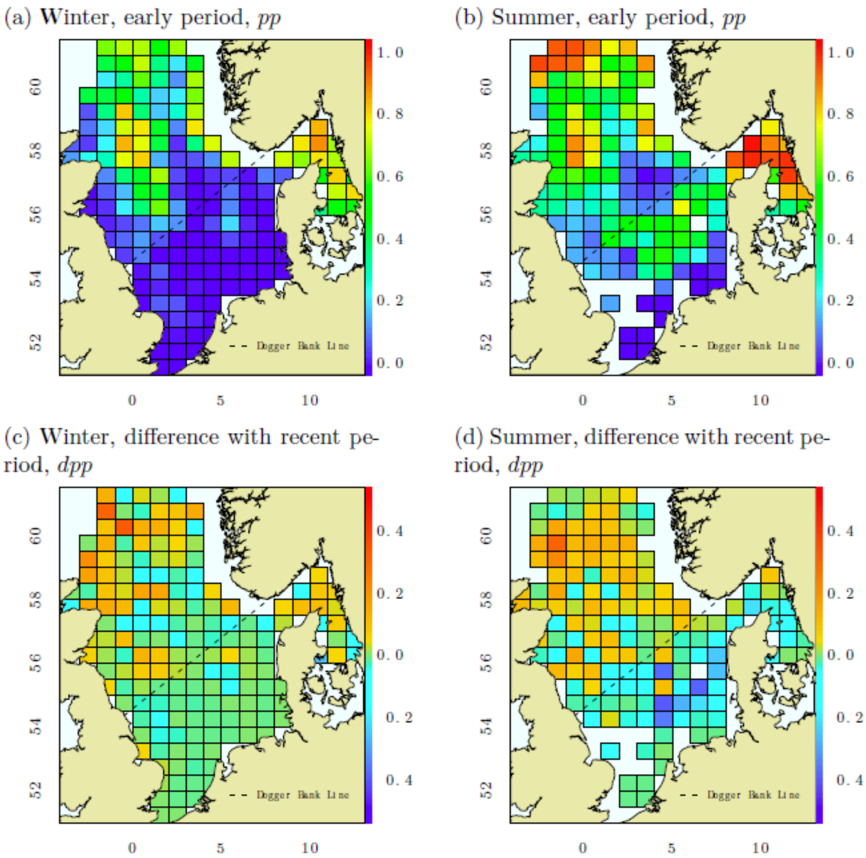


Figure 4: Hake presence probabilities, *pp*, predictions maps for the early period, 1991-1996, in (a) winter and in (b) summer. Changes in hake distributions over the last twenty years resulting from the difference between recent, 2007-2012, and early period in (c) winter and in (d) summer. Note the difference of scale for (c) and (d) where the colour gradient displays a difference of presence probabilities, *dpp*.

<u>Annex 4.</u> Extract from Drinkwater (2005).

Drinkwater, K. F. 2005. The response of Atlantic cod (Gadus morhua) to future climate change. e ICES Journal of Marine Science, 62: 1327e1337.

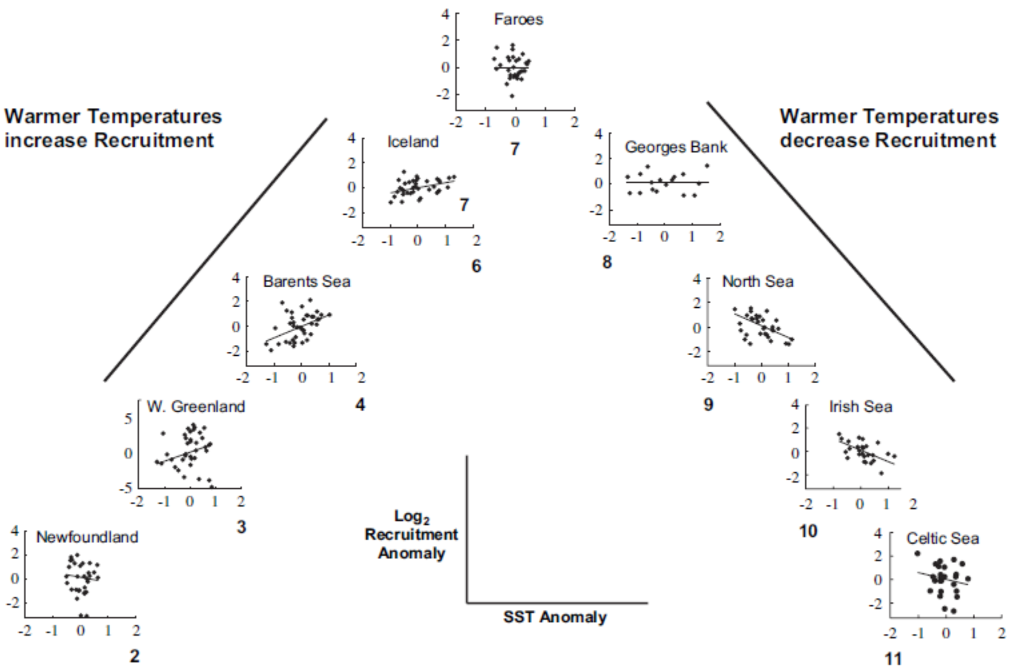


Figure 2. The relationship between the log_2 of the recruitment anomaly and sea surface temperature (SST) anomaly in °C for various cod stocks. The large axis in the bottom centre of the diagram shows the axis legends for all of the plots. The numerical value at the bottom of each plot represents the mean annual bottom temperatures for the stocks. Note that stocks are plotted with bottom temperature increasing to the right. For the cold-water stocks, the SST-recruitment relationship is generally positive while for the warm-water stocks it is negative. There is no relationship in the mid-temperature range. Modified from Planque and Frédou (1999).

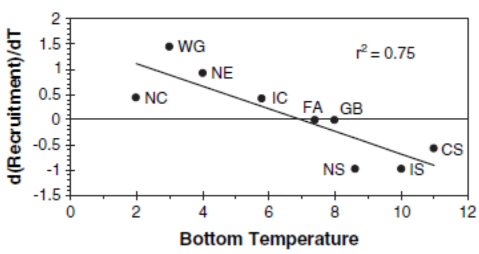


Figure 4. The rate of change in recruitment per unit change in sea surface temperature as a function of bottom temperature (°C) for various cod stocks. (NC = Northern Cod, WG = West Greenland, NE = Northeast Arctic Cod, IC = Iceland, FA = Faroes, GB = Georges Bank, NS = North Sea, IS = Irish Sea, and CS = Celtic Sea).

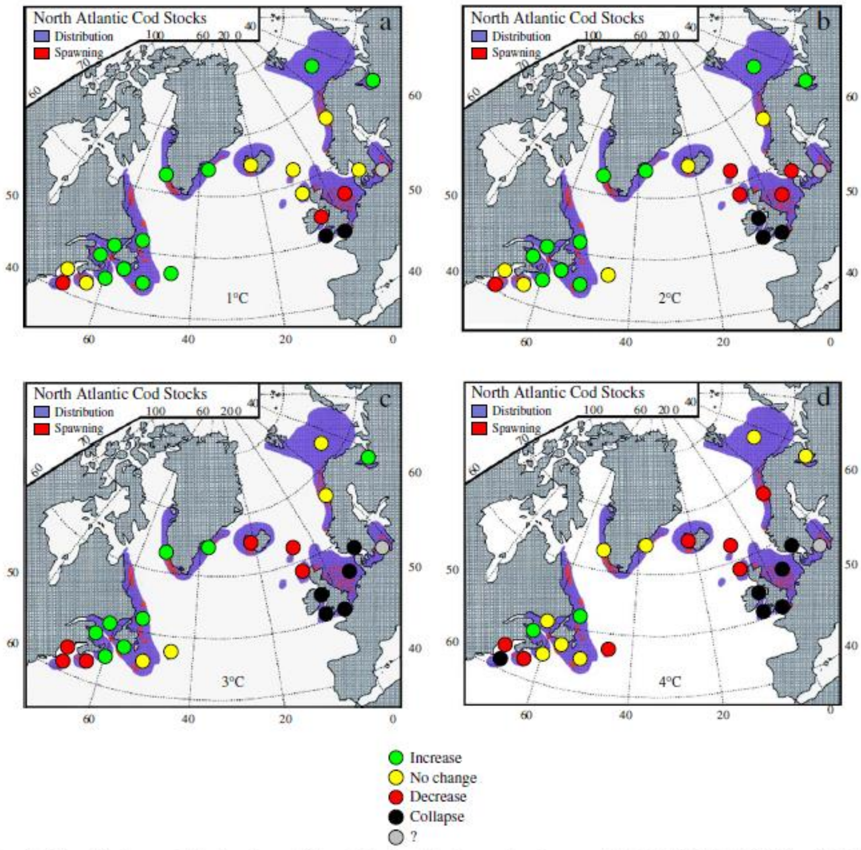


Figure 5. Expected changes in the abundance of the cod stocks with a temperature increase of (a) 1 °C, (b) 2 °C, (c) 3 °C, and (d) 4 °C above current levels.