Fisheries and Oceans Canada / Pêches et Océans Canada
Ecosystems and Oceans Science / Sciences des écosystèmes et des océans

Arctic Region and Ontario and Prairie Region

Canadian Science Advisory Secretariat
Science Advisory Report 2023/020

REVIEW OF CANDIDATE STOCK ASSESSMENT FRAMEWORKS FOR THE NORTHWEST ATLANTIC FISHERIES ORGANIZATION SUBAREA 0+1 (OFFSHORE) GREENLAND HALIBUT STOCK

Greenland Halibut, Reinhardtius hippoglossoides*. DFO 2018.*

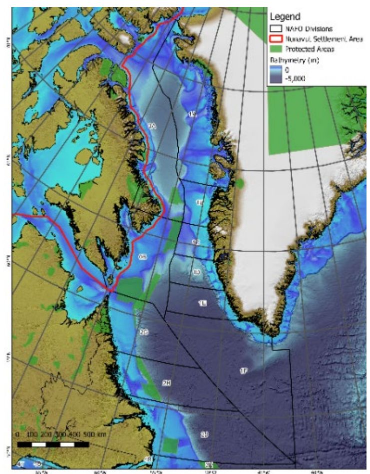

Figure 1. Map of NAFO Subareas 0+1 showing Divisions 0A-B and 1A-F. Red line indicates the boundary of the Nunavut Settlement Area. Established Protected Areas are shown as green polygons.

Context:

Fisheries and Oceans Canada (DFO) Science and the Greenland Institute of Natural Resources (GINR) have conducted multi-species bottom trawl surveys in Northwest Atlantic Fisheries Organization (NAFO) Subareas 0 and 1 to support assessment of the Subarea 0+1 (offshore) Greenland Halibut stock using a GINR research vessel and standardized trawl gear since 1999. In 2018, the GINR research vessel was retired before its replacement vessel was in service, preventing comparative trawl surveys to be completed and thus, bringing to an end the abundance index used to determine allowable exploitation levels since 2001.

Given the absence of paired comparative trawl experiments and subsequent loss of the time series index of abundance, DFO Fisheries Management has requested DFO Science explore analytical method(s) and/or frameworks for the Subarea 0+1 (offshore) stock assessment that could incorporate data collected by multiple vessels and gears, including fishery-independent surveys and commercial fishery data. This review aims to support the NAFO Scientific Council’s assessment of this stock and industry led Marine Stewardship Council certification process.

This Science Advisory Report is from the December 12–15, 2022 Review of Candidate Stock Assessment Frameworks for the Northwest Atlantic Fisheries Organization Subarea 0+1 (Offshore) Greenland Halibut Stock. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule](#) as they become available.

SUMMARY

- The North Atlantic Fisheries Organization (NAFO) Subarea (SA) 0+1 (offshore) Greenland Halibut (GH-0+1) stock had been assessed using an index-based approach based on surveys up to 2017, when the standardized vessel and gear were decommissioned. A new survey time series started in 2022 with a new vessel and gear but will require at least 3–4 data points before an empirical index can be re-established. In the interim, analytical methods are sought to support the provision of Science advice and to evaluate the feasibility of transitioning to a conventional assessment framework over the longer term.
- Fishery-dependent and fishery-independent data relevant to this stock were compiled and used to inform various aspects of population and distribution models. Additionally, a list of potential factors affecting catchability was provided.
- Exploratory modeling work was conducted using an age-structured population dynamics model (Spatially Integrated Statistical Catch-at-Length; SISCAL) and a spatiotemporal stock distribution model (species distribution model in Template Model Builder; sdmTMB). Both approaches showed potential; however, further development will be required for these models to be considered for the provision of Science advice for this stock.
- The exploratory modeling work using SISCAL highlighted some key uncertainties—including stock size, somatic growth and harvest rate—that could be addressed through additional data collection (e.g., additional surveys, tagging).
- Given its potential to provide Science advice in the near term (i.e., for the next NAFO Scientific Council (SC) assessment scheduled in 2024), it is recommended that a model-based survey index calibration method be further investigated. This approach should be tested empirically using a retrospective analysis of the previous survey index, and/or via analysis of existing comparative fishing data from other time periods and regions.
- Concurrently, it is recommended that an age-structured stock assessment continues to be developed, aiming to provide harvest advice and an evaluation of stock status relative to reference points for the NAFO SC assessment in 2026.
- If an acceptable age-structured stock assessment cannot be developed, an index-based management procedure that is simulation tested in a Management Strategy Evaluation (MSE) is considered to be a suitable alternative to provide harvest advice over the longer term.

BACKGROUND

Fisheries and Oceans Canada (DFO) and the Greenland Institute of Natural Resources (GINR) jointly assess the status of Greenland Halibut (*Reinhardtius hippoglossoides*) in Northwest Atlantic Fisheries Organization (NAFO) Subarea (SA) 0+1 (offshore). In order to provide an unbiased index of stock abundance and biomass, DFO and GINR conduct research surveys using the same vessel and fishing gear, and combine the data to conduct a single assessment for the shared stock. The assessment results are presented to, and reviewed by the NAFO Scientific Council (SC) who then provides advice to resource managers in Canada and Greenland regarding sustainable harvest levels.

From 1999 to 2017, the GINR research vessel (RV *Paamiut*) was the sole vessel used to conduct Greenland Halibut surveys for SA 0+1. The RV *Paamiut* was decommissioned in 2018, prior to the launch of the GINR's replacement vessel and before any comparative fishing experiments could be conducted to help mitigate the impacts of transitioning to a new vessel and gear on the survey index data time series.

During this period of transition, without benefit of a standardization experiment between the old and new research vessels, and complicated by a gap in survey data between 2018 and 2021, DFO is exploring the feasibility of developing a new assessment framework and analytical approaches that could be used to provide science-based advice on the status of the SA 0+1 (offshore) Greenland Halibut stock (GH-0+1).

Factors Affecting Assessment of Greenland Halibut

Greenland Halibut is a cold-water species found at depths from near the surface to 2,200 m (Boje and Hareide 1993, Hareide and Garnes 2001), but is mainly found between 500 and 1,000 m (Jørgensen 1997) throughout the Northwest Atlantic. Recent tagging (Vihtakari et al. 2022, Barkley et al. 2018) and genetics (Ferchaud et al. 2022) research have expanded on earlier work (Boje 2002, Roy et al. 2014), indicating that Greenland Halibut in the Northwest Atlantic are highly mobile, moving between inshore and offshore areas, as well as among larger offshore areas, and likely comprise a single population. However, for management purposes this population is divided into two offshore stocks (SA 0+1 offshore and SA2+3KLMNO) and several inshore stocks located in both Canada and Greenland. Splitting a population into multiple stocks complicates management because advice is requested at the stock level, but the reliability of population models is best when they capture dynamics of the whole population. Models developed for a subcomponent of a population artificially divide population processes into interactions or connectivity between stocks, or knowingly ignore larger processes.

The species is long-lived (greater than 30 years) and exhibits sexually dimorphic growth and longevity patterns (i.e., females generally grow to larger sizes and live longer than males) (Gregg et al. 2006, Treble et al. 2008, Dwyer et al. 2016). The timing and locations of spawning are not known precisely due to the remote and difficult conditions that make year-round sampling impossible. However, available data point to a major spawning area in or near the Davis Strait, south of the ridge between Canada and Greenland that separates Baffin Bay and the Labrador Sea (Simonsen and Gundersen 2005, Gundersen et al. 2010). Greenland Halibut have an unusual reproductive strategy in that egg development is a multi-year process, so that females have two sizes/groups of eggs that are not spawned in the same year (Kennedy et al. 2011, Rideout et al. 2012). There have also been observations of large females that do not have any developing eggs, suggesting a portion of the population is resting or there is a prolonged juvenile phase (Junquera et al. 2003, Gundersen et al. 2010). These factors make it difficult to predict the reproductive potential of a population/stock (i.e., estimates of spawning stock biomass).

Young Greenland Halibut, ages 0–3 years, are captured during the GINR fish and shrimp survey that occurs at depths 50–800 m along the West Greenland coast (Divisions 1A-F) using a Cosmos shrimp trawl. A majority of Greenland Halibut caught in this survey are age-1 (Treble et al. 2022). The primary survey used to establish the Greenland Halibut abundance and biomass indices occurs at deeper depths, 400–1500 m, and used an Alfredo groundfish trawl (in 2022 this was replaced with a Bacalao trawl). This trawl gear catches some large female Greenland Halibut, but the selectivity is dome shaped around 50–55 cm, so this survey does not provide sufficient data to estimate spawning stock biomass and to date it has not been possible to establish a correlation between abundance of age-1 fish in the 1A-F survey and abundance in the offshore 0A-South+1CD survey or the fishery catches (Treble et al. 2022). This gear selectivity also limits the ability to estimate fishing mortality using conventional methods. Population dynamics models rely on the ability to make reasonable assumptions about factors such as growth (size at age), mortality, productivity, and maturity rates (skip spawning). Given some of the gaps or uncertainties in our knowledge of Greenland Halibut biology and the limitations in the available survey data, some model assumptions may be easier to meet than others and proxies or other approaches may be necessary.

Factors Affecting Catchability

Catchability is a concept in fishery biology that reflects the efficiency of a particular fishery or vessel and gear to capture individual species (Arreguín-Sànchez 1996). The following table was developed to identify factors that can contribute to differences in catchability of Greenland Halibut and other fish and invertebrate species (Table 1).

Note that some surveys (e.g., the Canadian Northern Shrimp Research Foundation survey) have operated under the assumption that inter-vessel comparability can be achieved by maintaining gear consistency and tow characteristics (tow speed, sensors to monitor net geometry) (Hedges and Raffoul 2023). However, in the case of DFO and GINR multispecies surveys in SA0+1, significant inconsistencies in tow characteristics between vessels were found which precludes the ability to make this assumption (Nogueira and Treble 2020).

Table 1. Factors that affect catchability during surveys and fishing.

Factor Category	Example Factors	Potential Impact
Vessel	Horsepower, size, age, noise, trawling speed, tow duration	Affects trawl avoidance behaviour, frequency of hang-ups, trawl damage
Vessel stern morphology	Width of stern	Affects ability to fish in ice and rough conditions
Trawl	Design, dimensions, material, mesh size (liners), colour, footgear	Affects trawl avoidance behaviour, minimum size retained, length frequency, frequency of hang-ups and damage
Trawl sensors	Presence or absence	Use of sensors can improve consistency in trawl morphology and bottom contact
Captain/crew	Crew size, vessel/gear experience, local knowledge	Consistency in bottom contact, trawl morphology, inconsistency in handling/gear repair
Environmental conditions	Sea and/or ice state, bottom type, currents, light, depth	Consistency in bottom contact, trawl morphology, facilitates trawl avoidance
Species	Size, morphology, distribution, behaviour (seasonality)	Trawl avoidance, species availability

ASSESSMENT

Greenland Halibut SA 0+1 Data

Data from several research surveys conducted in the offshore waters of SA 0+1 were used for analysis in the modeling exercises. DFO and GINR have conducted depth stratified random surveys in deep waters of Divs. 0AB and 1CD, respectively, using an Alfredo III groundfish trawl and GINR also conducts a depth stratified random coastal/shelf survey in Divs. 1A-F using a Cosmos shrimp trawl (Tables 2 and 3, Figure 2).

Table 2. Surveys conducted in the offshore waters of SA 0+1 used for analysis in the modeling exercises. See Table 3 for information on years covered by each survey.

Name (Code)	Area	Vessel(s)	Gear	Depth range	Period
DFO Multispecies (RV_0A)	Division 0A-South of 72° N	*Paamiut*	Alfredo trawl	400–1500 m	2 weeks between late September and mid-November
		Helga Maria			2 weeks in August 2019
GINR Multispecies (RV_1CD)	Divisions 1C-D	*Paamiut* *Helga Maria*	Alfredo trawl	400–1500 m	2 weeks in August or September
GINR Shrimp and small fish (RV_SFW1AF)	Divisions 1A-F	*Paamiut* *Sjurdarberg* *Helga Maria*	Cosmos trawl	50–700 m	4 weeks between July and August

Table 3. Surveys completed each year: deep water (green) and coastal/shelf water (orange). Differences in shading indicate different vessels were used for the survey. Letter codes indicate vessel and gear used: PAA – Paamiut with Alfredo trawl; HMA – Helga Maria with Alfredo trawl; PAC – Paamiut with Cosmos trawl; SUC – Sjurdarberg with Cosmos trawl; HMC – Helga Maria with Cosmos trawl.

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
DFO 0A-South	PAA	-	PAA	-	-	PAA	-	PAA	-	PAA	-	PAA	-	PAA	-	PAA	PAA	PAA	PAA	-	HMA	-
GINR 1CD	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	PAA	-	HMA	-
CINR 1AF	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	PAC	SUC	HMC	HMC

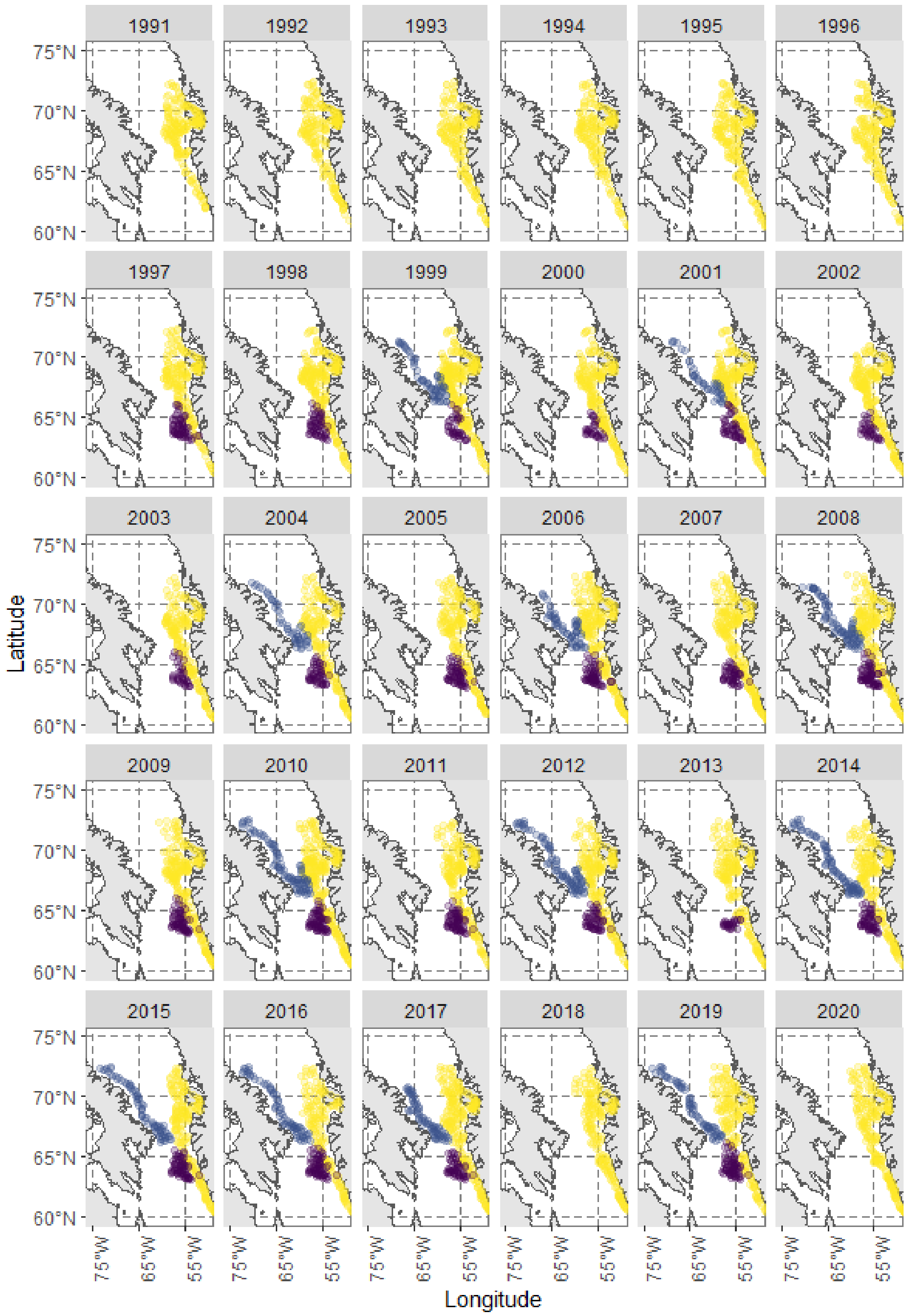

Figure 2. Survey coverage by year from 1991 to 2020, DFO Div. 0A-South (blue), GINR Divs. 1C-D (purple) and GINR Divs. 1A-F (yellow).

In addition to data from science surveys, commercial fishing effort and catches are recorded in logbooks, and in Canada, at-sea observers (ASO) collect length, weight, sex, and age samples. In Div. 0A, all vessels commercially fishing Greenland Halibut are required to have an ASO on board (100% observer coverage). In Div. 0B, all trawl vessels fishing for Greenland Halibut are required to have an ASO on board, as are 20% of gillnet vessels. The various types of fishery-dependent and fishery-independent data each year are shown in Figure 3.

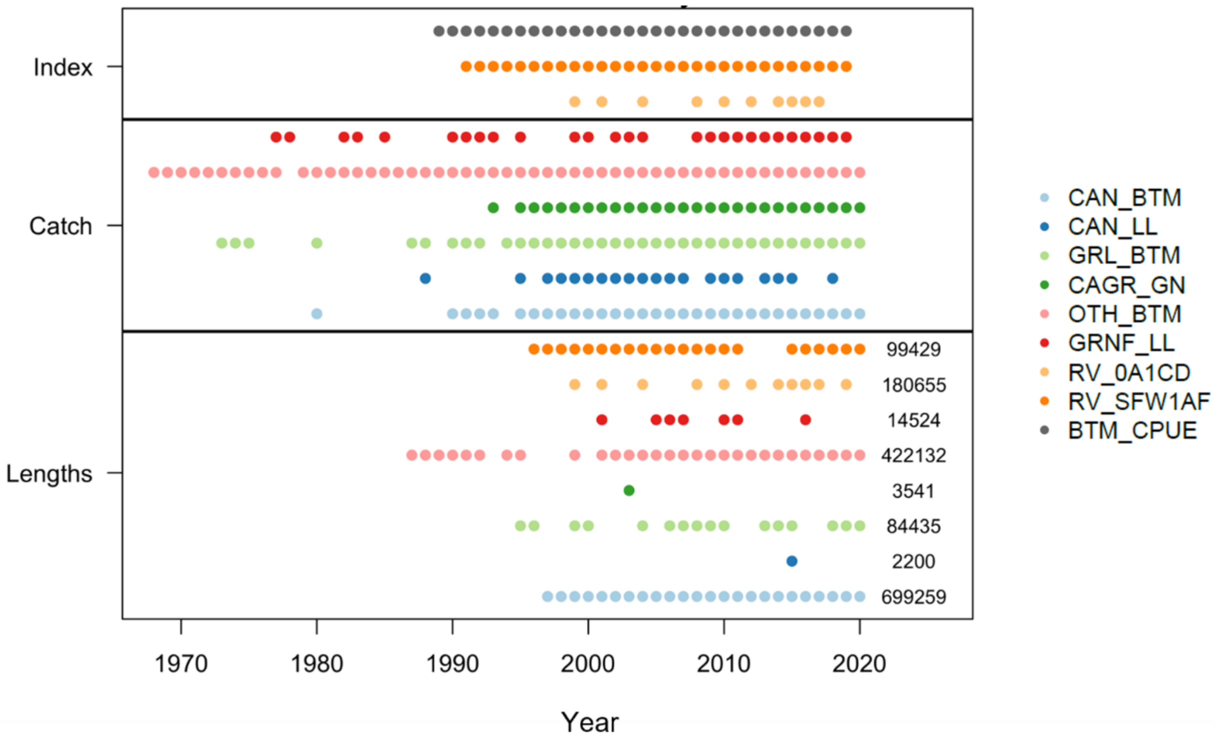

Figure 3. Summary of available index, catch, and length-composition data used in the analysis of Greenland Halibut in SA 0+1, 1968–2020. Points indicate the presence of data in each year (x-axis) and fleet (colours explained in figure legend). For length composition data, the total sample size (all years combined) is shown at the right hand end of the panel (Johnson and Cox 2023). CAN_BTM = Canada Bottom Trawl; CAN_LL = Canada Longline; GRL_BTM = Greenland Bottom Trawl; CAGR_GN = Canada Greenland Gillnet ; OTH_BTM = Other Bottom Trawl; GRNF_LL = Greenland Norway Faroe Islands Longline; RV_0A1CD = Research Vessel 0A1CD Survey; RV_SFW1AF = Research Vessel Shrimp and Fish West Greenland 1AF; BTM_CPUE = Bottom Trawl Catch per Unit Effort.

Greenland Halibut caught in surveys are sampled for length, sex, maturity, and otoliths are collected for age estimation. At-sea observers also collect length, sex, and otoliths from fish caught in the commercial fisheries. Greenland Halibut are difficult to age and researchers have been working for many years to develop and validate age estimation methods for this species (Gregg et al. 2006, Treble et al. 2008, Albert et al. 2009, Albert 2016, Dwyer et al. 2016, Brogan et al. 2021). The growth curve developed for this analysis was based on sub-samples of 365 and 326 otoliths collected during the 2014 and 2017 surveys, respectively.

Analytical Frameworks: Two Illustrative Case Studies

The available data was used to inform two different analytical approaches to illustrate the feasibility of using these methods in the GH-0+1 context. An overview of each approach follows.

Development of Spatial Operating Models to Test Survey Design and Calibrate A New Survey Index

Huynh and Carruthers (2023) developed a spatial operating model and demonstrated how the model could be used to simulate population dynamics for GH-0+1 by using various software packages, including SimSurvey (Regular et al. 2020), sdmTMB (Anderson et al. 2021), and the age-structured rapid conditioning model in SAMtool (Huynh et al. 2023). The results were used to compare two indices of abundance (0A-South+1CD, 0AB+1CD) that differed in spatial coverage.

The simulation (operating) model (referred to as GH-sdmTMB) consisted of two parts: i) a simple age-structured population dynamics model, conditioned on fishery monitoring data, and ii) a spatio-temporal generalised linear mixed model (GLMM) that functions as a species distribution model (SDM) by fitting to density (numbers-per-unit-effort) data from the surveys in Divisions 0A and 1CD and using bathymetry data to predict spatial distribution for the GH-0+1 stock area. In each year, numbers-at-age are spread out across the stock area according to yearly proportions estimated by the species distribution model, and a simulated survey is conducted by sampling the spatially distributed Greenland Halibut population, assuming observations are binomially distributed with parameters taken from the population, prior survey catchability, and swept area.

A subsequent analysis evaluated the ability of the SDM to estimate a calibration factor without the benefit of data from comparative tow studies. Calibration would facilitate extension of a new index using the time series from the previous vessel (RV *Paamiut*). The analysis used data from the 2019 FV *Helga Maria* survey in 0A-South and 1CD (i.e., data obtained with a different vessel but using the same gear) to calibrate the 2019 index value and continue the old index series (which is based on the previous RV *Paamiut* surveys in the same area and depth strata). The model estimated lower catchability for deeper depth strata, supporting previous analysis (Nogueira and Treble 2020), although this effect could also have been confounded by a difference in timing of the 2019 survey. Possible future application of this method (e.g., calibration of the RV *Tarajoq* relative to the RV *Paamiut*) will need to be supported by additional work, including simulation analysis and validation from case studies using data from previous comparative fishing experiments in other areas and times.

Development of a Spatially Integrated Statistical Catch-At-Length (SISCAL) Operating Model and Assessment Framework

Johnson and Cox (2023) presented an example of an end-to-end (data-to-advice) assessment modelling framework. Initially, a statistical catch-at-age model was developed, integrating all available fishery monitoring and survey data into a Spatially Integrated Statistical Catch-At-Length (SISCAL) operating model for the GH-0+1 stock (referred to as SISCAL-GH). The model was validated using standard goodness of fit metrics, assessment of retrospective model behaviour, and sensitivity analyses. Subsequently, the SISCAL operating model was used to demonstrate how this type of framework could be used to:

1. Estimate GH-0+1 stock status and biological reference points from fishery and survey data;
2. Simulation test the assessment model to better understand the range of estimation performance (i.e., bias and precision of estimates) given the available data types, quality and quantity; and,
3. Condition the operating model to simulation test precautionary harvest strategies.

As a final demonstration, the performance of a hypothetical adaptive model/index-based management procedure was assessed using the SISCAL-GH operating model in a closed loop simulation framework and compared to the relative performance of a non-adaptive index-based management procedure.

Considerations for Model Development

Given the high cost and complexity of implementing research surveys, the ability to evaluate survey design and assess expected abilities to estimate population trends prior to implementation is highly desirable and can be used to justify changes to a more effective sampling protocol or assessment regime when warranted.

Both the GH-sdmTMB and SISCAL-GH approaches were based on a similar overall framework, illustrated in Figure 4. While both approaches involved the development of plausible operating models, only the SISCAL-GH approach demonstrated the full closed-loop functionality of the simulation framework.

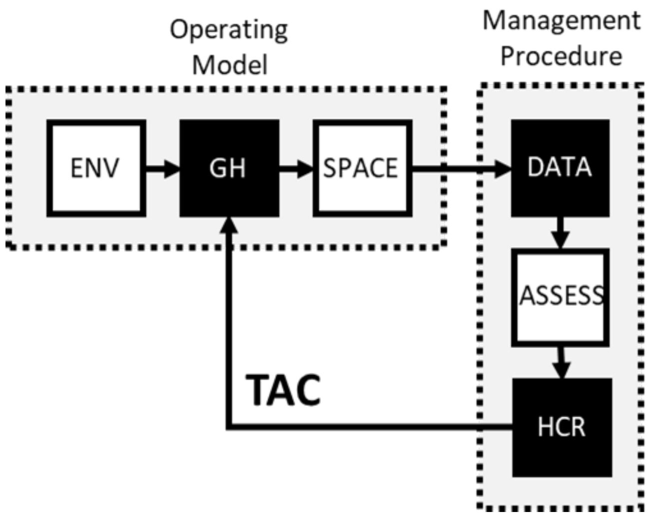

Figure 4. Overview of a data-to-advice assessment framework. The Operating Model (OM) is comprised of a catch-at-length population model for Greenland Halibut (GH) and parameters for associated Environmental effects, process error, etc. (ENV). The GH-sdmTMB OM also contained a Species Distribution Model (SPACE) component. The Management Procedure uses sample data generated by the OM, conducts the stock assessment and applies a Harvest Control Rule (HCR) to determine the Total Allowable Catch (TAC), as demonstrated by the SISCAL-GH approach. Through appropriate simulation, this type of closed loop simulation framework can be used to test a range of hypotheses and model assumptions (as demonstrated by Johnson and Cox 2023). Black boxes are required in a closed-loop management strategy evaluation framework while white boxes are optional.

Choice of Operating Model Structure

The choice of operating model structure varies depending on the type of data available to inform the model and the range of uncertainty underlying the data (although the potential impacts of various sources of uncertainty can be evaluated through sensitivity analyses). While there are model structures more suitable for data-limited situations that could be used for the GH-0+1 stock, it was determined through this exploratory work that there was sufficient data to inform more data-rich approaches such as the two operating models outlined above (i.e., statistical catch-at-age assessment models, either with or without inclusion of a spatially explicit species distribution model).

The two approaches outlined here were aimed at testing very different parts of the GH-0+1 fishery system. As such, there were several differences in the way that each approach used the data, as well as the resulting inferences and recommendations derived from each model. However, both approaches were centred around a general age-structured population dynamics model and it is worthwhile comparing the overlapping components, which had two main differences. First, SISCAL-GH used time-varying mortality and catchability parameters, making SISCAL-GH more flexible (to better fit to fishery CPUE data) while the GH-sdmTMB population dynamics sub-model excluded that data series. Second, both models treated spatial variability differently. Where possible, SISCAL-GH split catches into fleets corresponding to nations in an areas-as-fleets approach, which fished in distinct areas, to implicitly reflect differences in fish availability over space. In comparison, GH-sdmTMB aggregates all catch by gear type, excluding spatial variation in GH-0+1 data from the population dynamics model component. Instead, spatial variation is isolated to the species distribution model component and therefore reflected in simulated GH-sdmTMB abundance indices.

Despite these differences, the population dynamics model component of GH-sdmTMB was demonstrated to give similar results to SISCAL-GH when fit to similar data (and some estimates from SISCAL-GH). Similar results between the two models provided additional insight into the consistency in general population dynamics parameters consistent with the available data (regardless of model structure), including key uncertainties. Ultimately, the choice of model structure is expected to evolve iteratively as additional data and information become available, and objectives become clearer. While the population dynamics components of both approaches give consistent results, they are aimed at solving distinct problems and have only been reviewed with respect to their distinct solutions. The SISCAL-GH approach is aimed at performing stock assessments and simulation testing feedback harvest strategies, and has been reviewed in that context. Based on participant comments during the peer-review, additional thought may be required to define a range of plausible operating models for harvest strategy testing. In contrast, the GH-sdmTMB approach is aimed at simulating alternative survey designs and has been reviewed in the context of providing possible survey calibrations; however, the population dynamics component of GH-sdmTMB has not been reviewed as an assessment or as an operating model for testing harvest strategies, and additional work would be required to achieve that functionality (including further peer review of those components).

Testing the Validity of the Model

Model misspecification can have serious consequences for any subsequent application of the model (e.g., to generate science advice and/or inform management actions). A number of methods, including but not limited to those outlined below, should be employed to assess the suitability of any model prior to its broader use.

Goodness of Fit, Retrospective Analyses and Simulation Self-testing

Standard statistical goodness of fit measures can be used to provide preliminary confidence in the suitability of the operating model based on available data (i.e., by examining model residuals for evidence of undesirable patterns or properties). Given the large number of parameters, assumptions and choices underlying an assessment model, these metrics alone are likely insufficient to assess the overall ability of the model to represent the real-world dynamics of the GH-0+1 stock.

Retrospective analyses provide assessments of the stability of the model estimates and are performed by fitting the same model to successive ‘peels’ of data going back in time (i.e., leaving out a year and refitting the model). Resulting estimates of key model parameters (e.g., spawning biomass time series, unfished biomass, unfished recruitment, natural mortality, and stock-recruit steepness) from each peel are compared to evaluate the effect of new data on model equilibria.

Simulation self-testing can be used to test an operating model's ability to reproduce key model parameter estimates when it is re-run using "new" data simulated from the model (i.e., with new observation errors). Self-test performance is assessed through standard measures of bias and precision of the estimates produced by simulation self-testing.

Sensitivity Analyses

Sensitivity analyses are used to test how robust a model is to its key assumptions. For example, changes in model outputs (e.g., estimates of unfished biomass, unfished recruitment, optimal biomass, optimal harvest rate, and/or maximum sustainable yield) can be compared between models that use different underlying assumptions about model parameters. Examples include examining the use of time-varying or constant parameters; choice of priors for asymptotic length, natural mortality, or steepness of the stock-recruit curve; treatment of length composition data; or whether to use a sex-structured model or not.

Refer to Johnson and Cox (2023) for examples of the model validity tests and sensitivity analyses described here.

Use of Simulation

Simulation can be used to test a range of hypotheses or options. For example, Huynh and Carruthers (2023) used a simulation approach to compare the outcomes of two operating models that varied in their spatial coverage to decide if increased spatial coverage could be expected to yield better population estimates. More generally, operating models used in a closed loop simulation framework were found to provide a practical and realistic representation of GH-0+1 stock dynamics, fishery harvesting processes, and fishery monitoring data so that non-linear feedbacks and data uncertainties could be accounted for in annual Total Allowable Catch (TAC) advice (Johnson and Cox 2023). These processes interact to determine short- and long-term performance of fishery harvest strategies with respect to (hypothetical) fishery objectives. Note that selecting an appropriate range of operating models to evaluate management procedure performance can be informed through sensitivity analyses, as described above (e.g., the range of operating models should include a variety of plausible assumptions for parameters that are found to impact model outcomes significantly).

Closed loop simulation testing uses an operating model (such as those outlined above) in an iterative framework to test the relative expected future performance of one or more management procedures (Figure 4). In contrast to conventional stock assessment, closed-loop simulation incorporates feedback between the implementation of management procedures and the system representing the fish stock and its environment, described by one or more operating models. Generally, the simulation starts with the outputs of the assessment model, using it to calculate a recommended catch limit, applying the catch limit to a simulated fishery, and then repeating the assessment-to-fishery cycle for a specified number of years into the future (Figure 4). Replicating this process a sufficient number of times (e.g., 100 replicates, in the case of the demonstration in Johnson and Cox (2023)) allows for the calculation of quantitative performance statistics across all replicates.

Other Model Considerations

Decisions around what data to include are important and will affect the choice of model structure. The data should be representative of the population or stock over the time series. Start and end years need to be determined, although the latest year of data should not make a big difference to the model outputs. In the case of GH-0+1, fishing began in the late 1960s and the longest survey time series started in the late 1990s.

Management Strategy Evaluation

The example operating models and data-to-advice assessment framework demonstrated through this review could be used to inform a full, peer-reviewed Management Strategy Evaluation (MSE), where a fully specified "management strategy" includes consideration of survey design, assessment and harvest control rules. MSE builds upon the closed loop simulation approach outlined in this review by enabling the systematic assessment of management strategy performance over a select number of strategies and plausible operating models. Further, extending the current work to undertake closed-loop projections in an MSE framework would also allow for robustness testing of management strategies (combined survey design, assessment and harvest control rules) under changing ocean conditions, for example systematic spatial shifts due to climate change.

An MSE approach aims to identify strategies that provide satisfactory performance over the range of operating models being considered (i.e., demonstrates they are robust to different assumptions about how the underlying system operates), or perhaps more importantly, removes from consideration any strategies that are shown to perform poorly under one or more operating models. In addition, a full MSE process enables participants (i.e., co-management partners, stakeholders, or more generally, anyone with an interest in the stock) to contribute to decisions about the fishery objectives, management strategies and associated performance metrics included in the evaluation. As MSE and MSE-like approaches have become more common in fisheries stock assessments, best practices have emerged that can guide practitioners in the future application of this approach for this stock (e.g., Punt et al. 2016).

Sources of Uncertainty

The impact of assumptions and data on model estimates can be evaluated by using appropriate sensitivity analyses (outlined above).

Preliminary sensitivity analyses showed that uncertainty in stock size and associated effects on estimates of current harvest rate are key factors in determining stock status. Other key uncertainties included natural mortality, growth, and gear selectivity.

Key gaps that could be addressed by additional, targeted data collection and further analyses include:

- additional length-at-age sampling, particularly of large Greenland Halibut (i.e., that are poorly sampled by current trawl surveys) to inform estimates of selectivity and growth, allowing improved characterization of unobserved biomass occurring in deep water (e.g., additional length-at-age data from the gillnet fleet, adding a new deep water longline survey);
- collection of gonad samples to evaluate the accuracy of macroscopic field estimates of skipped spawning, and to examine its frequency and potential impact on stock reproductive potential;
- studies to better estimate total mortality and understanding of population movement through the management areas;
- expanded ageing work and development of an ageing error matrix to inform variability in age observations and improved estimates of recruitment and mortality.

Spatial models become increasingly uncertain as they extrapolate beyond the survey footprint (including depth). Tools like SimSurvey (Regular et al. 2020) can be used to optimize survey design given logistical constraints.

CONCLUSIONS AND ADVICE

This work has demonstrated that there is sufficient fishery-dependent and fishery-independent data for GH-0+1 to develop plausible operating models that can explore hypotheses regarding stock abundance and the spatial distribution of the stock.

Exploratory modeling work was conducted using an age-structured population dynamics model (SISCAL-GH) and optionally, a spatiotemporal stock distribution model (GH-sdmTMB). Both approaches showed potential; however, further development will be required for these models to contribute to the provision of Science advice for this stock.

Given its potential to provide advice in the near term (i.e., for the next NAFO Scientific Council (SC) assessment scheduled in 2024), it is recommended that a model-based survey index calibration method be further investigated. This approach should be tested empirically using a retrospective analysis of the previous survey index, and/or via analysis of existing comparative fishing data from other time periods and regions.

Concurrently, it is recommended that an age-structured stock assessment model continues to be developed, aiming to provide harvest advice and an evaluation of stock status relative to reference points for the NAFO SC assessment in 2026.

If an acceptable age-structured stock assessment model cannot be developed, an index-based management procedure that is simulation tested in a full, peer-reviewed MSE is considered to be a suitable alternative to provide harvest advice over the longer term.

It is recommended that work towards these objectives begin with research documents prepared for presentation and discussion at the NAFO SC meeting in June 2023, including new data from the 2022 surveys on the RV *Tarajoq*.

OTHER CONSIDERATIONS

An appropriate simulation-based assessment framework can be used to test many aspects of stock, fishery and/or assessment dynamics. For example, such a framework could be used to assess potential impacts from environmental changes (e.g., changes in the ocean temperature regime, currents and/or food web dynamics), optimize survey designs (e.g., to find the optimal set density per strata to minimize overall survey variance), assess potential value of information gained from additional sources of data (e.g., adding a deep water survey, oceanographic information), and allow exploration of appropriate reference points.

Additional data collection programs will help provide a more comprehensive understanding of the SA 0+1 (offshore) Greenland Halibut stock. In 2017, DFO commenced an annual survey to collect oceanographic, primary productivity and prey availability data in Div. 0A-south. These data will support environmental monitoring and inform stock assessments in the area, including future assessments of the Greenland Halibut SA0+1 stock. In addition, the Ocean Tracking Network (OTN) has been using acoustic and satellite tags to assess movement patterns, habitat use and individual behaviour in Greenland Halibut since 2010. DFO is a partner on the OTN projects in Baffin Bay and the resulting data are improving our understanding of stock structure and connectivity among fishing areas.

Given the deep and remote habitats used by Greenland Halibut, several demographic and life-history parameters have not been determined for the SA 0+1 (offshore) stock (e.g., age, selectivity, estimates of total mortality (Z), or natural mortality (M)). When developing population models, values for these parameters need to be borrowed or extrapolated from other stocks. Survey and commercial fishing also do not collect animals throughout their full habitat range; in particular, Greenland Halibut are not caught or sampled from the deepest waters of Baffin Bay and Davis Strait, where it is too deep to trawl.

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Kris Vascotto	Atlantic Groundfish Council
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SOURCES OF INFORMATION

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ISSN 1919-5087
ISBN 978-0-660-48671-0 N° cat. Fs70-6/2023-020E-PDF

Correct Citation for this Publication:

DFO. 2023. Review of candidate stock assessment frameworks for the Northwest Atlantic Fisheries Organization Subarea 0+1 (Offshore) Greenland Halibut stock. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2023/020.

Aussi disponible en français :

MPO. 2023. Examen des cadres d'évaluation des stocks candidats pour le stock de flétan du Groenland dans la sous-zone 0+1 (au large des côtes) de l'Organisation des pêches de l'Atlantique Nord-Ouest. Secr. can. des avis sci. du MPO. Avis sci. 2023/020.