WORKSHOP ON STOCK IDENTIFICATION OF WEST OF SCOTLAND SEA COD (WK6aCodID; outputs from 2021 meeting)

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Contents

i Executive summary

The Workshop on stock identification of West of Scotland cod (WK6aCodID) convened to recommend the most plausible scenario of population structure for stock assessment and fishery management advice. The review considered geographic variation and movements of cod life-stages inferred from genetic analyses, scientific surveys, fishery data, tagging, and otolith microchemistry and shape. Based on the review, several population structure scenarios were hypothesized (including the scenario assumed in the current advisory unit), and the plausibility of each scenario was evaluated. Practical implications of the most plausible scenario, including the derivation of a catch time-series, were considered to form recommendations for benchmark stock assessment workshops.

The workshop considered three hypotheses - hypothesis 1: closed homogenous population; hypothesis 2: a metapopulation with overlapping subpopulations (but not necessarily with areas within Division 6.a) (Clyde, Dogger inshore, Dogger offshore) and hypothesis 3: multiple overlapping subpopulations related to Dogger stocks (between Division 4.a and Division 6.a) and a separate subpopulation of Clyde.

While hypothesis 3 provides the strongest scientific evidence, treating the Clyde as a separate population is problematic with respect to reconstructing historical catches and undertaking assessments. Over the last two decades of local management with the Clyde cod closure, incorporating minimal catches into subpopulations is unlikely to impact assessments at the present time.

Given the current weak state of Clyde cod, hypotheses 2 and 3 would be practically indistinguishable in terms of assessment outcome and the workshop considers hypothesis 2 amenable to stock assessment in the short- to medium-term, while investigations continue into the assessment of the Clyde cod and the improvement of data availability. Given linkages of the inshore and offshore subpopulations to cod in Division 4.a, it is recommended to combine the North Sea and West of Scotland cod assessments in a future benchmark.

The workshop elaborated two scenarios with respect to a potential ICES data submission consistent with the modelling approaches being considered for the North Sea cod stock (cod in Subarea 4, Division 7.d and Subdivision 20); namely, either that data are submitted for the whole of Division 6.a as for the current ICES stock assessment, or that data are split into stock components as defined under hypothesis 2 (and hypothesis 3). In these cases, the workshop suggested that two approaches be considered based on data availability and a conversation between ICES national data submitters and ICES stock assessors.

ICES data submitters and ICES stock assessors should agree on a suitable time period for data splitting; considering the current assessment time-series for both West of Scotland and North Sea stocks and data quality back in time.

Having addressed its Terms of Reference, the workshop noted that there is potential for much reshaping of Atlantic cod stock assessments currently. With the four primary cod assessments (Celtic Sea, Irish Sea, West of Scotland and North Sea) presently exhibiting issues. Primarily these revolve around continued low catch tonnage, which translates into low catch numbers-at-age and resolves with heightened uncertainties in assessments. To investigate and review further, the workshop proposes that a planned approach be developed within ICES, through initial *roadmapping* for improving assessments and the basis for advice.

ii Expert group information

Expert group name	Workshop on stock identification of West of Scotland cod (WK6aCodID)
Expert group cycle	Annual
Year cycle started	2021
Reporting year in cycle	1/1
Chair(s)	Carl O'Brien, United Kingdom
Meeting venue(s) and dates	29 November – 1 December 2021, online meeting (16 participants)

1 Introduction

1.1 Terms of reference (ToRs)

A **Workshop on Stock Identification of West of Scotland Sea Cod (WK6aCodID)** chaired by Carl O'Brien, UK, will meet online from 29 November – 1 December 2021 to:

a) Review information on stock identification of West of Scotland cod and adjacent areas in the context of the Atlantic cod population structure, including critical evaluation of inferences from each source of information, to build up a picture of cod sub-stock structure in the West of Scotland and adjacent areas, based on the following:
   i) Distribution and movements of different life-stages of cod, including changes over time, inferred from:
      1) Tagging
      2) Scientific Surveys
      3) Commercial landings
      4) Dispersal models (e.g. of cod eggs and larva/juveniles)
   ii) Genetic analyses
   iii) Otolith microchemistry
   iv) Morphometrics and meristics
   v) Life-history and parasites
   vi) Other approaches not listed above

b) Based on the evidence from ToR a), formulate scenarios for cod stocks West of Scotland and adjacent areas, and assess the evidence-based plausibility of each of these scenarios (including current definitions).

c) Consider the practical implications, for data, particularly historical time-series of catch data, of each of the scenarios in ToR b), and how any difficulties might be dealt with. For example, considering spatial components with mixing in a single model has different implications for data compared to split stock units. Considerations should include how to deal with changes over time.

d) Make recommendations for which cod stock scenario(s) to take forward in the forthcoming cod benchmark, including in what format data should be requested and prepared.

The Workshop will report by 20 December 2021 for the attention of ACOM and FRSG.

1.2 Background

The 2020 benchmark stock assessment of cod West of Scotland (ICES, 2020a) was not primarily focused on stock identification but reported: *Stock structure remains an issue for cod in Division 6.a. The latest evidence […] suggests that there are at least three sub-stocks which remain largely geographically isolated throughout the year with the northern offshore component (currently responsible for the majority of the landings) more closely linked to cod in the northern North Sea than the rest of Division 6.a.*

WK6aCodID was established to reconsider the stock identification of West of Scotland cod and adjacent areas.

1.3 Conduct of the meeting

The list of participants and agenda for the workshop are presented in Annex 1 and Annex 2, respectively.

Intersessional work had taken place ahead of the WK6aCodID meeting by its participants, and this was presented during the first day and the morning of the second day. The presentations were used to define the work programme for the remainder of the workshop and to address the ToRs.

Given ICES role as a knowledge provider, it is essential that experts contributing to ICES science and advice maintain scientific independence, integrity and impartiality. It is also essential that their behaviours and actions minimise any risk of actual, potential or perceived Conflicts of Interest (CoI).

To ensure credibility, salience, legitimacy, transparency and accountability in ICES work, to avoid CoI and to safeguard the reputation of ICES as an impartial knowledge provider, all contributors to ICES work are required to abide by the ICES Code of Conduct. The ICES Code of Conduct document dated October 2018 was brought to the attention of participants at the workshop and no CoI was reported.

1.4 Plenary presentations

Seven presentations were given during the plenary sessions of WK6aCodID; presenter and title below.

Thomas Regnier:

Otoliths, microchemistry and tagging

- Presentation summarising studies involving otolith shape and microchemistry, tagging studies (those led my MSS and an historic one with key results), a reanalysis of tagging data for NScod in 2020 and a proposed population structure in 6.a based on a review of evidence from different sources at MSS, following a similar approach used in Holmes *et al*. 2014).

Mathieu Lundy:
Review of Celtic Seas and West of Scotland tagging records

- Background figures produced during an EASME-funded cod tagging project in the Irish Sea; compiled by Victoria Bendall (Cefas, UK) as a review of tagging records in ICES Divisions 6.a, 7.a and 7.g).

David Murray:

Summary of genetic data from previous studies on West of Scotland cod and adjacent areas

- Presentation on research involving the genetic structure of Atlantic cod within ICES Division 6.a, as well as adjacent ICES areas including Divisions 4.a and 7.a.

Helen Dobby:

Sub-stock survey biomass and recruitment trends

- Trends with an assumed sub-stock definition, not about determining sub-stock definition/stock identification.

Jakob Hemmer Hansen:

Figures 2.13 and 2.14 – heatmap (ICES, 2020b)

Nicola Walker:

North Sea cod mixing with 6.a cod

- A description of survey analyses combining data from the North Sea and Division 6.a, explored at the recent benchmark of North Sea cod (WKNSEA, 2021) and explanation of the ad hoc adjustment currently used in the North Sea cod assessment to account for connectivity with 6.a cod.

Helen Dobby:

West of Scotland cod - catch data and misreporting

1.5 Structure of the report

The structure of the report is as follows:

- Section 2 focuses on a review of information on stock identification of West of Scotland cod and adjacent areas – ToR a);
- Section 3 focuses on plausible scenarios for cod stocks West of Scotland and adjacent areas – ToR b);
- Section 4 focuses on practical implications of cod stock scenarios – ToR c); and
- Section 5 focuses on recommendations for West of Scotland cod stock scenario(s) to progress within ICES – ToR d).

Instead of providing conclusions from the workshop at the end of the report as is customary with ICES reports, each of the Sections 2–5 provides a synthesis of the material presented within each Section in either a summary or future work Section.

Initial compilation of the draft report was agreed to be completed by 13 December 2021; with final comments and review by the participants of the workshop to be completed by 17 December 2021 to ensure completion by the 20 December 2021.

1.6 References

ICES. 2020a. Benchmark Workshop for Demersal Species (WKDEM). ICES Scientific Reports. 2:31. 135 pp. http://doi.org/10.17895/ices.pub.5548

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

2 Review information on stock identification of West of Scotland cod and adjacent areas

2.1 Introduction

This section focusses on ToR a).

2.2 Otoliths, microchemistry and tagging

Otolith shape analyses

A single study used otolith shape analyses to identify spawning groups in ICES Divisions 6.a, 7.a and 4.a. Galley *et al*. (2006) sampled cod aged 2 to 4 years old on known spawning grounds in the Irish Sea, the Firth of Clyde, the South Minch, Papa Bank, Shetland, Viking Bank and the Moray Firth and analysed differences in general shape descriptors (e.g. rectangularity, circularity etcetera) and harmonics produced by Cartesian Fourier analysis. The produced otolith shape descriptors were analysed by two methods: (i) a randomization analysis of Fourier descriptors and (ii) a discriminant analysis of both general and Fourier descriptors. Results indicate significant differences in the otolith shape of fish collected at different spawning sites including neighbouring sites. In particular, the shape of otoliths of Clyde cod was different from the one of fish sampled in the Irish Sea or the South Minch, indicating the presence of distinct spawning groups. The otolith shape of fish spawning in the South Minch was also found to be different from the one of fish spawning on the East coast of Scotland in the Moray Firth. The population structure of cod in 6a appears to be complex with coastal spawning grounds associated with distinct spawning groups over a relatively small spatial scale.

Otolith microchemistry

Two studies used otolith microchemistry to investigate population structure in cod around the Scottish coast with at least a sample originating from Division 6.a (Wright *et al*. 2006a, Gibb *et al*. 2007). Gibb *et al*. (2007) used whole solution Inductively Coupled Plasma Mass Spectrometry (ICPMS) analyses to investigate the difference in otolith chemistry between nursery areas in the Firth of Clyde, Shetland, the Moray Firth and Buchan. Results indicate significant differences between areas and the potential for otolith chemistry to discriminate between fish from distinct geographical origins. As only young of the year (age 0) cod sampled on nursery grounds and a single nursery ground from 6.a was sampled (Firth of Clyde), the results are of limited significance to the objective of this workshop (i.e. at best no exchange of juvenile fish between the Firth of Clyde nursery and nurseries to the East of Scotland and Shetland).

Wright *et al*. (2006a) considered connectivity between nursery and spawning areas. In this study, sampling targeted 0-group cod from the 2001 year-class on nursery grounds and then the same year-class at age 2 when they first spawned. Based on solution ICPMS of whole 0-group otoliths, samples from the Scottish west coast could be distinguished into three regions; the Minch, Inner Hebrides and Clyde. The 0-group component of adult cod were micro-milled from the otoliths for comparison with the regional 0-group chemistry. Adult cod in the Inner Hebrides and the Clyde had a chemistry consistent with local origin as 91% and 100% of adult fish were assigned to the local 0-group respectively (Wright *et al*., 2006a). The lack of a chemistry signal from Minch 0-group would suggest there is little exchange between the Minch and cod further south. Up to 9% of Inner Hebrides adult were assigned to the Firth of Clyde nursery. While this result can be largely due to classification error arising from overlapping chemical signatures, it is possible that

a small fraction of Clyde fish spawn in the Inner Hebrides. As such this might suggest that the northern part of the Celtic unit may extend to the Inner Hebrides but not further north.

Tagging

The tagging evidence reviewed in this section originates from four peer-reviewed articles (Easey 1987, Wright *et al*. 2006a,b, Neat *et al*. 2014) as well as a re-analysis of the tagging data realised at the Workshop on Stock Identification of North Sea Cod (WKNSCodID 2020).

Easey (1987) examined the extent of mixing between the North Sea and the West of Scotland using tag-recapture data from adult cod released at 4 locations, Papa Bank (limit 6.a/4.a), Sumburgh (SE Shetland), North Shetland (4.a) and the West Hebrides (6.a). The release locations in Division 6.a considered in this study are situated more offshore than in more recent studies (Wright *et al*. 2006a,b, Neat *et al*. 2014). 82% of fish released on Papa Bank were recaptured in an area between Northern Ireland and North Orkney and 14% near Shetland with a larger extent of movement observed in fish recaptured in Q1 and Q2. The fish released near Shetland (Sumburgh, North Shetland) were mostly recaptured around Shetland. While movements toward Papa Bank (6a limit) were observed for North Shetland individuals, the low sample size limits its significance. Individuals released at the West of the Hebrides were recaptured in majority near the Hebrides but a significant proportion (32%) was recaptured in Papa Bank and another 8% recaptured further East. The results indicate extensive movement across the 6.a/4.a limit, for fish released in offshore sites along the shelf edge to the North/Northwest of Scotland.

The study by Wright *et al*. (2006a) considers the level of residency and reproductive isolation in Scottish waters using tag recapture data collected between 1960 and 1984. The release locations comprised two sites in 4.a (St Andrews Bay and the Moray Firth) and three sites in 6.a (Clyde, Minch and Northern Coast). Contrary to the earlier study (Easey 1987) all release sites were coastal. Fish tagged in the Clyde and the Minch were recaptured locally during the spawning season. While most fish released on the Northern coast and the Moray Firth were recaptured locally, a significant overlap in the extent of movements was found between these two groups. The result indicate that cod recaptured on inshore spawning grounds on the West coast of Scotland were resident groups and that some mixing was apparent between cod spawning on the Northern coast (6.a) and the Moray Firth (4.a).

Site fidelity of spawning aggregations was investigated by Wright *et al*. (2006b) using tag-recapture data of cod released in spawning areas during the spawning season. The tag-recapture data was composed of conventional tag data collected between 1962 and 1981 and Data Storage Tag (DST) of cod released between 2002 and 2004. The release sites included three sites in 4.a (Viking Bank, East Shetland and the Moray Firth) and two sites in 6.a (Minch and Clyde) for the conventional tags and two additional 4.a sites for the DST data, however the very low recapture rate of DST tagged fish in 6.a provides no useful information for this type of tag. Average displacement distance between release and recapture was <100 km on average and lower in coastal sites (Minch, Clyde and Moray Firth) compared to offshore sites (Viking Bank and East Shetland) suggesting limited movements and residency. The reconstructed extent of movement of DST tagged individuals released to the West of Shetland indicated an overlap with 6.a near Papa Bank. The study therefore highlights differences between inshore and offshore spawning groups and possible mixing between offshore groups around the 4^0 limit between 6.a and 4.a, however offshore sites in 6.a were not considered in this study.

The study by Neat *et al*. (2014) aimed at describing the home ranges of cod released in nine geographic areas including the West of Scotland, North East Scotland and the Irish Sea. In this study, geolocations estimated from DST data were used to reconstruct home ranges and mixing between areas. As the data used for the West of Scotland originated only from inshore locations in the Clyde, Inner Hebrides and the Minch (no offshore groups) and the number of DST tags

recovered was low, limited conclusions could be drawn from this study regarding exchange with adjacent areas (4.a and 7.a). Despite the limited data, overlap between the home ranges of the Irish Sea and West Scotland cod was evident in the North Channel and the North of the Irish Sea.

At the recent Workshop on Stock Identification of North Sea Cod (2020) data from the English and Scottish conventional tagging experiments were reanalysed considering the three proposed North Sea units (Northwestern, Viking and Southern units, WKNSCodID 2020) and data for cod released in 6.a to the North of Scotland and West of the Hebrides (6.a group). Kernel Density Estimation (KDE) was used to estimate the extent of movements of fish released in these 4 areas.

2.3 Genetic data from previous studies on West of Scotland cod and adjacent areas

The genetic population structures of Atlantic cod on the west coast of Scotland have been relatively poorly investigated. Existing studies have mainly focused on the connectivity of ICES Division 6.a to adjacent advisory units such as the North and Irish Seas (Nielsen *et al*. 2009; Heath *et al*. 2014; ICES 2020; Wright *et al*. 2021). Arguably, Health *et al*. (2014) provided the most informative analysis of ICES Division 6.a cod population, using 96 single nucleotide polymorphisms (SNPs) to delimit populations around the UK. Both adult cod and eggs from adjacent spawning areas were tested with analysis revealing three distinct, spatially separated groups referred to as, i) Viking, ii) Dogger and iii) Celtic units (Heath *et al*. 2014). Both Dogger and Celtic units occupied areas within ICES Division 6.a, with Celtic units including cod from the Firth of Clyde inhabiting the southern region of the division, while Dogger units remained isolated from Celtic units at the northern extent of ICES Division 6.a, encompassing inshore and offshore areas of the Outer Hebrides (Heath *et al*. 2014). The observed population units identified within this study do not conform to current ICES advisory units with adult cod found around the Outer Hebrides sharing a genetic affinity with cod found across a broad swathe of the North Sea (ICES Subarea 4), while fish in the Firth of Clyde were clearly part of the Irish Sea cod (ICES Division 7.a) (Heath *et al*. 2014). Despite robust analyses with multiple discriminatory genetic markers, the lack of within site temporal replicates does question the stability of these populations across time.

Wright *et al*. (2021) used a limited marker set (13 SNPs) to describe the genetic structure within the northern extent of ICES 6a cod. Investigating areas from as far east as the Viking Bank to offshore of the Outer Hebrides between two time points (2002/3 and 2013/14) and seasons (spring and autumn), the authors observed clear and consistent genetic differentiation between cod from the Viking Bank (ICES Division 4.a) and those found inshore of the west of Scotland (ICES Division 6.a) (Wright *et al*. 2021). There was evidence of population substructures within ICES Division 6.a, with inshore and offshore cod being weakly differentiated within 2002/3 samples (Wright *et al*. 2021). However, as well as being temporally dependent, they were not significant when corrected for multiple testing (Wright *et al*. 2021). Conversely, the lack of significant genetic differences among samples to the west of Shetland (ICES 4a) out to offshore areas of the Outer Hebrides may suggest a greater exchange of genetic material (Wright *et al*. 2021). Similar to Health *et al*. (2014), genetic analysis indicates that the North Sea and west of Scotland do not correspond to the current advisor units, with the divergence between the two divisions being more complex than the current 4°W boundary currently separating ICES Divisions 6.a and 4.a (Wright *et al*. 2021).

Although there is evidence of genetic differentiation between cod within multiple regions of ICES Division 6.a, these studies do not suggest fixed structures produced by reproductive isolation (Heath *et al*. 2014; Wright *et al*. 2021). Using 10 microsatellites, Nielson *et al*. (2009)

investigated potential microgeographical population structures among cod at two sites within ICES Division 6.a, Firth of Clyde and Butt of Lewis. There was no evidence of genetic differentiation between these sites, suggesting significant levels of genetic exchange between the two areas (Nielsen *et al*. 2009). Consequently, the limited genetic evidence provided by these studies points towards a single metapopulation with multiple subpopulations, specifically inshore, offshore and Clyde subpopulations within ICES Division 6.a. These are not isolated populations, instead there appears to be gene flow between subpopulations, but importantly also between adjacent ICES Divisions 4.a and 7.a. Further studies will be required to confirm genetic subpopulation structures within these areas, ideally with multiple temporal replicates to confirm the consistency of these structures across time.

2.4 Sub-stock survey biomass and recruitment trends

Introduction

While the presence of cod sub-populations within the west of Scotland has been acknowledged for a number of years (Wright *et al*, 2006a, 2006b), exploration of trends in sub-population SSB and/or recruitment have not been routinely carried out. This has been due, in part, to uncertainty over the population boundaries and also due to changes to the design and gear used in the Scottish surveys, making analysis more difficult. The most recent study was presented in Holmes *et al*. (2014) who defined three putative sub-populations in Division 6.a and based on an analysis of Scottish quarter 1 survey data up to 2010 concluded that the subpopulations exhibited different trends in SSB. In the Southwest area, SSB had essentially collapsed while the declines in the Clyde and Minch were less severe and more in line with the overall decline in the west of Scotland assessment area. The aim of the work presented here was to update the sub-population trends in biomass presented in Holmes *et al*. (2014) using more recently defined sub-populations (Figure 6 in Wright *et al*., 2020) and additional survey data, including data from quarter 4 and from 2011 onwards, and furthermore, to explore the trends in recruitment in different sub populations.

Data and Methods

Survey data

Five different survey data series (two of which are discontinued) cover the area to the west of Scotland (See Table 2.5.1 below). Prior to 2011, the two annual Scottish surveys (SWC-IBTS) were conducted using GOV trawl with ground-gear 'C', using a design based on fixed stations within ICES rectangles and one or two hauls per rectangle (to cover the depth range) (ICES, 2010). In 2011, a new random stratified survey design was implemented and the ground-gear was modified (to GOV 'D') (SCOWCGFS). The changes to the ground-gear are considered likely to have had an impact on catchability and hence the surveys are treated as separate time series with different identifiers within DATRAS. In addition to the two annual Scottish surveys, an Irish survey is conducted in quarter 4 which covers the southern part of Division 6.a (south of approx. 56.5˚N).

Table 2.5.1 Summary of bottom trawl surveys covering Division 6a.

Quarter	Survey	Acronym	Gear	Spatial coverage	Years	Source
Quarter 1	Scottish West Coast Groundfish Survey	SWC-IBTS	GOV	6.a, 4.a (limited)	1985 - 2010	DATRAS
		SCOWCGFS	GOV	6.a	2011 - 2020	DATRAS
	Scottish West Coast Groundfish Survey	SWC-IBTS	GOV	6.a, 7.a (limited) & 7.b (limited)	2003 - 2009	DATRAS
		SCOWCGFS	GOV	6.a, 7.b (limited)	2011 - 2019	DATRAS
Quarter 4	Irish Groundfish Survey	IE-IGFS	GOV	6.a (South), 7.a, 7.b, 7.g, 7.j	2003 - 2019	DATRAS

SSB trends

SSB at the sub-population level was calculated following a broadly similar approach to that described in Holmes *et al*. (2014), with the exception that the haul-based catch rates at age were derived from the raw exchange format data (downloaded from the DATRAS database) by applying a modelled ALK (Berg and Kristensen, 2012) to the numbers-at-length (rather than using the relevant DATRAS data product). Numbers-at-age were averaged over all hauls within an ICES statistical rectangle and then summed over all rectangles within each subarea. SSB was calculated as the sum of products of the numbers-at-age index for each subarea, weights-at-age and maturity-at-age. Weights-at-age which are common across subareas were taken from the assessment WG report (ICES, 2021) and are assumed equal to the smoothed catch weights-at-age. Maturity-at-age has been demonstrated to vary between subareas (Baudron *et al*., 2020), but was kept constant over time. In order to identify potentially asynchrony in SSB trends across subareas, a GAM allowing for separate trends for each area in addition to a common trend was fitted to the log-transformed indices:

log SSB ~ A + s (Y) + s (Y, by=A),

where A denotes a categorical variable allowing a different level for each subarea, s (Y) a smooth function of year describing a common trend, and s (Y, by=A) are subarea specific smooth functions of year that describe smooth deviations from the common trend.

Given the changes in survey ground-gear, the analysis was carried out for each of the four Scottish surveys separately.

Recruitment

To explore trends in recruitment, an alternative approach was taken in which recruitment at age 1 was modelled using the 'surveyIndex' R package (Berg, *et al*. 2014) which implements a GAM modelling framework using data in the DATRAS format and allowing for a variety of different model assumptions. The general form of the model was as follows:

$$g(\mu_i) = Year_i + Gear_i + U(Ship_i) + f_1\left(\mathrm{lon}_i, \mathrm{lat}_i, Year\right) + f_2(\mathrm{depth}_i) + f_3(\mathrm{timeofday}_i) + \log(\mathrm{HaulDur}_i)$$

where g is the link function and μ_i is the expected numbers-at-age one in the ith haul (or probability of non-zero catch for the presence-absence part), $Year_i$ is a categorical effect, f_2 a thin-plate spline, f_3 a cyclic cubic regression spline, $Gear_i$ is a categorical effect of the gear (including

groundgear effect, see above) and U is a random vessel effect. A number of different formulations for the spatio-temporal interaction term were fitted and compared (f_1):

1. Moderate resolution 3-d tensor product smooth using cubic regression/thin plate regression spline
2. As above, but using duchon spline.
3. Fixed moderate resolution spatial effect with independent annual spatial deviances (low resolution).
4. Fixed moderate resolution spatial effect with time varying spatial deviances defined using 3-d tensor product smooth.
5. Independent annual low resolution spatial effects

The model diagnostics were compared and AIC was used to evaluate which model gave the best fit to the data. In addition, all models were tested using delta-lognormal, delta-gamma and Tweedie distributions.

Indices were calculated by first predicting abundance on a spatial grid (at haul positions nearest to the centroid of each grid cell) with other effects such as gear and ship held fixed at each prediction (i.e. the prediction is made for a standard gear/ship) and then summing over the grid points. Sub-population recruitment indices were then calculated by summing over the appropriate sub-set of grid points.

A single quarter 4 model was developed using data from the two Scottish surveys and the Irish survey while data from the two Scottish quarter 1 surveys were analysed separately due to a lack of overlap in the two surveys with different ground gear. Estimated sub-population indices were mean standardised and compared, and additionally comparisons were made with recruitment in the neighbouring Irish Sea using the age 1 index from the N. Irish Q1 groundfish survey taken from the most recent assessment WG report (ICES, 2021). Correlation between detrended (lag-1 differenced) sub-population log recruitment.

Results

SSB trends

The analysis of the early Scottish Q1 survey (SWC-IBTS Q1) shows a decline over the full time series (1986 to 2010). All subareas exhibit a relatively linear decline, although with some evidence of a steeper decline in the Northern Offshore area compared to the other areas. (Note that these results differ somewhat to those of Holmes *et al*. (2014) who showed – this appears to be due to the modified sub-population definitions rather than the use of a modified data set.) Evidence of declining SSB is less apparent in the early Q4 survey (SWC-IBTS Q4) with the trends in Clyde and N. Inshore estimated to be increasing.

The two current Scottish surveys (Q1 and Q4) show a consistent picture. In both surveys, SSB in the N. Offshore area shows a clear increase to around 2016 with a decline since then. This is in contrast to the continued declining trend observed in the S. Inshore area and the relatively stable SSB in the Clyde over the past 10 years (again consistent across both surveys).

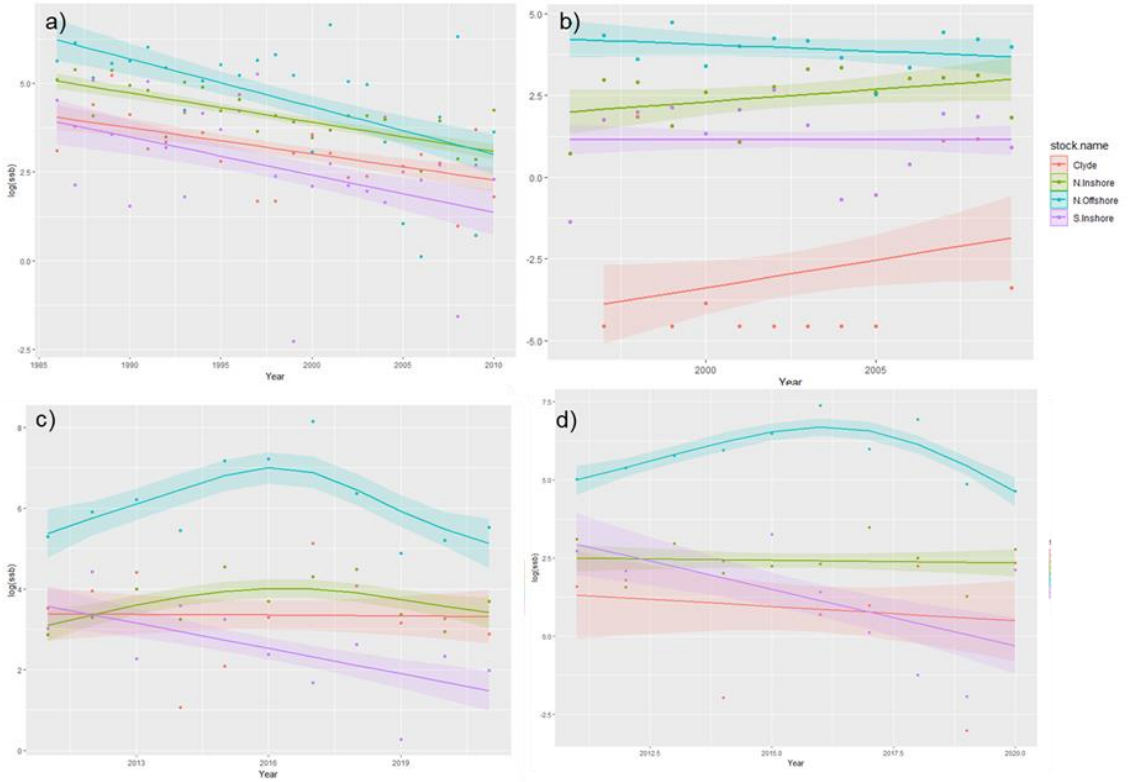

Figure 2.5.1 Log SSB indices and fitted smoothers for each putative sub-population using data from a) SWC-IBTS Q1, b) SWC-IBTS Q4, c) SCOWCGFS Q1, and d) SCOWCGFS Q4.

Recruitment

The most parsimonious model in terms of AIC varied across input data sets. However, the choice of final model made little difference to the conclusions and in all models/data sets there was a high degree of synchrony between estimated sub-population recruitment indices (Figure 2.5.3). Correlations are significant between all sub-populations for all models/quarters (example in Figure 2.5.4 for SWC-IBTS Q1).

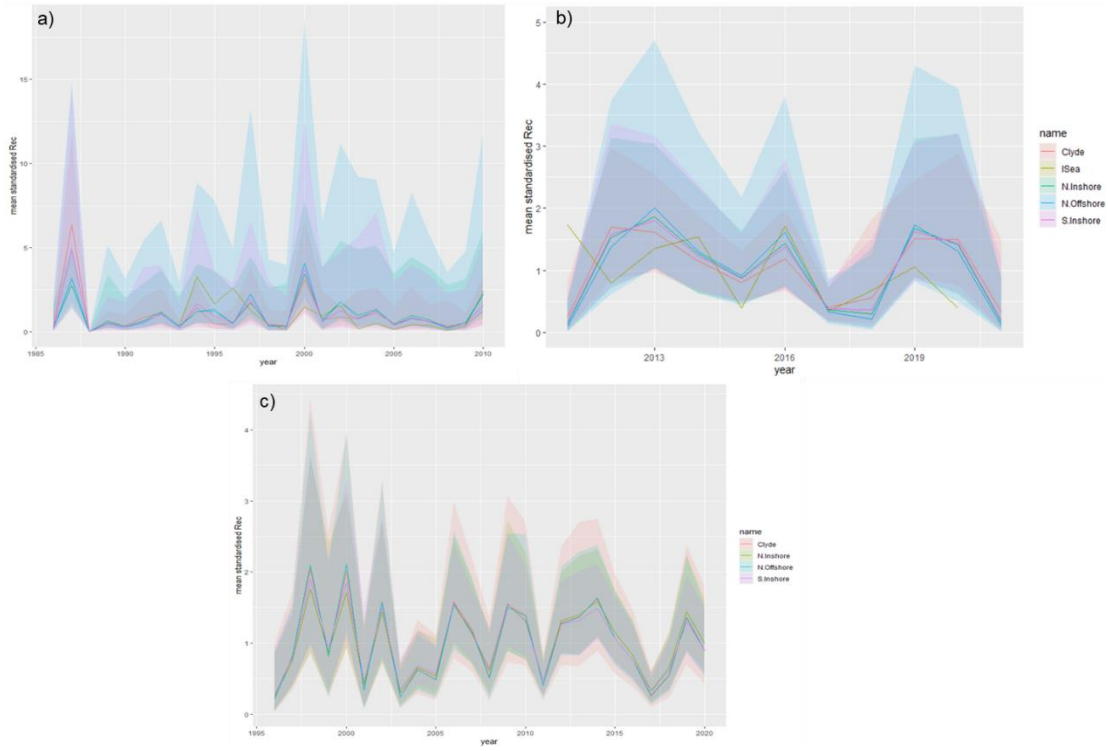

Figure 2.5.2. Mean standardised recruitment indices for each putative sub-population from delta-GAM models using data from a) SWC-IBTS Q1 (Model 3 with delta-logN), b) SCOWCGFS Q1 (Model 2 with delta-logN), and c) all Q4 data: SWC-IBTS, SCOWCGFS & IE-GFS (Model 2 with delta-logN). Irish Sea data (not modelled) are also shown for comparison in a) and b).

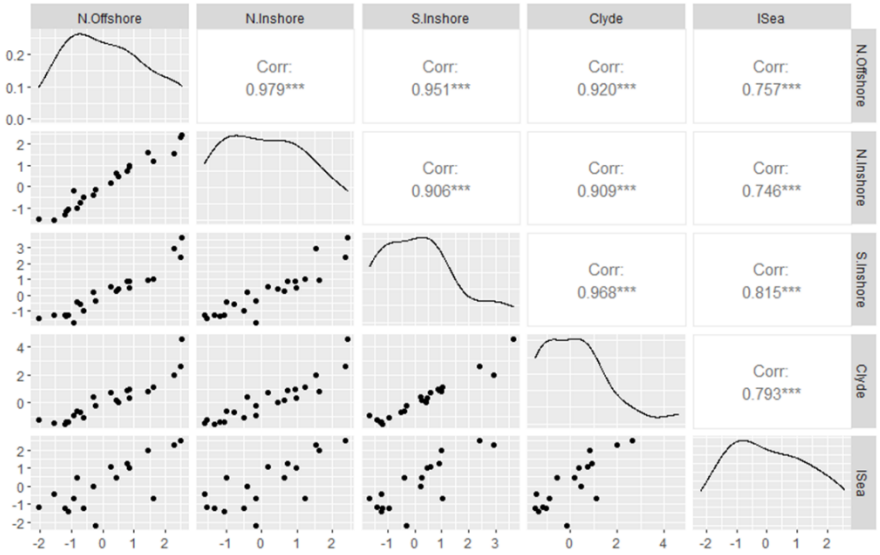

Figure 2.5.3. Correlations between lag-1 year differenced log recruitment indices by putative sub-population from SWC-IBTS Q1. Scatterplots show differenced log recruitment for each pair of sub-populations, the top right (numbers) are the Pearson correlation coefficient and the diagonal plots show the distribution of differenced log index values by sub area.

Summary

While the historical survey data (Q1) show a similar declining picture for SSB across all four sub-populations, there appears to have been a clear divergence in trends in the most recent 10-year

period. The most recent survey data show a recovery in biomass levels in the northern part of Division 6.a with declining/stable trends in the south of the region. The 'windsock' closure (in place since the early 2000s) in the northern part of Division 6.a may have contributed to the increase in SSB in this subarea.

In contrast to the recent differing trends in SSB, the estimated recruitment indices show very little asynchrony and are highly correlated across all subareas. This is also true, although to a slightly lesser degree, for the Irish Sea recruitment data which are not derived as part of the GAM modelling process and are based on data from the Northern Irish Q1 groundfish survey (i.e derived completely independently to the other indices). One explanation for the high correlation in recruitment given differing SSB trends could be that common environmental factors are affecting recruitment across all sub-populations

2.5 Summary and conclusions

Evidence from studies using otolith analyses (shape and microchemistry) and tag-recapture data indicated a complex cod population structure in 6.a. All studies pointed towards differences between inshore and offshore spawning groups in 6.a. Most inshore spawning groups were characterised by a high level of residency, relied on local recruitment and showed little to no mixing with neighbouring areas, even at a small spatial scale (e.g. Minch, Inner Hebrides and Clyde), however, the inshore group to the North of Scotland showed mixing with the Moray Firth in 4.a. Offshore groups to the West of the Hebrides and on Papa Bank showed a larger extent of movement with fish being recaptured from the South West of 6.a to Shetland in the North East (4.a) but did not show much mixing with the inshore groups. Mixing with across the 6.a/4.a limit was evident along the shelf edge with fish moving in both directions but also in inshore waters with also reciprocal movements found between the North of Scotland and the Moray Firth. While otolith shape and otolith chemistry show a strong level of residency for Clyde fish, tagging data suggest possible mixing with Irish Sea cod (7.a) in the Northern Channel and the Northern Irish Sea. Little evidence is available for the South West part of 6.a and while the distinction between inshore and offshore groups is assumed to follow the shelf edge contour (100m contour), uncertainty remains regarding where the limit should be placed in this part of Division 6.a.

The limited genetic evidence provided by these studies points towards a single metapopulation with multiple subpopulations, specifically inshore, offshore and Clyde subpopulations within ICES Division 6.a. These are not isolated populations, instead there appears to be gene flow between subpopulations, but importantly also between adjacent ICES Divisions 4.a and 7.a. Further studies will be required to confirm genetic subpopulation structures within these areas, ideally with multiple temporal replicates to confirm the consistency of these structures across time.

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3 Plausible scenarios for cod stocks West of Scotland and adjacent areas

3.1 Introduction

This section focusses on ToR b).

Using the data provided, WK6aCodID generated hypotheses related to cod population structuring within the west of Scotland (ICES Division 6.a);

- Hypothesis 1: Cod are a closed, homogenous population.
- Hypothesis 2: Cod exist as a metapopulation with overlapping subpopulations (Inshore, Offshore and Clyde units), but not necessarily with areas within ICES Division 6.a.
- Hypothesis 3: Cod exist as multiple overlapping subpopulations related to dogger stocks (between ICES Divisions 4.a and 6.a) and a separate Clyde subpopulation.

The evidence provided to WK6aCodID indicates that cod in the west of Scotland (ICES Division 6.a) are not a closed, homogenous population but exist as distinct subpopulations with connectivity to adjacent ICES cod units. Genetic, otolith and tagging data have highlighted patterns of differentiation among inshore, offshore and Clyde cod (Galley *et al*. 2006; Neat *et al*. 2014; Wright *et al*. 2021). These subpopulations generally inhabit different portions of the west of Scotland, with WK6aCodID proposing boundaries, as well as linkages to adjacent ICES Divisions, for each unit (see Figure 3.1.1) based on the available evidence.

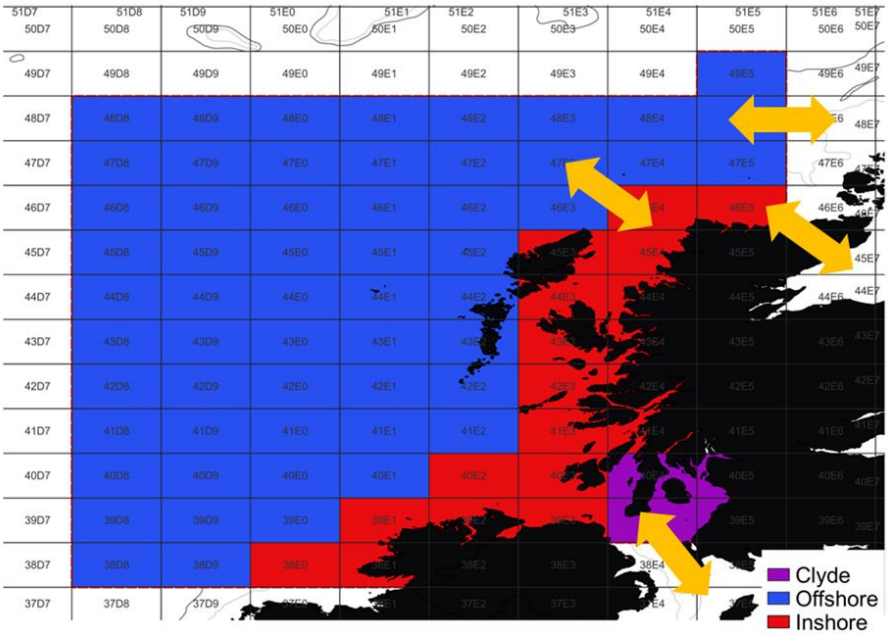

Figure 3.1.1. Putative subpopulations of cod within the West of Scotland ICES Division 6.a. Arrows represent potential mixing between subpopulations and between adjacent ICES Divisions.

3.2 Summary and conclusions

Heath *et al*. (2014) revealed two distinct spatio-genetic cod groups referred to as the "Dogger" (ICES Divisions 4.a, 4.b, 4.c, 6.a and 7.d) and "Celtic" (ICES Divisions 6.a, 7.a, 7.d, 7.e-k) units. Loci for the Celtic cod were found in the western channel, Celtic Sea, Irish Sea and Firth of Clyde, while the Dogger unit centred broadly on cod in the Dogger bank but also encompassing southern and western North Sea, and around the Outer Hebrides. These results highlighted the genetic differentiation between the Clyde and Inshore/Offshore (described by Health *et al*. 2014, as Dogger unit) subpopulations within ICES Division 6.a, but also their connectivity with adjacent advisory units (i.e. Firth of Clyde cod with ICES Division 7.a and Inshore/Offshore cod with ICES Division 4.a). Genetic analysis of north and west Scotland populations also revealed admixture between Dogger cod (ICES Division 4.a) and those inshore and offshore of the Outer Hebrides (ICES Division 6.a) (Wright *et al*. 2021). However, the same study revealed genetic evidence of separate Inshore and Offshore cod subpopulations within ICES Division 6.a (Wright *et al*. 2021). Finally, despite some separation, genetic evidence did not support the idea that Inshore, Offshore and Clyde cod are reproductively isolated populations. Instead, the evidence is suggestive of a metapopulation, whereby migration from one subpopulation to another occurs producing some degree of admixture (Nielsen *et al*. 2009; Heath *et al*. 2014; Wright *et al*. 2021).

Results revealed distinct otolith microchemical signatures related to specific nursery grounds in Buchan, Moray Firth and Shetland (all ICES Division 4.a), and the Minch, Inner Hebrides and Firth of Clyde (all ICES Division 6.a) (Wright *et al*. 2006; Gibb *et al*. 2007). Otolith signatures suggested there was little to no exchange of juveniles between ICES Division 6.a and ICES Division 4.a (Gibb *et al*. 2007). However, based on otolith microchemistry of age-2 cod, possible movement of cod from Shetland to the Inshore subpopulation and from this area to the Firth of Clyde subpopulation was observed. Similarly, Galley *et al*. (2006) used otolith shape to investigate spawning area fidelity of cod occupying multiple areas within ICES Division 6.a. Results from this study observed possible fine-scale stock structures within ICES Division 6.a, with differences in otolith shape between adult cod from Inshore and Firth of Clyde subpopulations (Galley *et al*. 2006).

Several studies have used conventional tag-recapture and digital storage tag (DST) experiments to discern cod movements within ICES Division 6.a, and between adjacent ICES Divisions (Easey 1987; Wright *et al*. 2006; Wright *et al*. 2006; Neat *et al*. 2014; ICES 2020). Easey *et al*. (1987) conventional tagging experiment observed cod released at the boundary between ICES 4.a and 6.a were recaptured in areas consistent with the offshore cod units proposed by WK6aCodID. Summaries from multiple tagging studies suggested reciprocated movement, with cod captured at the Outer Hebrides, associated with the offshore unit, being recaptured in ICES Division 4.a (Easey 1987; Wright *et al*. 2006; ICES 2020). Combining traditional tagging methods with digital storage tags, Wright *et al*. (2006) found cod from inshore and Clyde subpopulations travelled shorter distances suggesting more residential behaviour of these subpopulations. Likewise, a complementary conventional tagging study observed similar results with cod collected from inshore areas of the west of Scotland mainly remaining in these areas or being recaptured relatively short distances within the offshore component of ICES Division 6.a (Wright *et al*. 2006). Alternatively, cod released in offshore areas dispersed longer distances, moving to inshore regions of ICES Division 6.a, as well as sites such as the Moray Firth and Shetland within ICES Division 4.a (Wright *et al*. 2006). Cod from the Firth of Clyde were again observed displaying mainly residential behaviour with little or no migration to inshore or offshore regions recorded (Wright *et al*. 2006), but there was some limited evidence from Neat *et al*. 2017 to suggest that Clyde and Irish Sea cod were mixing between ICES Divisions 6.a and 7.a.

Holmes *et al*., 2014 examined trends in spawning stock biomass (SBB) between ICES 6.a subpopulation boundaries derived from genetic, tagging and otolith microchemistry studies. Trends in SBB suggest the presence of distinct inshore and larger offshore subpopulations within the west of Scotland (Holmes *et al*. 2014). Analysis of more recent survey data (Section 2.4) also suggests asynchrony is SSB trends across subpopulations.

In conclusion, hypotheses 2 and 3 are both supported by the available evidence. However, while scenario 3 is supported by the strongest scientific evidence, treating the Clyde as a separate population is problematic with respect to reconstructing historical catches and undertaking assessments. Over the last two decades of local management with Clyde cod closures, incorporating minimal catches into subpopulations are unlikely to impact assessments at the present time. Given the current weak state of Clyde cod, hypotheses 2 and 3 would be practically indistinguishable in terms of assessment in the short to medium term while investigators continue into the assessment of the Clyde cod and improvement of data availability.

3.3 Future work

Data pertaining to cod population structuring within the West of Scotland was relatively limited. Considerably more data will be required to test our hypothesis for accurate long-term cod stock assessments within ICES Division 6.a. From a genetic perspective, future work applying full genome sequencing with full site and temporal replicates would provide in-depth information regarding subpopulations at finer geographical scales and the stability of these structures across time.

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4 Practical implications of cod stock scenarios

4.1 Introduction

This Section of the report focusses on the ToRs c) and d).

Practical implications for data are considered and recommendations made for a potential data submission.

4.2 Catch data

There are two scenarios with respect to a potential data submission consistent with modelling approaches being considered for the North Sea cod stock (cod in Subarea 4, Division 7.d and Subdivision 20): that data are submitted for the whole of Division 6.a as for the current stock assessment, or data are split into stock components.

In the case of the latter, the workshop suggests two approaches be considered based on data availability and a conversation between data submitters and stock assessors:

a) The preferred option is to separate catches based on rectangles representing inshore and offshore subpopulations (Figure 4.2.1). Due to uncertainty, there are several rectangles that are considered flexible (hatched rectangles in Figure 4.2.1) and could be assigned as either inshore (red) or offshore (blue) based on practical considerations and data availability.

b) If (a) is not possible, to separate catches at a fleet level making the approximation that OTB_CRU represents inshore catches and OTB_DEF offshore catches.

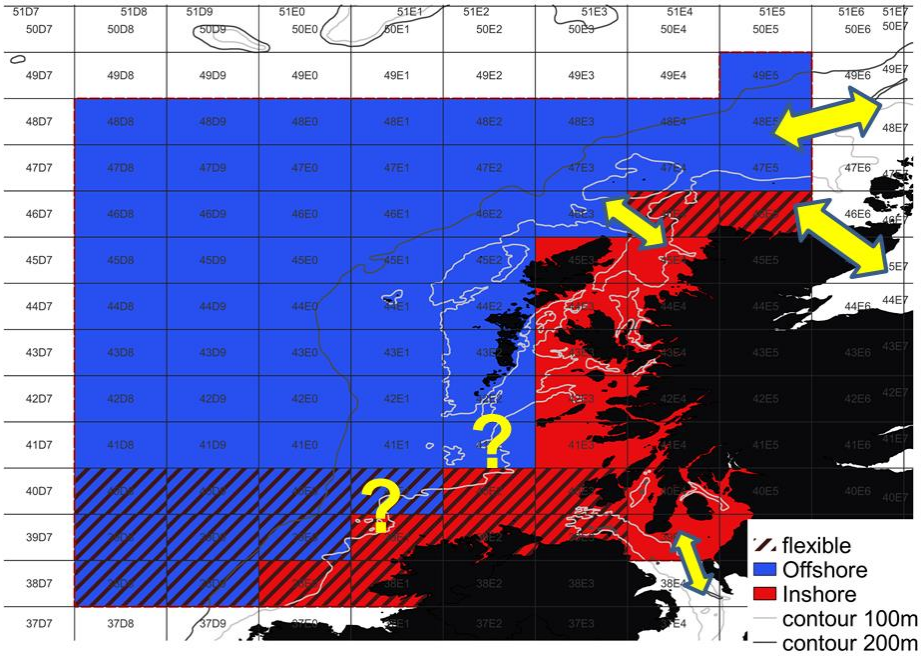

Figure 4.2.1. Rectangles considered inshore of offshore for the purposes compiling fishery and survey data. Flexible rectangles are more uncertain and can therefore be assigned as either inshore or offshore based on practical considerations. Question marks represent uncertainty about the border between the inshore and offshore subpopulations while arrows represent potential mixing both within and outside of Division 6.a.

Assuming a split of the catch data can be achieved, comparisons should be made with the catch data for the whole 6.a stock, as currently used in the stock assessment, to check for quality and consistency. Furthermore, data submitters and stock assessors should agree on a suitable time period for splitting the catch data, considering the current assessment time-series for both West of Scotland and North Sea cod stocks and data quality back in time.

4.3 Survey and biological data

The workshop suggests separating survey and biological data into inshore and offshore components using the rectangles in Figure 4.2.1. The hatched rectangles in Figure 4.2.1 are flexible, as described above, but their assignment should match that used for the catch data if a split of the catch data can be achieved following option (a) above. Subpopulation survey indices could be developed in collaboration with the Working Group on Improving use of Survey Data for Assessment and Advice (WGISDAA).

5 Recommendations for West of Scotland cod

5.1 Introduction

In this Section, WK6aCodID collates their main recommendations which addresses the four ToRs a), b), c) and d).

5.2 Recommendation 1 – population structure

WK6aCodID considered three hypotheses - hypothesis 1: closed homogenous population; hypothesis 2: a metapopulation with overlapping subpopulations (but not necessarily with areas within Division 6.a) (Clyde, Dogger inshore, Dogger offshore) and hypothesis 3: multiple overlapping subpopulations related to Dogger stocks (between Division 4.a and Division 6.a) and a separate subpopulation of Clyde.

While hypothesis 3 provides the strongest scientific evidence, treating the Clyde as a separate population is problematic with respect to reconstructing historical catches and undertaking assessments. Over the last two decades of local management with the Clyde cod closure, incorporating minimal catches into subpopulations is unlikely to impact assessments at the present time.

5.3 Recommendation 2 – stock assessment

Given the current weak state of Clyde cod, hypotheses 2 and 3 would be practically indistinguishable in terms of assessment outcome and the workshop considers hypothesis 2 amenable to stock assessment in the short- to medium-term, while investigations continue into the assessment of the Clyde cod and the improvement of data availability. Given linkages of the inshore and offshore subpopulations to cod in Division 4.a, it is recommended to combine the North Sea and West of Scotland cod assessments in a future benchmark.

5.4 Recommendation 3 – data submission

The workshop elaborated two scenarios with respect to a potential ICES data submission consistent with the modelling approaches being considered for the North Sea cod stock (cod in Subarea 4, Division 7.d and Subdivision 20); namely, either that data are submitted for the whole of Division 6.a as for the current ICES stock assessment, or that data are split into stock components as defined under hypothesis 2 (and hypothesis 3). In the latter case, WK6aCodID suggests that two approaches be considered based on data availability and a conversation between ICES national data submitters and ICES stock assessors.

ICES data submitters and ICES stock assessors should agree on a suitable time period for data splitting; considering the current assessment time-series for both West of Scotland and North Sea stocks and data quality back in time.

5.5 Recommendation 4 – future road-map

WK6aCodID noted that there is potential for much reshaping of Atlantic cod stock assessments currently with the four principal cod assessments (Celtic Sea, Irish Sea, West of Scotland and North Sea) presently exhibiting issues. Primarily these revolve around continued low catch

tonnage, which translates into low catch numbers-at-age resulting in increased uncertainties in assessments. To investigate and review further, the workshop proposes that a planned approach be developed within ICES, through initial road-mapping for improving assessments and the basis for advice; based on these principal assessments and then more widely within the North-east Atlantic; e.g. cod stocks in Norwegian waters, and including those under the jurisdiction of Canada and the United States of America.

Annex 1: List of participants

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Annex 2: Workshop agenda

Workshop on stock identification of West of Scotland cod
WK6aCodID

29 November – 1 December 2021 (MS Teams - online)

PLEASE NOTE: time table = Copenhagen time

Agenda

29 November (Monday)

11:00-11:30

- Introductions & meeting Terms of Reference (ToRs)
- ICES Code of Conduct and Conflict of Interest (CoI) [All participants to read and inform meeting of CoI]
- Draft agenda

11:30-13:00 [no break]

ToR a:

- Presentation & plenary discussion:

  Thomas Regnier: Otoliths, microchemistry and tagging
  - presentation summarising studies involving otolith shape and microchemistry, tagging studies (those led my MSS and an historic one with key results), a reanalysis of tagging data for NS cod in 2020 and a proposed population structure in Division 6.a based on a review of evidence from different sources at MSS, following a similar approach used in Holmes *et al*. 2014)

  Mathieu Lundy: Review of Celtic Seas and West of Scotland tagging records
  - Background figures produced during an EAMSE-funded cod tagging project in the Irish Sea; compiled by Victoria Bendall as a review of tagging records in ICES Divisions 6.a, 7.a and 7.g.

13:00-14:00 Lunch break

14:00-17:00 [Comfort break 15:30-15:45]

ToR a (continued):

- Presentation & plenary discussion

  David Murray: Summary of genetic data from previous studies on West of Scotland cod and adjacent areas

  Helen Dobby: Sub-stock survey biomass and recruitment trends
  - Trends with an assumed sub-stock definition, not about determining sub-stock definition/stock identification

  Jakob Hemmer Hansen: Figures 2.13 and 2.14 WKNSCodID 2020 report

30 November (Tuesday)

11:00-13:10 [Comfort break 12:00-12:15]

ToR a (continued):
Nicola Walker: North Sea cod mixing with 6.a cod
Helen Dobby: West of Scotland cod - catch data and misreporting
ToR b:

- Plenary discussion

13:00-14:00 Lunch break

14:10-18:00 [Comfort break 16:00-16:15]

ToR b (continued):

- Plenary discussion and drafting

1 December (Wednesday)

11:00-13:00 [Comfort break 12:20-12:30]

ToRs b & c:

- Plenary discussion

13:00-14:00 Lunch break

14:00-16:30 [Comfort break 15:50-16:05]

ToRs c & d:

- Plenary discussion
- Report structure and assignment of tasks
- Next steps