Fisheries and Oceans Canada | Pêches et Océans Canada
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Canadian Science Advisory Secretariat
Maritimes Region **Science Response 2023/017**

STOCK STATUS UPDATE OF ATLANTIC COD (*GADUS MORHUA*) IN NAFO DIVISIONS 4X5Y FOR 2022

Context

In the Canadian Atlantic, Atlantic Cod (*Gadus morhua*) ranges from Georges Bank to northern Labrador. There are several concentrations of Atlantic Cod within this range, including those on the southern Scotian Shelf and Bay of Fundy in Northwest Atlantic Fisheries Organization (NAFO) Divisions 4X and 5Y. In 2010, the Committee on the Status of Endangered Wildlife in Canada assessed the southern population unit (4X5YZjm) as Endangered, and a Recovery Potential Assessment was completed in 2011 (DFO 2011). The latest 4X5Y Atlantic Cod stock assessment was conducted in 2018, along with a framework assessment which included a review of data inputs, ecosystem information, modelling approaches, and data-limited approaches. The last stock status update was provided in 2020. Fisheries and Oceans Canada (DFO) Fisheries Management has requested that DFO Science apply the modelling approach developed in 2018 with updated survey and catch indices to provide catch advice.

This Science Response Report results from the Regional Peer Review on the Update of Stock Status for Cod in 4X5Y held on December 6-7, 2022.

Summary

- 4X5Y Atlantic Cod landings have remained below the bycatch Total Allowable Catch (TAC) of 825 mt in recent years, with landings of 507 mt in 2020 and 630 mt in 2021.
- Both the 4X5Y Atlantic Cod commercial and survey catch at age have shown a truncation in age structure since the 1990s.
- Survey biomass and Age 1 abundance indices from the DFO Summer Research Vessel survey remain low in the past three years surveys were conducted.
- Results from the accepted 3MFfirst Virtual Population Analysis (VPA) model fit to updated survey and catch indices showed 4X5Y Atlantic Cod underwent a decline after a relatively stable period in the 1980s and 1990s and has remained at low levels in the last decade.
- The 2022 beginning of year estimate of Spawning Stock Biomass (SSB) from the VPA model is 4,918 mt. This value is below the Limit Reference Point of 22,193 mt meaning this stock remains in the Critical Zone.
- The latest levels of recruitment for the 2020 year class estimated by the 3MFfirst model for this stock was 1.6 million individuals.
- Fishing mortality (F) shows a step-wise decline for fully-recruited ages after 1994, which is consistent with management measures implemented over the past three decades. The most recent estimate of F is 0.12.
- Natural mortality (M) has increased over time for older fish (Ages 5+) and appears to have stabilized at high levels in the past 5 years, with the latest 5-year average of M estimated at 1.64.

- Projections from the model estimate indicate that SSB will remain relatively stable over the next three years, both with a status quo bycatch TAC and in the absence of fishing.

Background

Atlantic Cod (*Gadus morhua)* is a bottom-dwelling species that has a broad distribution in the western Atlantic, with several concentrations along the Canadian Atlantic coast. Atlantic Cod in the NAFO Divisions 4X and the Canadian portion of 5Y exhibit two different growth rates: a faster-growing component in the Bay of Fundy (NAFO areas 4Xqrs5Yb), and a slower-growing component on the Scotian Shelf (4Xmno; Figure 1). NAFO Division 4Xp is considered a mixing area for these two components, as fish caught in 4Xp exhibit characteristics of both growth curves (Andrushchenko et al. 2022). Although the two-stock component structure within 4X5Y persists through time, they have been managed and assessed as a single unit since 1985.

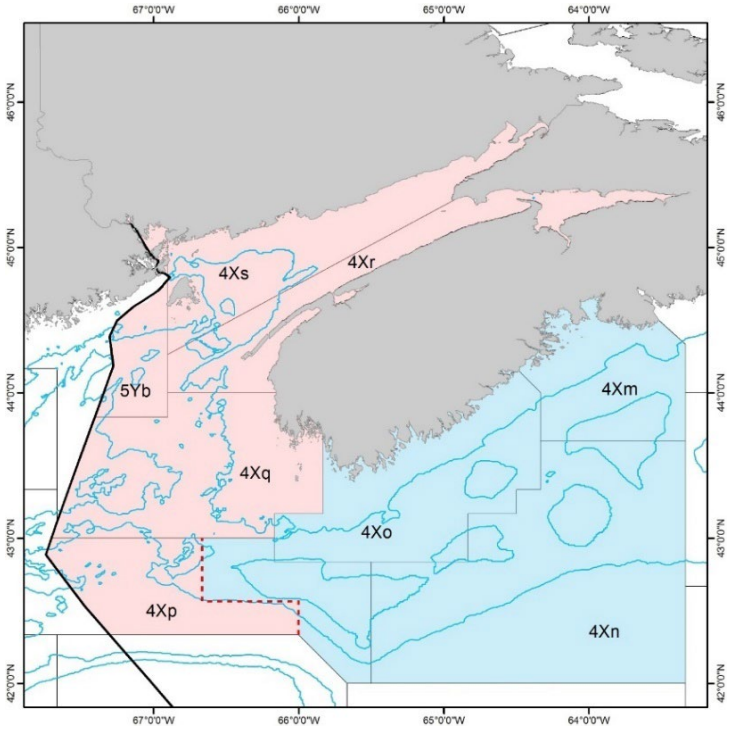

Figure 1. Management area of 4X5Y Atlantic Cod, depicting split between eastern (blue) and western (pink) components.

Description of the Fishery

Atlantic Cod are captured as part of a multi-species groundfish fishery in NAFO Divisions 4X and the Canadian portion of 5Yb. Historically part of a domestic inshore fishery, the fishing intensity increased throughout the 1960s with the introduction of mobile gears (Figure 2). There have been consistent reductions in Total Allowable Catch (TAC) since the mid-1990s (Figure 2). After the Recovery Potential Assessment was completed in 2011 (DFO 2011), TAC was further reduced to 1,650 mt. Directed fishing for Atlantic Cod was prohibited in 2019, resulting in 4X5Y Atlantic Cod becoming a bycatch-only fishery.

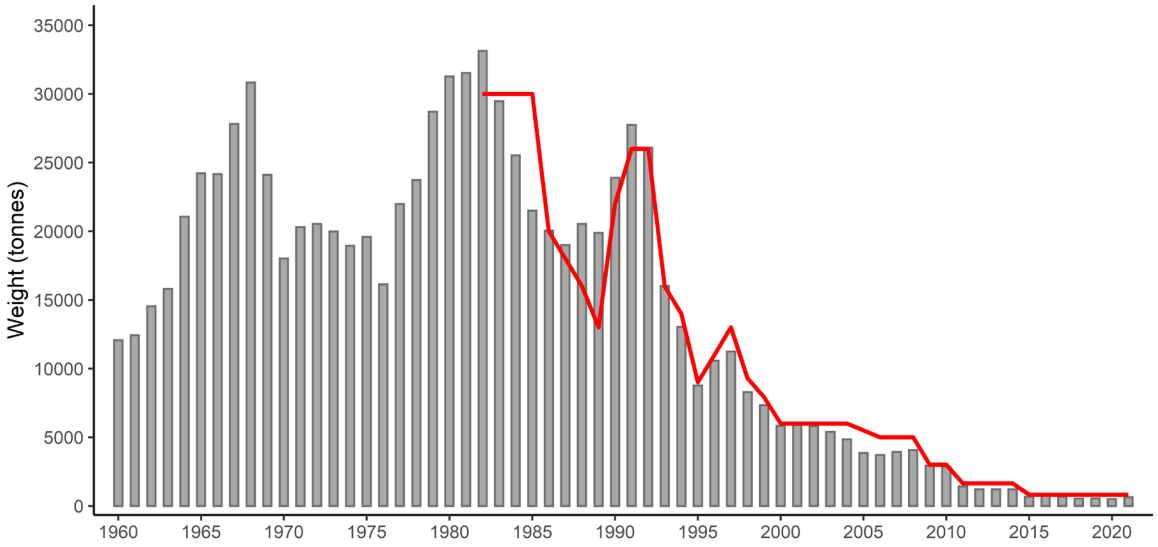

Figure 2. Landings (grey bars) and Total Allowable Catch (TAC) (red line) for NAFO Divisions 4X5Y Atlantic Cod by calendar year (January 1st–December 31st). After 1999, landings and TAC are reported by fishing year (April 1st–March 31st).

Historically, the proportion of Atlantic Cod landings from the Scotian Shelf has been greater than the Bay of Fundy but switched with the redistribution of fishery efforts in the late 1990s. The contributions of the two components became similar in the late 2010s. In the past three years, removals of Atlantic Cod from the Bay of Fundy have decreased substantially, resulting in Scotian Shelf landings accounting for 70% of the total fishery removals in 4X5Y. Landings in 4Xp increased starting in the 1980s and have remained at, or below, 30% of landings since the early 2010s (Figure 3).

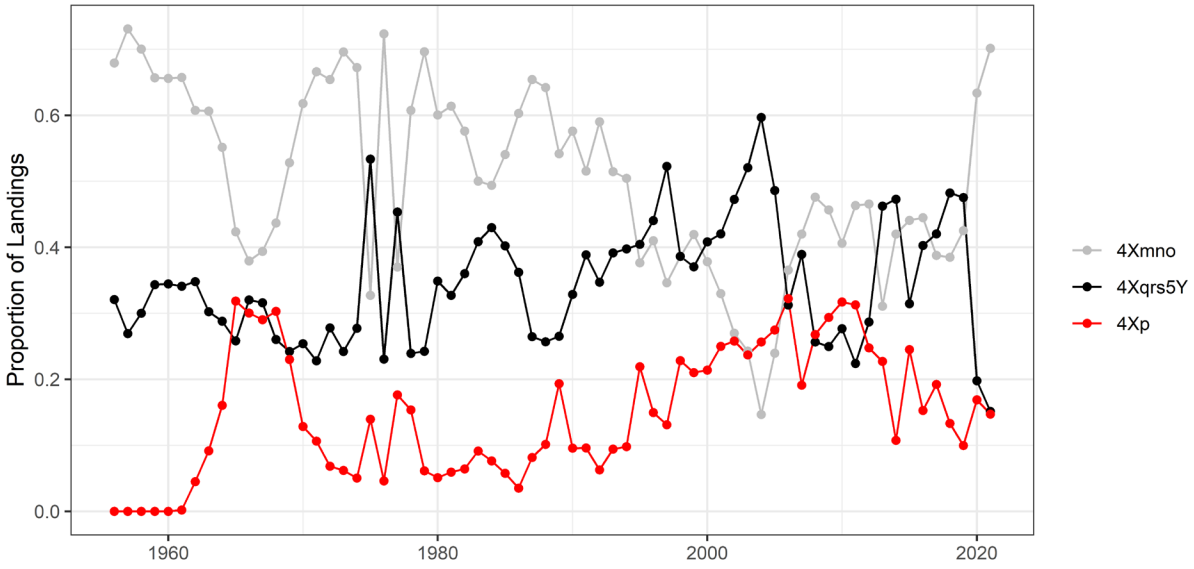

Figure 3. Proportion of landings in 4X5Y Atlantic Cod by Scotian Shelf (4Xmno; grey), Bay of Fundy (4Xqrs5Yb; black) and mixing area of 4Xp (red). Catches from NAFO Division 4Xu (unknown) are excluded from the figure.

Atlantic Cod quotas and catches have declined throughout the time series. Overall, catches have remained below the TAC in recent years. Landings for the 2020/2021 management year were the lowest in the time series at 507 mt, while landings in 2021/2022 increased to 630 mt (Table 1).

Table 1. Total Allowable Catch (TAC) and landings by management year of 4X5Y Atlantic Cod in metric tonnes (mt).

Management year	1982–1991 Average	1992–2001 Average	2002–2011 Average	2012–2021 Average	2020/2021	2021/2022
TAC	23,500	11,821	4,615	1,072	825	825
Landings	24,075[1]	11,178[1]	3,887	801	507	630

[1]Landings for 2001 and prior are based on the calendar year, landings post-2001 are based on the management year (April–March).

Analysis and Response

Indicators of the Stock Status

Fishery

Fishery catch-at-age underwent a consistent truncation in age structure starting in the 1990s until 2014 when no fish above the Age of 8 were detected in the fishery. Since the mid-2010s, some older fish have reappeared in both the Bay of Fundy and Scotian Shelf components, but numbers remain low. Younger fish (< Age 3) from the Scotian Shelf fishery were observed in greater numbers in 2020 and 2021, but this pulse of younger fish was not detected in the Bay of Fundy component. Overall, the numbers of younger fish remain lower than those observed before 2010 (Figure 4).

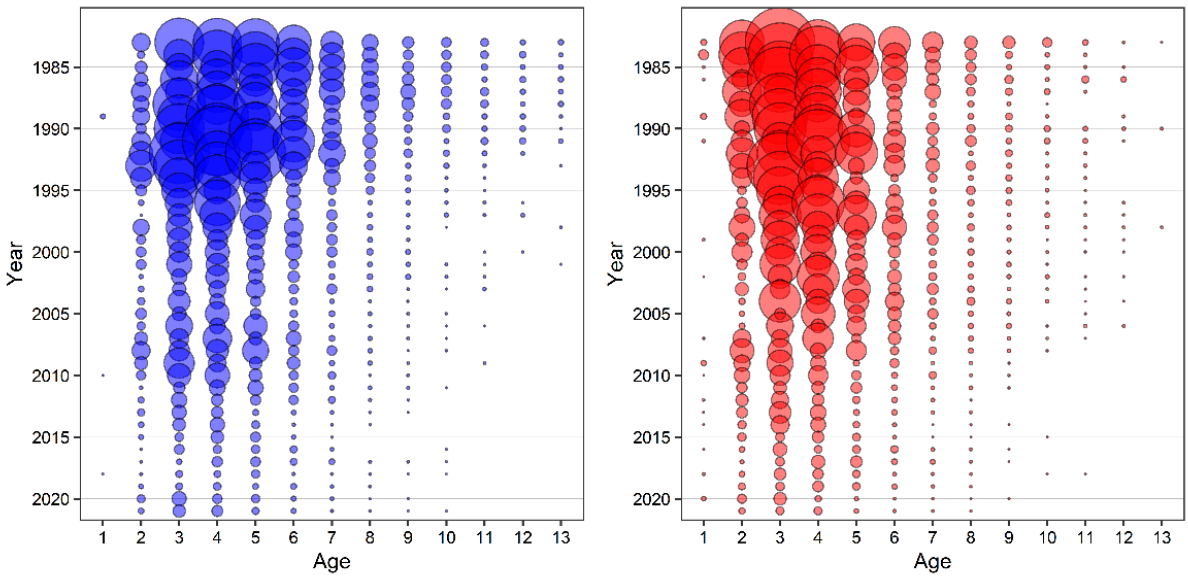

Figure 4. Commercial fishery catch-at-age for Scotian Shelf (blue) and Bay of Fundy (red) Atlantic Cod since 1983. Bubble area is proportional to abundance.

Other fishery-derived metrics were examined in this update to investigate recent statements made by fishers about seeing larger Atlantic Cod in recent years (Pers. Comms., SFGAC 2021); these are shown for investigative purposes only. The maximum length of Atlantic Cod caught in the 4X5Y fishery was estimated as the mean length of the ten longest fish measured by port samples. This value has declined throughout the time series and fluctuates considerably within and among years (Figure 5). Starting in the early-2010s, the maximum length of fish has shown marginal improvements in both components, of which only the Scotian Shelf seems to persist, noting the intra-annual variability.

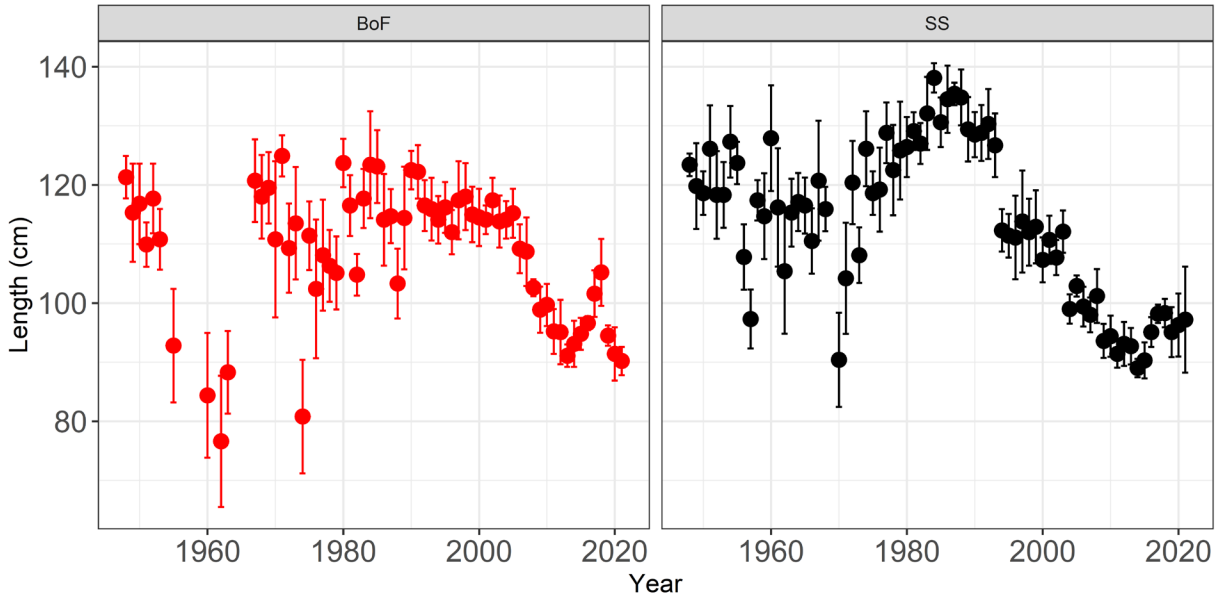

Figure 5. The mean length of the ten longest fish measured (cm) from port samples in the 4X5Y Atlantic Cod fishery. Red represents the Scotian Shelf component while black is the Bay of Fundy. Error bars represent 95% confidence intervals.

Survey

The annual bottom trawl DFO Summer Research Vessel (RV) survey has been conducted since 1970, providing fishery-independent information for groundfish species, including Atlantic Cod in the 4X5Y management area. Sampling of 4X5Y is conducted in the summer season (June–August). In 2021, the RV survey was completed using a new vessel with a new fishing net but comparative fishing has not been completed. Consequently, the 2021 abundance and biomass data are not comparable to other years until valid conversion factors are developed and are absent in this assessment. The 2022 survey covered all strata in 4X5Y and was completed with existing vessels and fishing nets making data comparable to the entire time series.

The total biomass index for 4X5Y Atlantic Cod has been steadily decreasing since the 1990s and has remained low since 2010 in both management units (Figure 6). The total biomass estimates for Atlantic Cod from the past three summer surveys (2019, 2020 and 2022) have been the three lowest values on record for this species, with 2022 being the lowest.

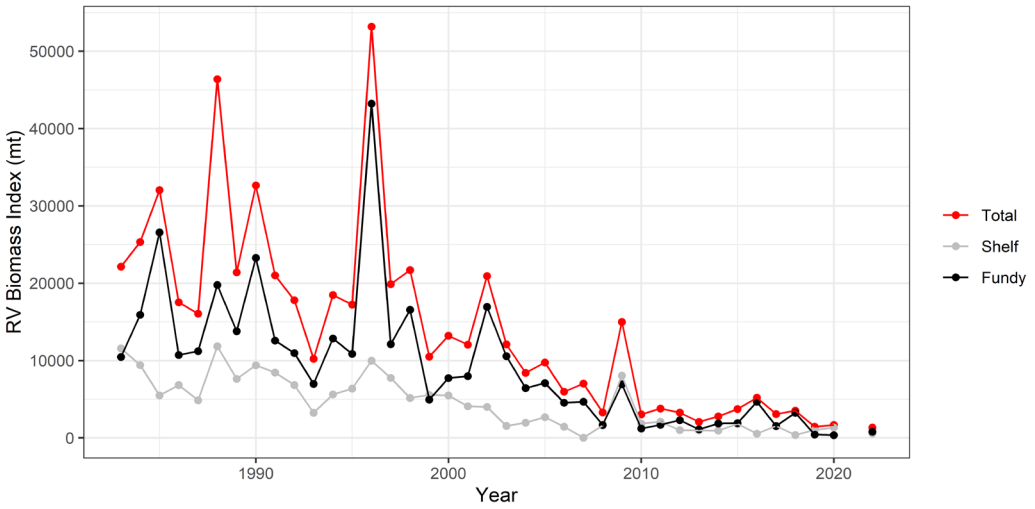

Figure 6. Total biomass index (mt) from the DFO summer RV survey for all of 4X5Y (red), Scotian Shelf (grey) and Bay of Fundy (black) since 1983.

Atlantic Cod catches from the 2022 survey were low compared to previous years and historical catches, and were absent from most of the tows completed (DFO 2020, DFO 2021). There have been notable shifts in Atlantic Cod distribution throughout this 40-year time series and overall, weight per tow has decreased across all areas (Andrushchenko et al. 2022). Atlantic Cod in the Bay of Fundy have receded from the coast and are now found mostly in the deeper waters of the Bay of Fundy, while those on the Scotian Shelf are concentrated on Browns, LaHave, Roseway, and Baccaro banks (Figure 7).

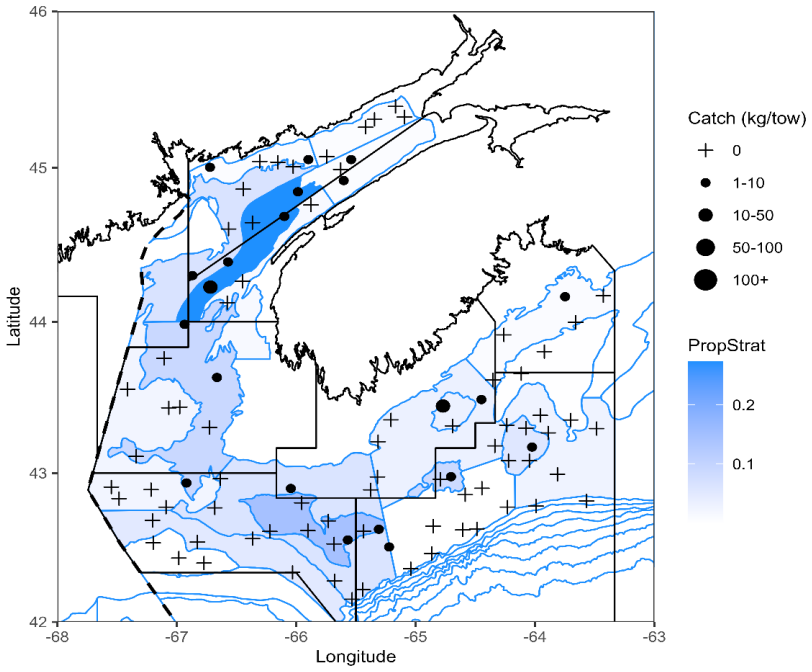

Figure 7. 4X5Y Atlantic Cod catch distribution (kg/tow) for all valid Summer RV survey sets in 2022 represented by the + symbol (zero catch) and the black circles (proportional to the catch size). Blue lines represent the survey stratum and blue shading represents the mean annual proportion of the total Atlantic Cod biomass by strata from 2008–2018. Black lines represent NAFO divisions.

Similar to the commercial catch-at-age, survey catches show a truncation of older ages (6+) since the mid-1990s to a low in 2013–2014. Older fish reappeared on the Scotian Shelf between 2015 and 2019, with very few fish Ages 6+ seen since then in both components. The survey catch-at-age has tracked some large year classes through time, notably in the Bay of Fundy (Figure 8). Overall, few large year-classes have been detected in both components in the second half of the time series (Figure 9).

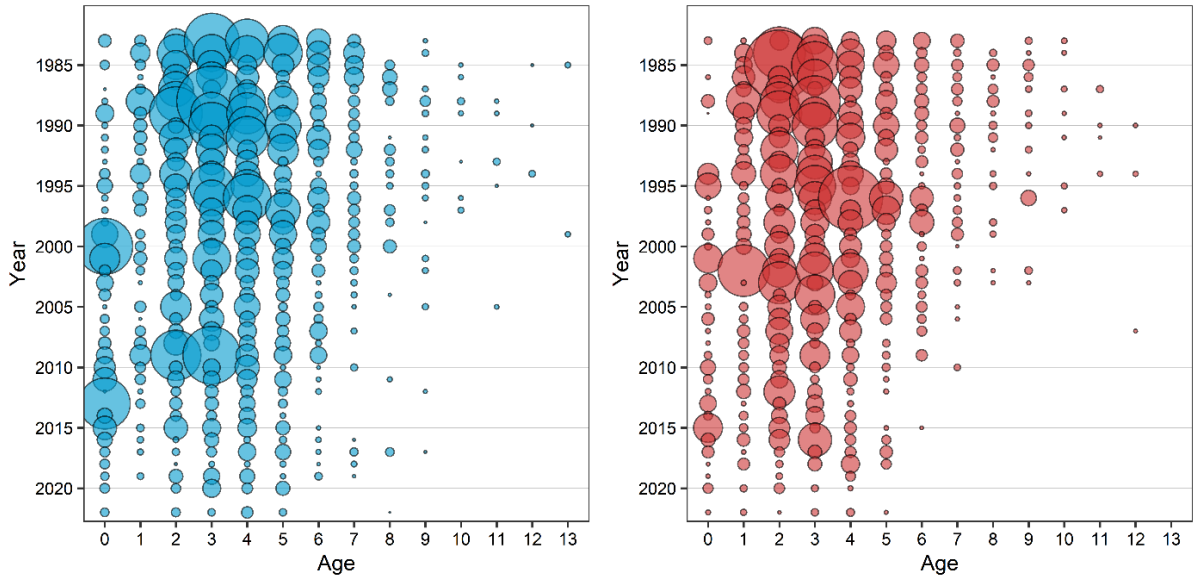

Figure 8. RV Survey indices at age for Atlantic Cod in Scotian shelf (blue) and Bay of Fundy (red). Bubble area proportional to survey catch.

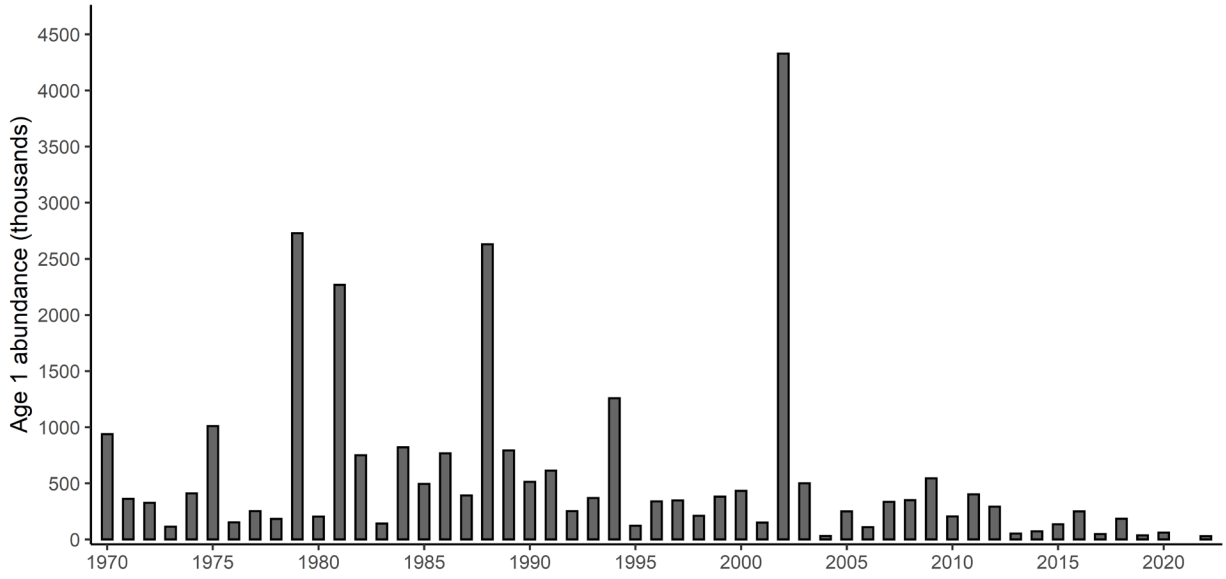

Figure 9. Age 1 recruitment index from DFO Summer Research Vessel survey from 1970–2022.

The stratified total estimates of Atlantic Cod abundance-by-length in 2019, 2020, and 2022 were at or below the average observed from 2010–2018 except for fish 10 and 13 cm in 2020, and well below the long-term average from 1983–2018 (Figure 10). Additionally, there were more fish over 60 cm in 2022 compared to the past two years.

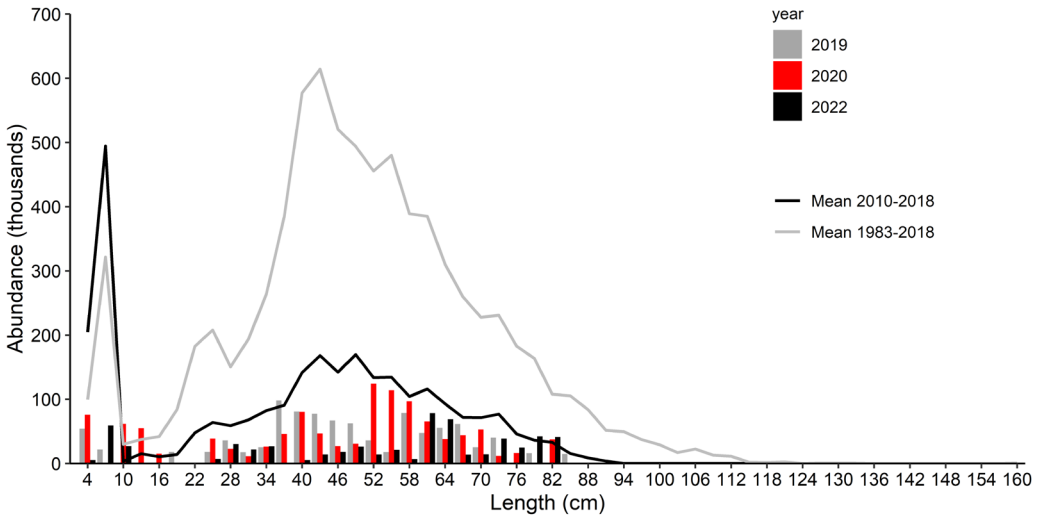

Figure 10. Length frequency indices for Atlantic Cod in 4X5Yb from the DFO Summer Research Vessel Survey. Bars represent the number in thousands at length from the 2019 (grey), 2020 (red) and 2022 (black) surveys. The solid black line represents the average number in thousands at length from 2010–2018, while the grey line represents the average number in thousands at length from 1983–2018.

On average, fish from the Bay of Fundy component have higher Fulton's K values, than fish from the Scotian Shelf, indicating better condition in this component (Figure 11). This metric of condition exhibits fluctuations throughout the time series without a trend, though some signs of improvement are apparent in the Bay of Fundy Atlantic Cod in recent years, which is consistent with statements made by industry stakeholders (Pers. Comms., SFGAC 2021).

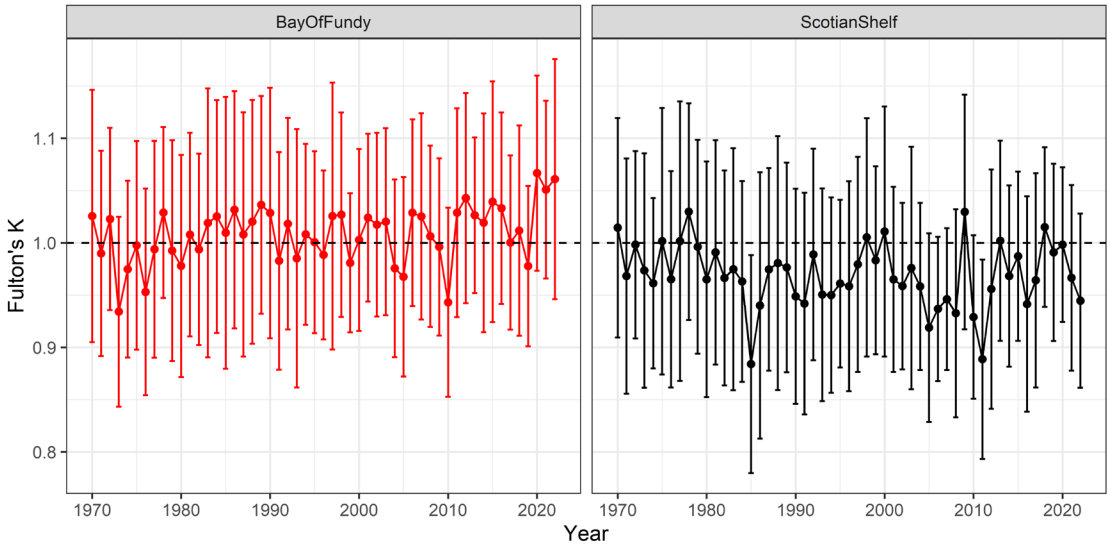

Figure 11. Fulton's K (weight/length^3) condition factor for 4X5Y Atlantic Cod in the Scotian Shelf and Bay of Fundy components. Error bars represent 95% confidence intervals.

Assessment

Reference Points

At the 2018 peer review of the assessment framework, a Limit Reference Point (LRP) of 22,193 mt was chosen based on the $Sb_{50/90}$. The $Sb_{50/90}$ is one of the methodologies suggested at the 2002 DFO National Workshop on Reference Points for Gadoids and is the point below which the population is unlikely to produce average recruitment under good early life-history stage survival conditions (DFO 2002). It is a standardized, reproducible approach, which uses the full time series; however, it tends to give an optimistic perspective on recruitment (Wang and Irvine 2022). The $Sb_{50/90}$ LRP of 22,193 mt replaces the previous LRP of 24,000 mt adopted in 2011 (DFO 2011). An Upper Stock Reference (USR) of 48,000 mt was developed for this stock in 2012 at the Scotia Fundy Groundfish Advisory Committee (SFGAC) meeting (DFO 2012) and remains unchanged. No fishing mortality reference point was proposed in the 2018 framework, as the stock was expected to decline even in the absence of fishing. In the absence of Science advice, a proxy removal reference was agreed to at the 2019 SFGAC meeting (SFGAC 2019). This proxy was defined as the mean value of relative fishing mortality (F) between 2015 and 2018 (0.19), with the expectation that annual relative F will be compared against this proxy (SFGAC 2019).

Model Formulation

The 4X5Y Atlantic Cod stock is assessed using the 3MFfirst Virtual Population Analysis (VPA) model formulation, which was accepted at the Assessment Framework for 4X5Y Atlantic Cod: Part 2 - Review of Modelling Approaches in November 2018 (Wang and Irvine 2022). This model uses the entire time series back to 1983 and has a terminal year of 2021. Survey and fisheries at age abundance indices, and number-weighed weight-at-age (WAA) were the data inputs for the model. The model can handle missing values in the survey catch-at-age matrix for Ages 2+, but not for Age 1, so the second-lowest Age 1 abundance estimate in the last 5 years was used (50,000 individuals) as a substitute for RV survey 2021 Age 1 abundance. Consequently, population estimates for the 2021 cohort have increased uncertainty for the model and projections.

The model assesses 4X5Y as a single unit and treats older fish as a plus group (Ages 7+) due to the truncation of age structure in 2014 and 2015 (Wang and Irvine 2022). The 3MFfirst VPA model allows time-varying Natural Mortality (M) for three age groups (Ages 1–2, Ages 3–4 and Ages 5+), with a normal prior mean of 0.2 (M_{initj}) and a deviation of 0.05 ($M_{devj,y}$) on all ages in 1983. A normal prior for the deviation of M in the random walks was set at a mean of 0 and a standard deviation of 0.05. The model also assumes flat-top survey selectivity (q) for Ages 3–6, and F for Age 6 is calculated as the mean of F for Ages 3 through 5 before 1995, and as the mean F for Ages 4 and 5 after 1995.

Residuals were used to evaluate the model fit and there were no clear patterns observed. A retrospective analysis was used to detect any over- or underestimation of fishing mortality and biomass relative to the terminal year. Seven-year peels of Mohn's Rho showed acceptable values for both spawning stock biomass (SSB) and F for Ages 4–7.

Model Results

The beginning of year population biomass from the 3MFfirst model shows a declining trend throughout the time series (Figure 12). Since the 1980s and 1990s, the SSB has declined considerably and has remained below the LRP since 2008, with further declines since the preceding assessment in 2018 (DFO 2019, Figure 12). The total estimated SSB (Ages 4+) from the 3MFfirst VPA model in 2022 is 4,918 mt, which remains below the LRP of 22,193 mt

indicating that the stock remains in the Critical Zone (Figure 12, Table A 1). Overall, the SSB VPA estimates are in agreement with the survey index throughout the time series (Figure 6).

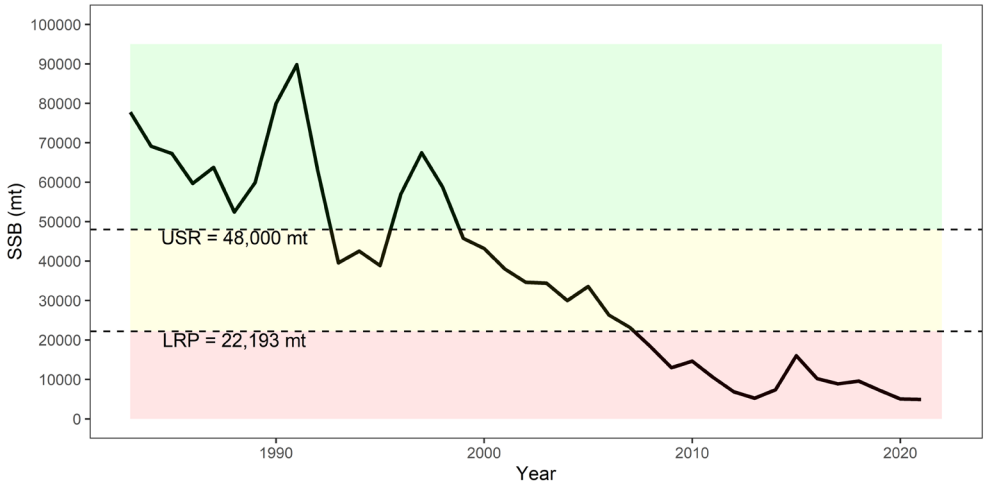

Figure 12. Spawning Stock Biomass (SSB; Ages 4+ in mt) from the 3MFfirst Virtual Population (VPA) model. Colours indicate Critical (red), Cautious (yellow) and Healthy (green) zones with stock reference points.

The most recent estimate of recruitment by the 3MFfirst VPA model for the 2020 year-class is 1.6 million fish, which is the second lowest in the series (Table A 2). Overall, recruitment levels remain low which is consistent with fewer spawning fish observed in the population.

Fishing Mortality from the 3MFfirst VPA showed a step-wise reduction in all fully recruited ages (number-weighted average of F on Ages 4+) after 1994 up to the late 2010s, consistent with management measures implemented. Fishing mortality on Ages 3–6 was higher than on older fish (Age 7+) up to the early 2000s, with F on Ages 7+ increasing substantially in the early 2000s and fluctuating at a high level since then. Following record low levels, F on Ages 4–6 appears to be gradually increasing since 2017 (Figure 13). The most recent F estimate for 2021 on fully recruited ages is 0.12 (Table A 3).

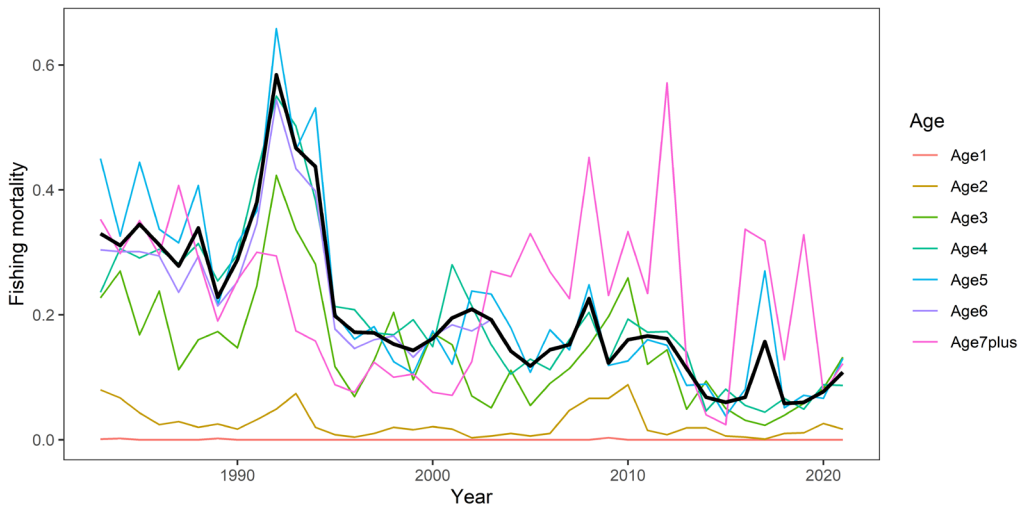

Figure 13. Fishing mortality by age from the 3MFfirst Virtual Population Analysis (VPA) model. The thick black line represents the fishing mortality for Ages 4–7.

Throughout the time series, M has marginally increased for fish Aged 1–2, and 3–4 (Table A 4), which is consistent with estimates of total mortality (Z) for Ages 2–4 from the DFO Summer RV survey (DFO 2021). For fish Ages 5+, M deviated substantially from the initial prior of 0.2 in 1983 to 0.34 and continued to increase throughout the time series up to 2014 when it was estimated to be 1.65. Since then, it has remained high but appears to be stabilizing at this level (Table A 4). High M for older fish is consistent with the truncation of the age structure observed in both survey and commercial catch-at-age (Figure 4, Figure 8).

In the absence of an accepted Removal Reference, the relative F is compared to the proxy relative F. The relative F is calculated using a 3-year mean of the survey biomass to dampen the variability of the annual survey. Relative fishing mortality for the stock declined around 1994, corresponding with a large decrease in TAC, which is consistent with model-dependent estimates of F (Figure 13, Figure 14). It remained at lower levels until the early 2010s and decreased again in 2014 when the TAC was reduced by 50%. After 2015, relative F fluctuated around the proxy relative F, periodically exceeding it.

Model-independent estimates of Z for fish Aged 4–7 increased in the early 2000s and remains high (Figure 15). This is consistent with low survivorship for older fish, reflected by the truncated age structure of both the survey and the fishery (Figure 4, Figure 8). A high Z is also in agreement with the VPA model outputs showing that a high M constitutes a large proportion of the total mortality experienced by this stock.

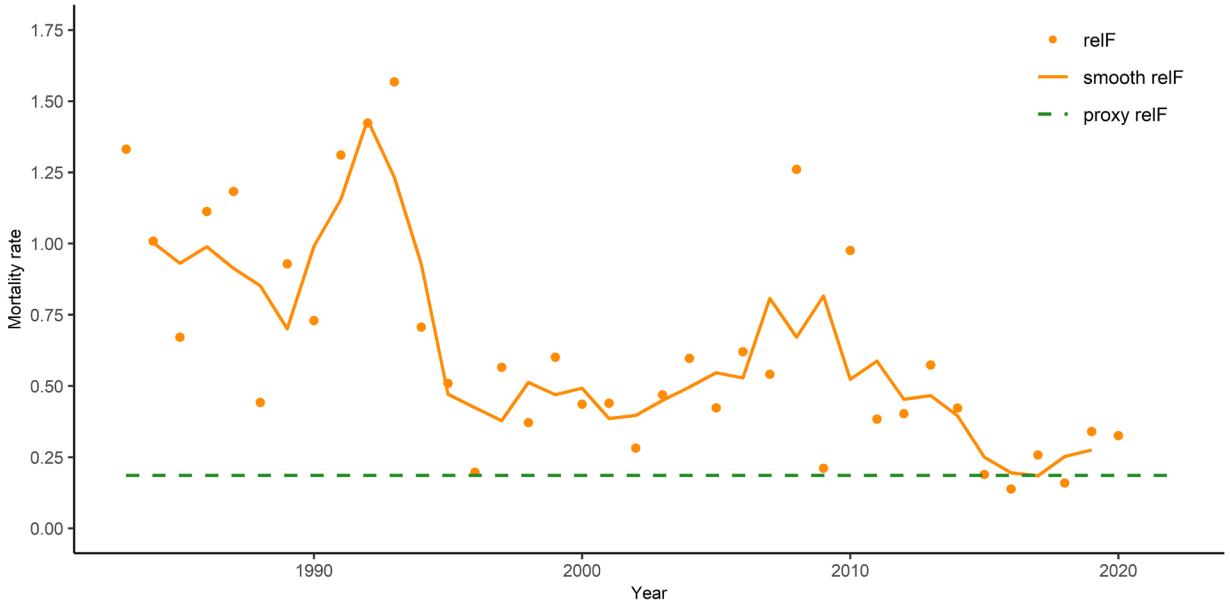

Figure 14. Comparison of annual relative fishing mortality (F; orange points) and smoothed relative F (annual catch / 3-year mean survey biomass; orange line). Green dashed line represents the proxy relative F set in 2019. Annual relative F is absent in 2021, and smoothed relative F is absent in 2019–2021 due to missing survey in 2021.

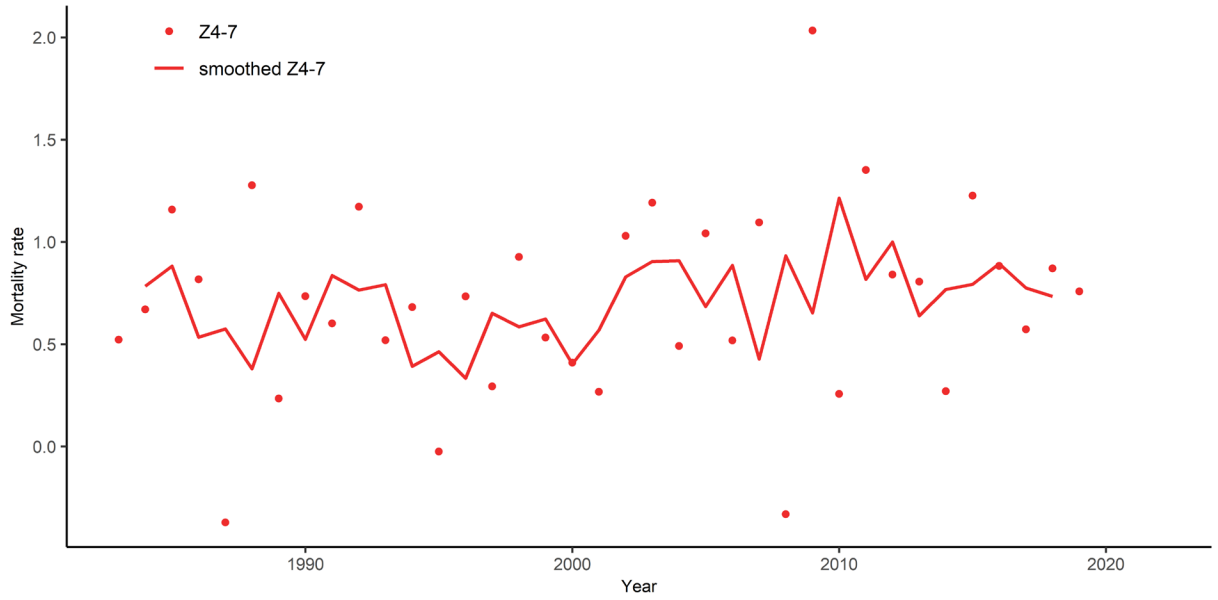

Figure 15. Total mortality for Ages 4–7 ($Z_{4–7}$; red points) and 3-year mean total mortality (red line) from the annual DFO Summer Research Vessel survey. Z calculations for the cohorts could not be completed from 2019–2021 due to the missing survey in 2021.

The 3MFfirst model indicates that the 4X5Y Atlantic Cod stock has declined substantially from pre-1994 levels and remains in the Critical Zone. Despite decreases in fishing mortality, the productivity of the stock remains low and there is high mortality for older fish.

Projections

At the framework review in 2018, it was agreed that projections provided for the 4X5Y Atlantic Cod stock assessments would be based on the most recent 5-year average of recruitment, mortality estimate by age group and the most recent 3-year average of WAA and partial recruitment.

Updated projections assume a 2022 catch of 660 mt, and are run under three harvest scenarios for 2023 and 2024:

- current TAC (660 mt annually);
- half of current TAC (330 mt annually); and
- no catch.

The projected SSB at the beginning of the calendar year for each harvest scenario is provided in Table 2. Projections are also presented as a probability that the beginning of the year SSB in 2023 is greater than that projected in 2024, and similarly for 2024 and 2025. In all three harvest scenarios, SSB is projected to remain relatively stable at approximately 3,500–4,500 mt, noting the large credible intervals for each projected value. The probability that the population will decrease between projected years is approximately 50% for each scenario, further indicating potential stability at low levels for this stock. The terminal year projections are subject to increased uncertainty as only survey index data up to 2020 is used, and the abundance of Age 1 fish in 2021 is estimated (Age 4 in 2025).

Table 2. Short-term projection outputs of Spawning Stock Biomass (SSB), Fishing Mortality (F) and probability (P) of SSB change under 3 harvest scenarios. Numbers in parentheses indicate the 95% credible interval.

Harvest scenario (mt)	Median SSB (95% CI)			Median F (95%)		P(SSB_{2024} < SSB_{2023})	P(SSB_{2025} < SSB_{2024})
	2023	2024	2025	2023	2024		
660	3,550 (1,006–17,688)	3,719 (622–20,689)	3,517 (706–16,167)	0.32 (0.07–1.22)	0.32 (0.07–1.21)	48%	53%
330	3,550 (1,006–17,688)	4,018 (850–21,020)	4,009 (1,174–16,686)	0.15 (0.04–0.54)	0.15 (0.04–0.45)	43%	50%
0	3,550 (1,006–17,688)	4,327 (1,086–21,352)	4,505 (1,654–17,079)	0	0	40%	47%

The estimated M continues to be high (1.64) in the current assessment, equating to a survivorship estimate of 19%. As was done in the 2018 assessment, a 10-year projection with zero fishery catch and various levels of Ages 5+ M was conducted to assess the likelihood of stock recovery (DFO 2022). These projections showed that the stock may exceed the LRP if M was reduced by 80%, showing that if M for fish Aged 5+ increases or continues to be high, the stock is unlikely to rebuild above the LRP within the next 6 years.

Assessment Schedule

The next update for 4X5Y Atlantic Cod is expected in 2024 given the Science workload for stock assessments. This update is expected to follow the same format as previous updates (DFO 2021), including whether exceptional circumstances should trigger an assessment for the following year using updated survey information and projections. These trigger mechanisms were defined in the 2018 framework review, are focused on detecting a change in the current stock productivity dynamics and are defined as follows (Wang and Irvine 2022):

1. The 3-year median abundance for Ages 7 through 9 is above 0 for all three ages.
2. If the q-adjusted, 3-year-median, survey SSB index falls outside of the 95% confidence interval of the projection.
3. If the 3-year median of the Age 7+ group abundance index falls outside of the 95% confidence interval of the projection.
4. The q-adjusted 3-year median survey biomass index exceeds B_{lim}.

In addition to these four trigger conditions, a framework review would be triggered if a useable time trend on bycatch from non-groundfish fisheries or discarding of Atlantic Cod becomes available, the perception of stock structure changes or a framework is developed for incorporating ecosystem information into the stock assessment. Triggers 1 and 4 were evaluated for this update, and neither condition was met. Although some work has been done to quantify the interaction of 4X5Y Atlantic Cod with the Lobster fishery (Cook et al. 2022[1]),

[1]Cook, A.M., V. Howse and C. Denton. Updated Bycatch Analyses from the Inshore Lobster Fishery. Unpublished report.

additional analyses are needed to translate those estimates into Atlantic Cod mortality before they can be incorporated into the Atlantic Cod stock assessment.

Ecosystem Considerations

Availability of existing data, including data on key prey species (e.g., Sand Lance), hindered the quantitative incorporation of ecosystem considerations into the Atlantic Cod stock assessment during the 2018 Framework (Andrushchenko et al. 2022). Although indicators of key prey species are still missing, a general overview of notable changes to the Scotian Shelf and Bay of Fundy ecosystem are summarized to provide context around changes, or lack thereof, seen in the assessment of 4X5Y Atlantic Cod.

Overall, the productivity, trophic interactions and structure of the Scotian Shelf ecosystem have undergone significant changes in the past four decades (Choi et al. 2005, DFO 2015, Frank et al. 2005). Increases in bottom water temperature are accompanied by increases in invertebrate landings, while demersal fish biomass from the RV survey has decreased in 4V and 4W (DFO 2020). Biomass of demersal fish in 4X has not shown a directional change, as decreases in the biomass of species like Atlantic Cod have been counteracted by increases in the biomass of species like redfish (DFO 2020). A shift towards smaller zooplankton from larger, energy-rich copepods has been observed since 2010 and may indicate less productive conditions for planktivorous fish (Casault et al. 2020). Additionally, the abundance of Grey Seals (*Halichoerus grypus*) has increased substantially on the Scotian Shelf beginning in the 1960s, and breeding colonies were re-established in southwest Nova Scotia in the early 1990s (den Heyer et al. 2021). While the rate of increase for the total population growth has slowed down more recently (1.5% per year between 2016 and 2021; DFO 2022) there has been a more rapid increase in the pup production at the breeding colonies in southwest Nova Scotia (den Heyer et al. 2021). The increase in Grey Seals likely results in increased predation pressure on Atlantic Cod, contributing to higher natural mortality.

Of note also is the increased abundance of young-of-the-year fish (< 15 cm) Atlantic Cod in recent years; an observation which is also apparent in 4X5Y Haddock (DFO 2020). As noted in DFO (2020), this likely reflects earlier spawning due to environmental shifts, rather than a sign of strong recent recruitment for the Atlantic Cod stock.

Conclusions

The 4X5Y Atlantic Cod stock has declined since the 1990s and remains in the Critical Zone. Despite decreases in fishing mortality, the productivity of the stock remains low. Few older fish have reappeared in the population and natural mortality for fish Ages 5+ continues to be high. With current productivity conditions, biomass for this stock is projected to stay relatively stable over the next three years, with or without fishing removals. In keeping with the Precautionary Approach, catch levels should be kept as low as possible and monitoring of Atlantic Cod bycatch/discarding in all fisheries should be improved.

Sources of Uncertainty

Several data gaps and uncertainties were identified during the last modelling assessment framework (Wang and Irvine 2022) and assessment (DFO 2019), which continue to persist for 4X5Y Atlantic Cod:

- Although 4X5Y Atlantic Cod is regarded as a data-rich stock with age-structured fishery and survey information dating back to 1983, periods of bias in the historical catch, time-varying natural mortality and stock mixing are problematic for modelling this stock. The lack of

fisheries independent information from RV surveys in 2021 also introduces uncertainty in population modelling and reduces accurate tracking of cohorts through time.

- High natural mortality rates persist in the stock from the latest 3MFfirst model, which could be aliasing other factors contributing to the decline of Atlantic Cod. These include the emigration of fish to deeper, colder waters, predation or unreported/discarded catch of Atlantic Cod from all 4X5Y fisheries.
- Any unaccounted-for fishing mortality is included in the population modelling as natural mortality. This would include recreational fishing and catch from non-groundfish fisheries within the management area. Presently, this source of mortality is not incorporated into the population modelling for this stock but should be pursued.
- Fish movement, population structure and the extent of mixing between multiple spawning components in 4X5Y and adjacent management units are not fully understood. Recent genetic analyses have shown that the population structure of Atlantic Cod is complex in this region, with some genetic similarities between Browns and Eastern Georges banks, while Atlantic Cod in the Bay of Fundy appear to be isolated from the rest of the Gulf of Maine (Puncher et al. 2021). Incorporation of this, and other population structure information into a population model could be considered in future science frameworks.
- Many basic ecosystem indicators (e.g., abundance indices of prey items of juvenile Atlantic Cod and indicators of larval Atlantic Cod abundance) and the magnitude of their effect on the abundance and distribution of various life stages of Atlantic Cod are undetermined, hindering the incorporation of ecosystem considerations into the stock assessment.
- Additional research should be conducted to assess drivers of Atlantic Cod productivity in 4X5Y and determine other sources of natural mortality.

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Appendix

Outputs from the 3MFfirst model.

Table A1. Population biomass (metric tonnes) estimated from the 3MFfirst Virtual Population Analysis (VPA) model for Ages 1–7+, total and for spawning stock biomass (SSB). Dashes indicate absent values.

Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7+	Total	SSB (4+)
1983	229	3,171	14,994	19,956	18,114	14,287	25,379	96,131	77,736
1984	509	2,429	9,184	21,689	17,155	9,726	20,548	81,240	69,118
1985	822	3,754	10,213	12,034	22,181	14,285	18,765	82,055	67,266
1986	3,188	2,482	13,871	13,836	11,009	12,329	22,521	79,236	59,695
1987	989	8,166	5,954	19,103	13,735	8,317	22,581	78,846	63,737
1988	1,542	5,350	18,590	7,335	16,903	10,287	17,902	77,910	52,428
1989	793	6,674	15,407	27,061	7,478	10,473	14,906	82,792	59,918
1990	1,406	2,740	19,639	20,732	30,815	9,126	19,240	103,699	79,913
1991	1,665	3,862	6,617	28,336	20,820	23,231	17,397	101,929	89,784
1992	667	5,380	8,132	7,600	23,451	10,400	21,604	77,233	63,055
1993	1,725	3,091	13,076	8,628	5,141	12,753	13,017	57,432	39,539
1994	1,516	6,387	9,250	16,563	7,975	2,778	15,206	59,675	42,521
1995	496	3,633	17,318	10,574	15,178	3,971	9,146	60,315	38,869
1996	406	2,395	9,718	27,556	12,510	9,749	7,195	69,529	57,010
1997	493	984	7,291	17,826	31,112	9,451	9,065	76,221	67,454
1998	788	2,483	2,989	11,530	19,942	18,159	9,202	65,094	58,833
1999	520	1,355	8,268	5,417	13,086	11,864	15,400	55,909	45,767
2000	888	3,700	3,188	15,635	6,675	7,819	13,072	50,977	43,201
2001	308	2,569	11,369	5,877	18,448	3,960	9,685	52,214	37,969
2002	767	1,181	6,150	14,615	5,530	8,685	5,810	42,738	34,640
2003	164	3,716	4,543	9,768	15,775	2,390	6,459	42,815	34,391
2004	826	916	10,630	9,547	11,095	6,793	2,545	42,352	29,980
2005	75	2,789	2,929	15,471	11,180	3,814	3,113	39,371	33,578
2006	484	766	7,898	3,722	17,131	3,599	1,855	35,455	26,307
2007	347	2,110	3,072	13,300	3,738	4,877	1,268	28,711	23,183
2008	178	1,790	4,811	3,663	11,842	976	1,804	25,065	18,285
2009	261	963	5,229	5,319	3,366	3,602	678	19,419	12,965
2010	134	689	2,531	6,033	5,633	1,390	1,565	17,975	14,621
2011	543	734	1,323	2,688	5,969	1,132	726	13,116	10,515
2012	352	2,763	2,097	1,539	3,039	1,801	459	12,050	6,838
2013	97	1,404	3,520	2,473	1,446	746	551	10,239	5,217
2014	1,032	573	3,536	4,473	2,253	374	272	12,512	7,372
2015	108	2,130	1,454	4,459	10,797	580	156	19,685	15,992
2016	168	570	4,478	1,853	4,944	3,212	188	15,413	10,196
2017	3	896	1,657	5,253	1,918	987	714	11,427	8,872
2018	202	147	2,538	2,832	5,998	411	336	12,464	9,577
2019	47	631	993	3,087	2,470	1,511	192	8,932	7,260
2020	167	305	1,761	1,070	3,120	461	391	7,275	5,042
2021	44	585	1,117	2,761	1,236	708	214	6,665	4,918
2022	-	397	1,403	1,328	2,263	237	219	-	4,047

Table A2. Population abundance at age (thousands of fish) estimated from the 3MFfirst Virtual Population Analysis (VPA) model. Dashes indicate absent values.

Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7+
1983	19,199	14,822	20,085	12,819	6,614	3,597	3,597
1984	22,840	15,682	11,184	12,909	8,170	2,995	3,680
1985	14,498	18,632	11,986	6,882	7,661	4,119	3,456
1986	40,617	11,842	14,578	8,161	4,146	3,377	3,768
1987	27,376	33,172	9,446	9,251	4,843	2,001	3,599
1988	35,862	22,354	26,310	6,801	5,621	2,351	2,645
1989	11,922	29,273	17,883	18,046	3,999	2,444	2,437
1990	16,865	9,712	23,294	12,106	11,263	2,065	2,556
1991	21,383	13,758	7,793	16,174	7,236	5,164	2,251
1992	16,735	17,439	10,868	4,894	8,475	3,071	3,254
1993	33,122	13,647	13,544	5,718	2,268	2,605	2,498
1994	22,414	27,004	10,333	7,767	2,776	820	2,179
1995	15,886	18,266	21,578	6,256	4,244	909	1,342
1996	8,149	12,938	14,755	15,364	4,047	1,849	1,061
1997	15,735	6,632	10,485	11,010	9,978	1,755	1,314
1998	6,301	12,794	5,340	7,367	7,404	4,050	1,293
1999	14,663	5,118	10,182	3,464	4,957	3,057	2,153
2000	9,426	11,898	4,088	7,337	2,267	2,015	2,088
2001	8,587	7,640	9,448	2,724	5,000	815	1,560
2002	17,063	6,953	6,084	6,393	1,621	1,772	853
2003	4,847	13,801	5,605	4,450	4,048	470	824
2004	15,492	3,917	11,087	4,161	2,988	1,060	336
2005	5,574	12,511	3,133	7,733	2,919	758	358
2006	6,434	4,496	10,032	2,303	5,278	762	271
2007	9,245	5,182	3,584	7,103	1,595	1,251	245
2008	4,168	7,435	3,976	2,465	4,668	386	355
2009	2,186	3,347	5,589	2,623	1,543	1,015	149
2010	3,434	1,747	2,513	3,505	1,766	369	274
2011	11,412	2,751	1,282	1,473	2,195	395	130
2012	4,464	9,138	2,170	860	938	437	102
2013	2,359	3,572	7,255	1,419	546	170	91
2014	6,879	1,888	2,803	5,211	931	98	45
2015	2,677	5,502	1,481	1,925	3,755	164	26
2016	3,392	2,141	4,373	1,061	1,336	728	36
2017	1,369	2,712	1,705	3,189	756	253	145
2018	2,644	1,094	2,165	1,253	2,296	117	65
2019	1,591	2,112	866	1,567	882	428	33
2020	2,012	1,272	1,671	615	1,124	157	82
2021	1,649	1,608	990	1,158	424	202	42
2022	-	1,318	1,264	654	800	71	42

Table A3. Fishing mortality (F) outputs from the 3MFfirst Virtual Population Analysis (VPA) model. $F_{4–7}$ is fishing mortality on fully recruited ages. Dashes indicate absent values.

Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7+	$F_{4–7}$
1983	0.001	0.080	0.227	0.236	0.450	0.304	0.353	0.330
1984	0.002	0.067	0.270	0.306	0.326	0.301	0.298	0.311
1985	0.000	0.043	0.168	0.291	0.444	0.301	0.351	0.345
1986	0.000	0.024	0.238	0.305	0.337	0.294	0.296	0.312
1987	0.000	0.029	0.112	0.282	0.315	0.236	0.407	0.278
1988	0.000	0.020	0.160	0.314	0.407	0.294	0.291	0.339
1989	0.002	0.025	0.173	0.254	0.216	0.214	0.190	0.228
1990	0.000	0.017	0.147	0.296	0.315	0.253	0.255	0.288
1991	0.000	0.032	0.246	0.427	0.366	0.346	0.300	0.38
1992	0.000	0.049	0.423	0.550	0.658	0.544	0.294	0.584
1993	0.000	0.074	0.336	0.502	0.464	0.434	0.174	0.467
1994	0.000	0.020	0.281	0.383	0.531	0.398	0.158	0.437
1995	0.000	0.008	0.117	0.213	0.202	0.177	0.088	0.198
1996	0.000	0.004	0.069	0.208	0.161	0.146	0.076	0.172
1997	0.000	0.010	0.127	0.171	0.181	0.160	0.124	0.171
1998	0.000	0.020	0.204	0.168	0.125	0.166	0.100	0.153
1999	0.000	0.016	0.096	0.192	0.106	0.132	0.105	0.143
2000	0.000	0.021	0.171	0.149	0.174	0.165	0.076	0.162
2001	0.000	0.017	0.152	0.280	0.121	0.184	0.071	0.195
2002	0.000	0.003	0.070	0.214	0.238	0.174	0.125	0.209
2003	0.000	0.006	0.051	0.152	0.233	0.192	0.270	0.192
2004	0.000	0.010	0.111	0.105	0.179	0.142	0.261	0.142
2005	0.000	0.006	0.055	0.129	0.108	0.118	0.330	0.118
2006	0.000	0.010	0.090	0.112	0.176	0.144	0.269	0.144
2007	0.000	0.047	0.114	0.160	0.144	0.152	0.226	0.152
2008	0.000	0.066	0.151	0.204	0.248	0.226	0.452	0.226
2009	0.003	0.066	0.197	0.126	0.119	0.123	0.231	0.123
2010	0.000	0.088	0.259	0.193	0.126	0.160	0.333	0.16
2011	0.000	0.015	0.121	0.172	0.160	0.166	0.234	0.166
2012	0.000	0.008	0.144	0.173	0.151	0.162	0.571	0.162
2013	0.000	0.019	0.049	0.140	0.087	0.114	0.123	0.114
2014	0.000	0.019	0.094	0.046	0.089	0.068	0.040	0.068
2015	0.000	0.006	0.050	0.081	0.038	0.060	0.024	0.06
2016	0.000	0.004	0.031	0.055	0.081	0.068	0.337	0.068
2017	0.000	0.001	0.023	0.044	0.270	0.157	0.318	0.157
2018	0.000	0.010	0.039	0.066	0.051	0.058	0.128	0.058
2019	0.000	0.011	0.058	0.049	0.071	0.060	0.328	0.06
2020	0.000	0.026	0.082	0.088	0.066	0.077	0.075	0.077
2021	0.000	0.017	0.132	0.087	0.130	0.108	0.122	0.108

Table A4. Natural mortality (M) outputs from the 3MFfirst Virtual Population Analysis (VPA) model.

Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7+
1983	0.20	0.20	0.21	0.21	0.34	0.34	0.34
1984	0.20	0.20	0.22	0.22	0.36	0.36	0.36
1985	0.20	0.20	0.22	0.22	0.37	0.37	0.37
1986	0.20	0.20	0.22	0.22	0.39	0.39	0.39
1987	0.20	0.20	0.22	0.22	0.41	0.41	0.41
1988	0.20	0.20	0.22	0.22	0.43	0.43	0.43
1989	0.20	0.20	0.22	0.22	0.44	0.44	0.44
1990	0.20	0.20	0.22	0.22	0.47	0.47	0.47
1991	0.20	0.20	0.22	0.22	0.49	0.49	0.49
1992	0.20	0.20	0.22	0.22	0.52	0.52	0.52
1993	0.20	0.20	0.22	0.22	0.55	0.55	0.55
1994	0.20	0.20	0.22	0.22	0.59	0.59	0.59
1995	0.21	0.21	0.22	0.22	0.63	0.63	0.63
1996	0.21	0.21	0.22	0.22	0.67	0.67	0.67
1997	0.21	0.21	0.23	0.23	0.72	0.72	0.72
1998	0.21	0.21	0.23	0.23	0.76	0.76	0.76
1999	0.21	0.21	0.23	0.23	0.79	0.79	0.79
2000	0.21	0.21	0.23	0.23	0.85	0.85	0.85
2001	0.21	0.21	0.24	0.24	0.92	0.92	0.92
2002	0.21	0.21	0.24	0.24	1.00	1.00	1.00
2003	0.21	0.21	0.25	0.25	1.11	1.11	1.11
2004	0.21	0.21	0.25	0.25	1.19	1.19	1.19
2005	0.21	0.21	0.25	0.25	1.24	1.24	1.24
2006	0.22	0.22	0.26	0.26	1.26	1.26	1.26
2007	0.22	0.22	0.26	0.26	1.27	1.27	1.27
2008	0.22	0.22	0.26	0.26	1.28	1.28	1.28
2009	0.22	0.22	0.27	0.27	1.31	1.31	1.31
2010	0.22	0.22	0.28	0.28	1.37	1.37	1.37
2011	0.22	0.22	0.28	0.28	1.45	1.45	1.45
2012	0.22	0.22	0.28	0.28	1.55	1.55	1.55
2013	0.22	0.22	0.28	0.28	1.63	1.63	1.63
2014	0.22	0.22	0.28	0.28	1.65	1.65	1.65
2015	0.22	0.22	0.28	0.28	1.60	1.60	1.60
2016	0.22	0.22	0.28	0.28	1.58	1.58	1.58
2017	0.22	0.22	0.28	0.28	1.60	1.60	1.60
2018	0.22	0.22	0.28	0.28	1.63	1.63	1.63
2019	0.22	0.22	0.28	0.28	1.65	1.65	1.65
2020	0.22	0.22	0.28	0.28	1.65	1.65	1.65
2021	0.22	0.22	0.28	0.28	1.65	1.65	1.65

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