STOCK ASSESSMENT OF NORTHERN COD (NAFO DIVISIONS 2J3KL) IN 2021

Image: Atlantic Cod (Gadus morhua).

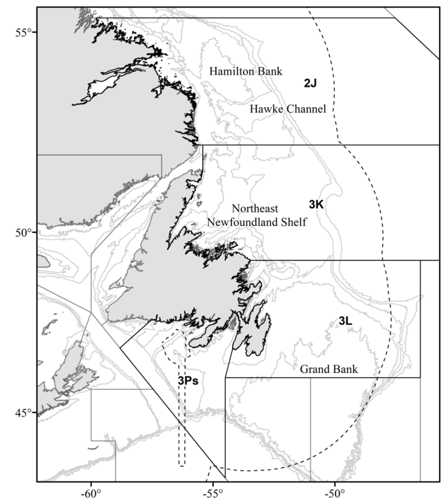

Figure 1: Stock area of Northern (2J3KL) cod. The dashed line indicates Canada's 200 nautical mile Exclusive Economic Zone (EEZ).

Context:

A conservation limit reference point (LRP) for Northern (Div. 2J3KL, Fig. 1) cod (DFO 2010; DFO 2019a) is defined as the average spawning stock biomass (SSB) during the 1980s. This reference point defines the boundary between the critical and cautious zones within the Precautionary Approach (PA) framework (DFO 2009) and defines the stock level below which serious harm is occurring. At these levels the stock is considered to have suffered serious harm and the ability to produce good recruitment is impaired. Stock status from the last full assessment (DFO 2019b) indicated that the SSB was at 48% (95% CI = 37–63%) of B_{lim} and scientific advice stated that removals must be kept to the lowest possible level until the stock has cleared the critical zone. A rebuilding plan for Northern cod was released in 2020 (DFO 2020), with a Harvest Decision Rule (HDR) aimed at keeping fishing mortality low while the stock is in the critical zone (specifically 25–75% of the LRP).

The Northern cod stock has been subjected to ongoing stewardship and recreational fisheries in the inshore since 2006. In the 2020 stewardship fishery, an overall maximum harvest amount of 12,350 t was allowed. In the 2020 recreational fishery, a maximum catch of 5 fish per person (for a maximum of 15 fish per boat) was permitted over a 39 day period.

In 2017, the Minister of Fisheries and Oceans Canada (DFO) announced that Northern cod would be assessed annually for five years starting in 2018. A full stock assessment, in accordance with the Sustainable Fisheries Framework, was requested by Fisheries Management to provide the Minister with advice on the status of the stock covering the period April 1, 2021 to March 31, 2022. This Science Advisory Report (SAR) is from the March 23–26, 2021 Stock Assessment of Northern cod (Divs. 2J3KL). Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada Science Advisory Schedule] as they become available.

SUMMARY

- The Newfoundland and Labrador climate experiences important fluctuations at decadal time scales, with potential impacts on ecosystem productivity. These large scale changes are linked to phases of the North Atlantic Oscillation (NAO) and patterns in large-scale ocean circulation (e.g., increased Labrador Current transport). The coldest period on record (late-1980s to early-1990s) coincided with the Northern cod stock collapse and has been linked to significant changes in the ecosystem. Warmer than average conditions have been observed over the last three years.
- Primary (phytoplankton) and secondary (zooplankton) productivity have improved to near or above average levels since around 2015, but with changes in zooplankton seasonality (lower spring, higher summer and fall biomass signals) and community structure (higher dominance of small-sized copepods).
- Ecosystem conditions in the Newfoundland Shelf and Northern Grand Bank (NAFO Divs. 2J3KL) remain indicative of overall limited fish community productivity, with low abundance of key forage species and total Research Vessel (RV) trawl survey biomass remaining well below pre-collapse levels. Diet composition of cod and other key predators indicate food limitation. Increases in groundfish observed from the mid-2000s to mid-2010s were associated with bottom-up processes, but have stalled as key forage species like Capelin and Shrimp have declined.
- Cod productivity has been linked to Capelin levels. Given the forecasted levels of Capelin for the next two years, the prospects for cod stock growth appear limited.
- The Newman Sound pre-recruit index suggests that cohorts from 2018 to 2020 will be weaker than those in the past ten years and the pre-recruit index is well below the mean of those in the 25-year time series.
- The stock is being assessed using an integrated model (Northern Cod Assessment Model, NCAM), which allows quantification of uncertainty in estimated and projected stock status.
- The estimate of Spawning Stock Biomass (SSB) in 2021 is 411 kt (95% CI = 307–549 kt). SSB currently remains in the critical zone, at 52% (95% CI = 39–69%) of the Limit Reference Point (LRP). The stock has remained at about the same level since 2017.
- Natural mortality rate (M) estimated from NCAM for ages 5+ for 2020 was 0.51 (95% CI = 0.30–0.89). The average M over the last 10 years was 0.39 (range = 0.29 to 0.63).
- The fishing mortality rate (F) estimated from NCAM for ages 5+ is currently low, and for 2020 was 0.018 (95% CI = 0.014–0.024). The average F over the last 10 years is 0.02 (range = 0.014 to 0.028).
- Recruitment (age 2) estimated from NCAM increased from the lowest estimated levels of 34 million fish in 1995 to an average of 314 million per year for cohorts from 2015 to 2019. This recent average is 25% of the pre-collapse period of the 1980s.
- A one year projection from NCAM with catch ranging from zero to 1.3 times (15,360 t) the model estimated catch for 2020 (11,816 t) indicated that the probability that SSB will reach the LRP by 2022 is <0.02. The probability of the stock being greater in 2022 than in 2021, across all catch scenarios examined ranged from 0.52 to 0.59. The calculation of the Harvest Decision Rule (HDR) for this stock in accordance with the Northern Cod Rebuilding Plan indicates removals for 2021 of 12,999 t for stewardship fishery catch. When accounting

for the recreational fishery these removals are likely to fall at, or above, the upper range of catch scenarios examined.

- Consistency with the DFO decision-making framework incorporating the precautionary approach requires that removals from all sources must be kept at the lowest possible level until the stock clears the critical zone.

INTRODUCTION

History of the Fishery

Reported landings of Northern cod increased during the 1960s to a peak of over 800,000 t in 1968, declined steadily to a low of 140,000 t in 1978, increased again to about 240,000 t through much of the 1980s, and then declined in the early-1990s in advance of a moratorium on directed fishing in 1992 (Figure 2).

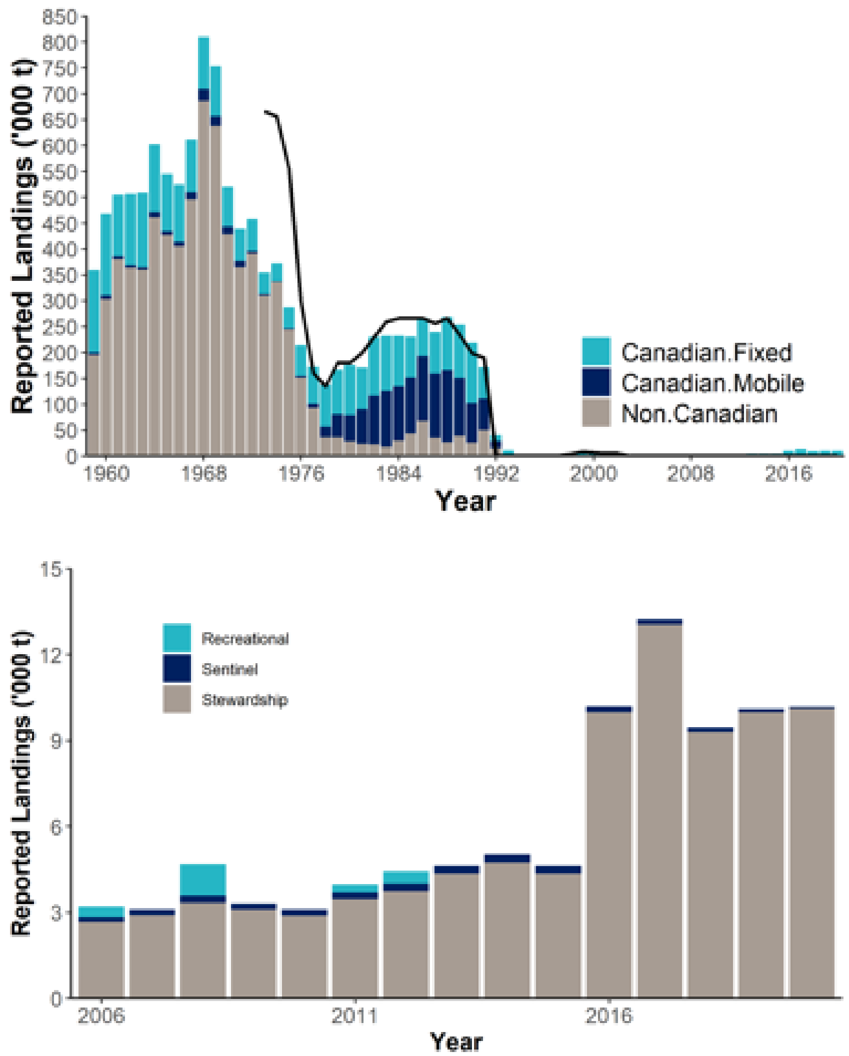

Figure 2: Top panel is Total Allowable Catches (TACs, black line) and reported landings (thousands of tons) from 1959-2020. The bottom panel is expanded to show trends from 2006 onwards. Direct estimates of recreational catches are only available for 2006, 2008, and 2011–12 in the past 17 years.

Landings during 1993–97 came from by-catches, food/recreational fisheries, and DFO-industry sentinel surveys that started in 1995. In addition, landings from 1998–2002 also came from a limited index/commercial inshore fishery restricted to fixed gear and small vessels (<65 ft). The directed commercial and recreational fisheries were closed in April 2003; most of the landings in 2003 came from an unusual mortality event in Smith Sound, Trinity Bay. During 2004 and 2005, substantial by-catches (>600 t) of cod were taken in the inshore, mostly in Divs. 3KL, in the Winter Flounder (blackback; *Pseudopleuronectes americanus*) fishery.

The directed inshore “stewardship” fishery and a recreational fishery for cod were re-opened in the inshore in 2006 and continue to present (Figure 2, bottom panel). Note that the management year extended from April 1 to March 31 the following year (since 2000), but catch statistics were reported in calendar years herein as there had been no significant landings from this stock during January-March (since around 1993). There was no formal TAC; commercial fishers were permitted a fixed annual allowance per licence holder. Beginning in 2016, the 2J3KL Northern Cod Stewardship Fishery had been managed using variable weekly catch limits, gear restrictions, seasons, and in 2018, a maximum authorized harvest amount (MAH; 9,500 t) was introduced. For the 2020 season, the MAH amount was set at 12,350 t.

Total reported landings in 2020 were 10,128 t: 10,063 t from the stewardship fishery, 60 t in the sentinel surveys, and 5 t taken as by-catch (mostly from the redfish [*Sebastes* spp.] and turbot [*Reinhardtius hippoglossoides*] fisheries). The Scientific Council of the Northwest Atlantic Fisheries Organization (NAFO) reported that the annual catches of cod by non-Canadian fleets outside the 200 nautical mile limit on the Nose of the Grand Bank (Div. 3L) were 300 t or less during 2000–20 (provisional value of 38 t in 2020).

Recreational landings were regulated by number of days (39 days in 2020) and number of fish per person (5 per person, and a maximum of 15 fish per boat). Currently there is no recreational licence regime and therefore no required mechanism to report recreational landings. Some effort has gone in to obtaining estimates of recreational landings (see Brattey et al. 2018; Seiden Pers. Comm.) and tagging data was used to determine the relative magnitude of recreational catches compared to reported landings. There were no direct estimates of recreational landings for eight of the past 10 years; therefore, reported landings were less than total catch in those years. Evidence from tagging data showed that although removals by the recreational fishery were substantial in some years since 1997, they have been about 20% of the commercial catch in the last three years (2018–20).

Catch at Age

The age structure of cod captured in the 2020 stewardship and sentinel fisheries showed an age range dominated by fish aged 8 and 9, which was somewhat unusual for a fishery dominated by gillnets (5½” and 6” mesh), and represented a shift to older fish. The relatively strong 2009 year class was apparent in the commercial catch as age 9 in 2018, 10 in 2019 and 11 in 2020.

Species Biology

Historically much of the Northern cod stock was highly migratory. They over-wintered near the edge of the continental shelf and migrated in spring/summer to shallow waters along the coast and onto the plateau of the Grand Bank. By the mid-1990s these offshore over-wintering components were barely detectable, but at the same time, there were aggregations of cod over-wintering in the inshore in Div. 3L and southern Div. 3K. These components appeared to be more productive during the 1990s than those in the offshore.

In recent years, the status of cod in the offshore improved and the shoreward seasonal migration pattern observed prior to the moratorium resumed. Over-wintering inshore aggregations, such as those observed in Smith Sound, Trinity Bay, had since diminished. The biomass of cod in the offshore increased in most of the stock area in the past decade, except in southern Div. 3L. The migration of cod from the offshore to inshore areas during summer was likely substantial.

Cod off Labrador and eastern Newfoundland grow slowly and are less productive compared with populations in the eastern Atlantic, the Flemish Cap (Div. 3M), and further south in the western Atlantic. Since the late-1980s female cod throughout 2J3KL have been maturing at about age 5, which is younger than in previous years.

Juvenile Cod Surveys

Coastal production of pre-recruit cod (age 0 and age 1 juveniles) was monitored in Newman Sound, Bonavista Bay, continuously since 1995. This work, in addition to periodic larger-scale surveys of pre-recruit cod, indicated that younger cod were primarily distributed inshore and highlighted the importance of shoreline habitats as important nursery habitat. Cod tended to disperse to the offshore as they aged. Strong correlations between the Newman Sound pre-recruit index and numbers of age 2 and 3 cod estimated by the Northern Cod Assessment Model (NCAM) suggested that indices from inshore nurseries may serve as good predictors of subsequent recruitment to the offshore population. The Newman Sound pre-recruit index suggested that cohorts from 2018–20 would be weaker than those in the past ten years and well below the mean of those in the 25-year pre-recruit time series.

In 2020, the “Fleming” survey was restarted as an inshore survey of juvenile cod on the east coast of Newfoundland (Lear et al. 1980). The reestablishment of the Fleming survey in 2020 enabled comparison of pre-recruit cod catch levels within the Fleming time series (1959–64; 1992–97; and 2001) at select juvenile cod nursery sites in St. Mary’s Bay, Conception Bay, Trinity Bay, Bonavista Bay, and Notre Dame Bay (Lewis et al 2022).

ECOSYSTEM INFORMATION

Physical Environment

The ocean circulation off Labrador and eastern Newfoundland was dominated by the southward flowing Labrador Current system which transported cold and relatively fresh water from the Arctic on the shelf, and warmer and saltier Labrador Sea water along the continental slope. The marine conditions on the NL shelf have varied considerably since the start of standardized measurements in the mid-1940s. A general warming phase reached its maximum by the mid-1960s. Sub-surface hydrographic properties on the shelf (e.g., bottom temperature and cold intermediate layer) were largely determined by the previous winter conditions and these properties were carried over by this current system. Summer conditions, especially near the surface, were influenced by other factors such as local winds, freshwater runoff, and air temperatures. The main features of an analysis of historical climate data showed mostly above average temperature conditions during the 1960s, a brief cold period during the early-1970s and again in the mid-1980s. Driven by a positive phase of the winter NAO, environmental conditions then reached their coldest level on record in the early-1990s and remained colder than normal until the mid-1990s. Since then there had been a significant warming trend with temperatures reaching record highs around 2010–11. After a short return to colder conditions between about 2014–17, data from recent years (2018–20) suggested that the system was returning to a warming phase.

The impact of these oceanographic changes on cod population dynamics was difficult to determine but, in general, Northern cod tended to be more productive when water temperatures were on the warmer end of the regional norm.

Ocean Productivity

Higher ocean nitrate concentrations observed since the mid-2010s were associated with an increase in the amount of chlorophyll *a* to near-normal or above-normal levels across NAFO Divisions 2J3KL since 2017 after six consecutive years of negative anomalies. Satellite ocean-colour data also indicated a trend toward earlier and more productive spring phytoplankton blooms during the same period. The overall increase in zooplankton abundance and biomass since the mid-2010s was characterized by weaker spring and stronger summer and fall signals. The trend in the zooplankton community structure of fewer large, energy-rich calanoid copepods (*Calanus finmarchicus*), but higher abundance of small, less energy-rich calanoid (*Pseudocalanus* spp.) and cyclopoid (*Oithona* spp.) copepods observed since the early-2010s weakened over the past 2–3 years. There was also a notable increase in the abundance of non-copepod zooplankton such as pteropods, appendicularians, and hyperiid amphipods since around 2010. It was unclear how these shifts in the zooplankton seasonality and community structure effected energy transfer to higher trophic levels and survival of planktivorous life stages of fish including Northern cod.

Ecosystem

Ecosystem conditions on the Newfoundland Shelf and Northern Grand Bank (NAFO Divs. 2J3KL) continued to indicate limited overall productivity of the fish community. Total biomass levels remained much lower than prior to the collapse in the early-1990s. After some recovery since the collapse, current levels of total biomass were lower than those observed in the early-2010s.

The increase in groundfish species observed in the late-2000s and early-2010s appeared associated with bottom-up processes, including an improved prey field with modest increases in Capelin availability in comparison with the 1990s. Declines in total finfish biomass in recent years were likely associated with simultaneous reductions in Capelin and shrimp availability.

The dynamics of the Northern cod stock are driven by an interplay between fisheries removals and bottom-up forces, such as availability of food, especially Capelin (*Mallotus villosus*) (e.g., Rose and O'Driscoll 2002, Drinkwater 2005, Shelton et al. 2006, Sherwood et al. 2007, Halliday and Pinhorn 2009, Buren et al. 2014, Morgan et al. 2017, Koen-Alonso et al. 2021). Shrimp has also been an important prey species for cod, and given the importance of prey for growth and survival, simultaneous low availabilities of two major forage species in the ecosystem could compromise the recovery of cod in particular, and the groundfish community in general. There was a decline in the proportion of Capelin and shrimp in cod diets in recent years. Stomach content weights also showed a declining trend, suggesting limitations in food availability.

Top-down control, such as predation on cod, has also been postulated as a factor limiting the recovery of the stock. Predation on cod by cod (cannibalism) and turbot has shown an important increase since the mid-2010s, which is consistent with prey field reductions. Predation by harp seals has also been proposed as a potential limiting factor, and while seals do eat cod, the available research indicated that harp seal predation is not a significant driver of cod population dynamics (Buren et al. 2014). Most notably, the increase in groundfishes in general, and Northern cod in particular, observed since the mid- to late-2000s, have occurred in a period of increasing harp seal population.

A recently developed bioenergetic-allometric model ("capcod"), which used research vessel (RV) survey cod biomass, catches, and acoustic estimates of Capelin biomass was examined (Koen-Alonso et al. 2021). This model indicated that the per capita net biomass productivity of Northern cod was linked to Capelin availability. Under the forecasted levels of Capelin for 2020–22 (DFO 2022), the capcod model indicated that Northern cod was expected to remain stable or decline under all catch levels considered, but modest improvements in the level of Capelin could positively affect this projection. Capcod in conjunction with the Capelin forecast model suggested that the prospect of the stock rebuilding to pre-collapse levels in the next 1–5 years was poor.

ASSESSMENT

Sources of Data

This assessment was based on the NCAM, an integrated state-space model developed specifically for Northern cod that utilized much of the existing information on the productivity of this stock (Cadigan 2016a and 2016b). The model used age-disaggregated information from the DFO fall offshore bottom-trawl survey (ages 2–14, 1983–2020), inshore Sentinel 5½" mesh gillnet index (combined Divs. 2J3KL; ages 3–10, 1995–2020), inshore acoustic biomass estimates (1995–2009), fishery catch age-composition information (1983–2020), reported fishery landings information (1983–2020), and tagging information (1983–2020).

Traditional stock assessment models such as virtual population analysis (VPA) required that catch was known without error and also typically assumed a fixed value for the level of M. Key features of the NCAM model were that it provided annual estimates of M and F along with measures of uncertainty (see Cadigan 2016a and 2016b for details). In addition, the model estimated the catch, rather than assuming that reported landings were an exact measure. The model required an interval identifying a likely range of catch (lower and upper bounds) and these were determined during discussions with stakeholders present at the assessment meetings in 2016 and 2017 and were presumed to be similar in 2018–20 as management measures and stock status had not greatly changed.

Stock Trends

Bottom-Trawl Survey Indices

The DFO fall RV bottom trawl surveys occurred over the continental shelf and slope edge and covered most of the stock area of Northern cod. Indexed strata (strata that had been consistently fished in the survey; in the depth range 100–500 m in Divisions 2J3K and between 55–366 m in Division 3L) were used for the assessment of Northern cod. In 2019, weather disrupted the survey so the number of completed survey sets (i.e., sampled sites) was a considerable reduction of 27% from the planned sets (346 planned sets versus 252 observed sets). However, most incomplete strata were in deep water (>750 m), deeper than the index strata used for this stock. Additionally, two index strata were not sampled in 2019 in Div. 3K. These two missed strata were relatively unimportant to the total biomass estimates for Northern cod (<1% on average). However, the precision of the 2019 survey index was likely reduced by the decrease in set density in other strata. In 2020, although there was overall reduced coverage (20% reduction in planned allocation of sets), all indexed strata were sampled.

The abundance and biomass indices from the DFO fall RV surveys had been low since the start of the moratorium in 1992 (Figs. 3 and 4). However, both abundance and biomass were at higher levels from 2012–20 compared to the previous 25 years. The three-year average (2018–

20) for both abundance and biomass indices was approximately 31% of the average during the 1980s. In 2020, there was one large set in Division 2J that accounted for a large proportion (about 15%) of the total biomass; this was not unusual and large catches occasionally occurred when cod aggregated and therefore it was considered appropriate to include in the analysis.

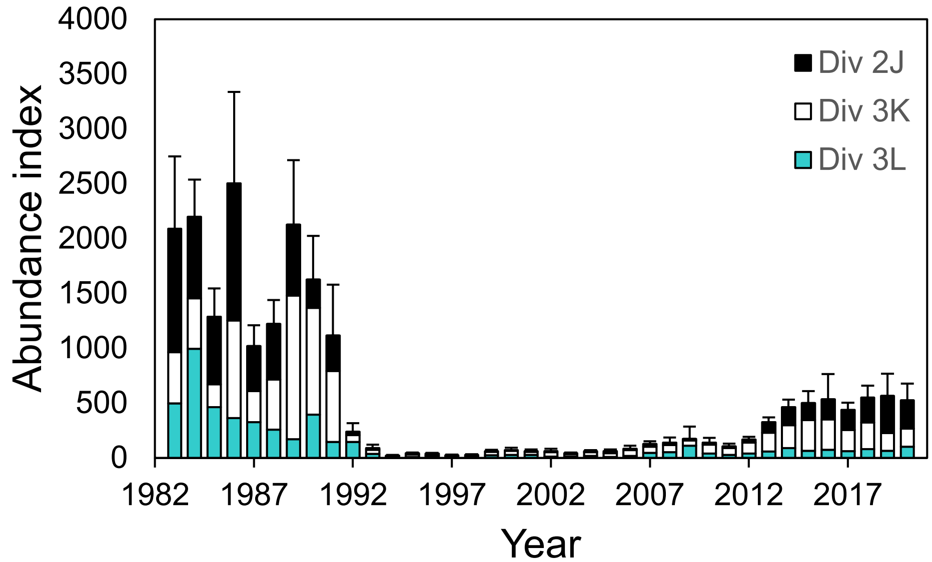

Figure 3: Offshore abundance index for cod (±2 standard errors) from fall RV surveys in NAFO Divs. 2J3KL.

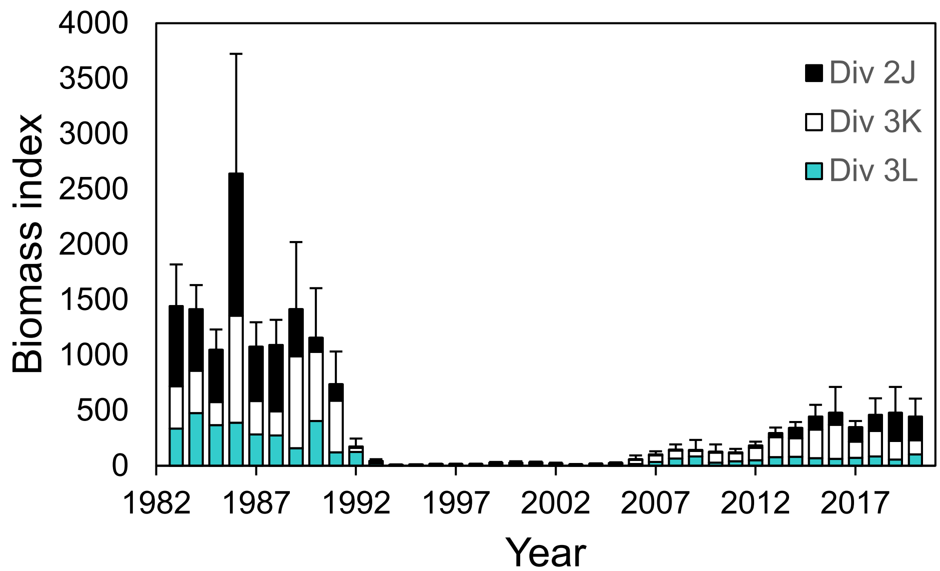

Figure 4: Offshore biomass index for cod (±2 standard errors) from fall RV surveys in NAFO Divs. 2J3KL.

There was an increase in the range of ages observed in the stock since around 2013, indicating that there was some reversal of the age truncation apparent during the post-moratorium period in the late-1990s and early-2000s.

Tagging

Information from recaptures of cod tagged during 1983–2020 was integrated in the assessment model, and these data were particularly important for estimating F and M. The tagging data used comprised 169,363 releases and 17,440 recaptures and the analysis incorporated methods to estimate the ages of tagged cod and adjustments for initial tagging mortality, tag loss, and reporting rates. The tagging data were also used to provide information on the magnitude of recent recreational fisheries and for setting catch bounds for the period 2006–20.

The reporting rate for low-reward tags (commercial and recreational combined) during 2020 was 44%. Generally, reporting rates slowly declined since 2003.

Recreational fishers were responsible for a substantial proportion of total Atlantic cod tag returns, accounting for an average of 29% of total annual tags returned from NAFO Divs. 2J3KL over the past 10 years (2011–20). When this number was adjusted for fishery specific reporting rate, the relative contribution of recreational fishers averaged about a third of commercial returns (0.34) between 2011–20, ranging from a low of 0.05 in 2019 to a high of 0.84 in 2014.

In the most recent years (2016–20), the relative contribution of recreational fishers declined slightly (average 0.19), likely due to increases in the commercial harvest. Overall the results indicated that recreational landings contributed to removals and that total removals were higher than reported landings.

Model results

The diagnostics from the 2020 model run indicated that there was generally a good fit of the model to the data. Retrospective analysis showed very little directional pattern. However, residuals in the RV survey for the older fish in recent years and the younger fish in the Sentinel index indicated a divergence in these indices. There were a number of factors which could have accounted for this issue, including the proportion and age-structure of the stock available to the Sentinel survey or whether there had been changes in growth that changed the age-specific catchability of the gillnets. These, and related other issues, will need to be explored further.

The abundance (2+ years) of Northern cod remained low after the collapse and moratorium in 1992, but increased from 229 million in 2005 to 1.1 billion (95% CI, 696 million–1.8 billion) in 2021 (Fig. 5, left panel). Biomass of fish aged 2+ showed a similar trend to abundance and increased from 87 kt in 2005 to 643 kt in 2021 (95% CI, 494–838 kt; Fig 5, right panel). Spawning stock biomass increased from 25 kt in 2005 to 411 kt (95% CI, 307–549 kt) in 2021.

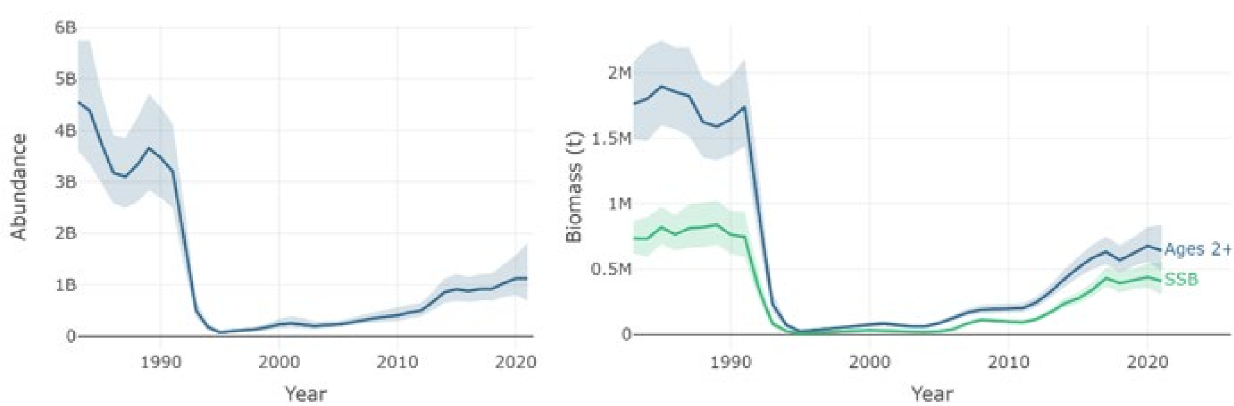

Figure 5: Model-based trends in Northern cod abundance (left panel) and biomass (right panel) from 1983–2021. Shaded areas are 95% confidence intervals.

F was variable during the earlier part of the time series, from 1983–2006 (Fig. 6, left panel). Average F for ages 5–14 were around 0.22 during most of the 1980s, and declined after the moratorium was imposed in 1992. Directed inshore fisheries for cod continued throughout most of the post-moratorium period. F (ages 5–14) was low (0.06) during 1995–97 when inshore fishing was highly restricted, but increased rapidly, reaching close to pre-moratorium values (F = 0.13 to 0.22) when a directed inshore fishery for cod was reopened in 1998–2002. Closure of the directed inshore fishery in 2003–05 resulted in a substantial reduction in F (0.04). For the most recent decade, F was low, averaging about 0.02 (see Fig. 2).

M was variable during 1983–2020 (Fig. 6, right panel), ranging from 0.3 to 0.4 in the early- to mid-1980s, increasing rapidly to a peak of 2.6 during 1992–94, then declining to approximately 0.37 during 1995–99. Additional periods of high M were evident in 2000–03 (M = 0.72 to 0.93) and 2008–10 (M = 0.61 to 0.65). The average M over the last 10 years was 0.39 (range = 0.29 to 0.63). In 2020, M was 0.51 (95% CI = 0.30–0.88) (equivalent to annual survival of roughly 60%).

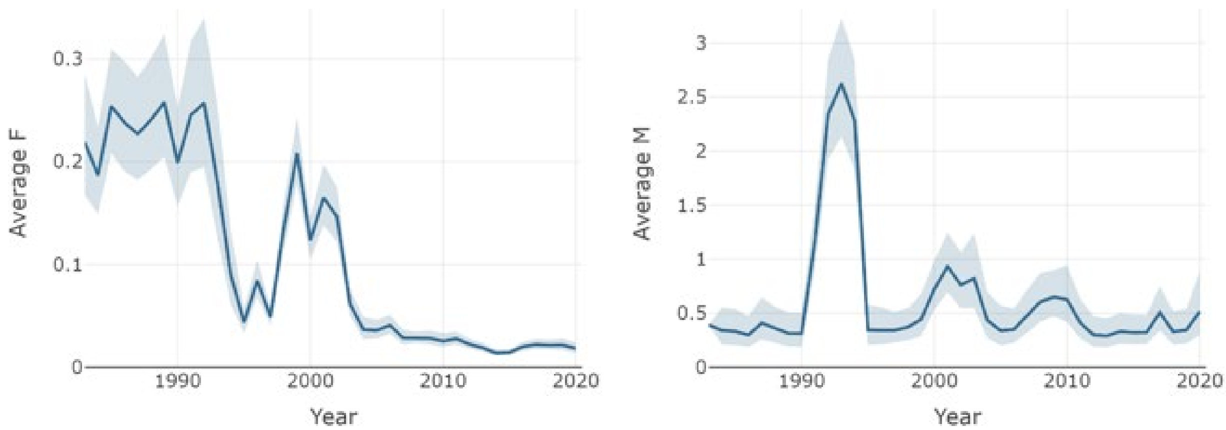

Figure 6: Trends in population-weighted fishing mortality rates (F, left panel) and natural mortality rates (M, right panel). Solid lines are the age-aggregated model estimates (ages 5–14) and shaded areas are 95% confidence intervals.

These NCAM-based relative magnitudes of F and M around the time of the moratorium were different from some published studies exploring the causes of the stock collapse (e.g., Hutchings and Myers 1994, Myers et al. 1996). In the NCAM model, M was estimated and information from tagging was integrated directly into the model, whereas in previous population models of Northern cod, M was an assumed constant value (typically M = 0.2) and tagging data were analyzed in isolation. The current model could assign the sudden disappearance of cod from the DFO RV survey to either F or M (or both), but to be consistent with the tagging data and censored landings, the model assigned much of the mortality to M. It should be noted that if there was unreported catch by Canadian and/or non-Canadian fleets, and tags from these fish were not returned, then a portion of the M estimated in the current analysis would actually be F. However, there was a growing number of studies documenting that the entire groundfish community (both commercial and non-commercial species) collapsed at the same time, leading to a regime shift where both fishing and environmental signals appeared as important drivers of these changes (Koen-Alonso et al. 2010, 2013; Buren et al. 2014; Dempsey et al. 2017, 2018; Pedersen et al. 2017, 2020; Koen-Alonso and Cuff 2018; NAFO 2019). This body of evidence lent weight to the idea that the collapse was not driven by fishing alone, but by the compounding effects of fishing and natural mortality. Investigations on the relative size of F versus M leading up to the moratorium and the current period are ongoing.

Recruitment (age 2) increased from lowest estimated levels of approximately 34 million fish in 1995 to an average of 314 million in 2015–19 (more recent age class estimates were less precise) (Fig. 7). This recent average was 20% of the pre-collapse period of the 1980s.

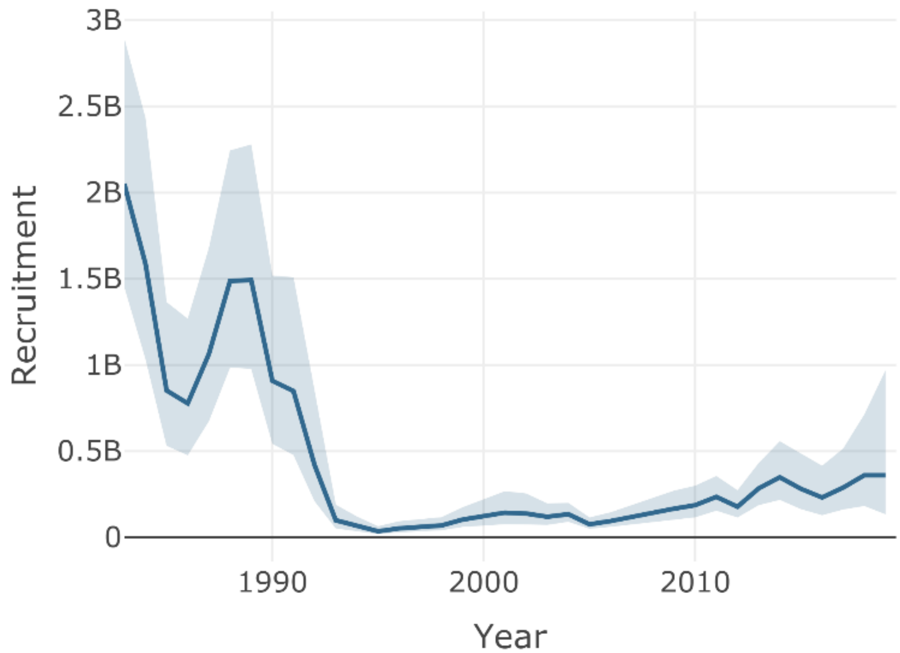

Figure 7: Trends in Northern cod recruitment (number at age 2). Solid line is the model estimate, and shaded areas are 95% confidence intervals.

Spawning Stock Biomass (SSB) remained in the critical zone in 2021, at 52% of the Limit Reference Point (LRP) (95% CI, 39–69%) (Fig. 8). This represented an increase from the estimate of 3% of B_{lim} in 2005.

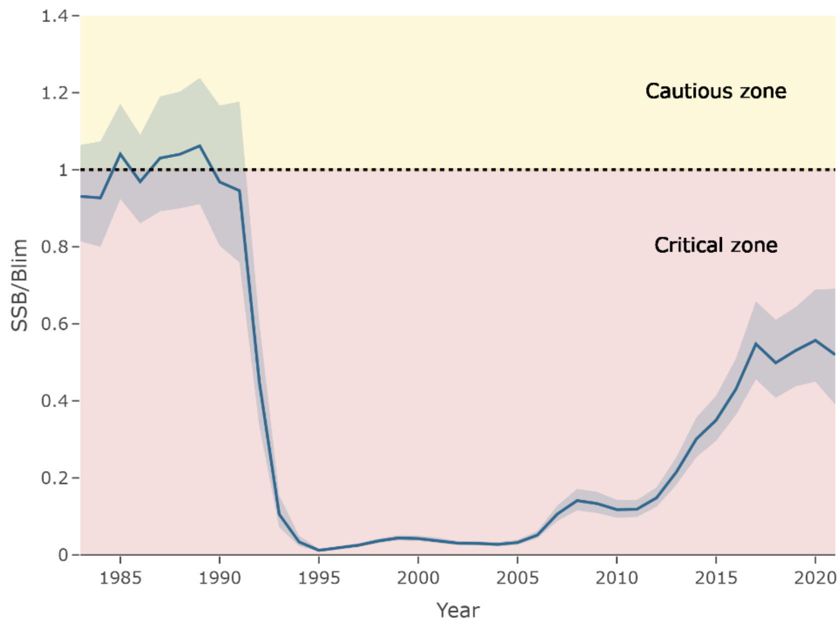

Figure 8: Trends in Northern cod SSB relative to the limit reference point B_{lim}, where B_{lim} (dashed line) is defined as the average SSB during the 1980s. Solid line is the model estimate and shaded areas are 95% confidence intervals.

Projections

A one year projection, to 2022, was carried out to investigate the potential impact of a range of catch scenarios from zero catch to a 1.3-fold increase in catch. Projections were based on the model estimate of catch for 2020 (11,815 t). The age-pattern in F values was assumed to be the same as in 2020. Projected recruitment, stock weights, and proportions mature were assumed to be equal to the mean of their 2018-20 values. Assumed recruitment (age 2) had no impact on the projected SSB as these fish did not reach SSB in the time period of projections. Projections beyond one year were not conducted due to uncertainty about the level of future natural mortality, and the diverging age patterns in the Sentinel and RV surveys.

Under all catch scenarios explored, the projections indicated that the stock would either remain at the same level or increase slightly and that there was a probability between 0.52 and 0.59 that SSB in 2022 would be above the current 2021 value. However, there was a very low probability (0.02) of exceeding B_{lim} in 2022 (Table 1). In 2022, under current catch levels, the SSB relative to B_{lim} was projected to be 0.53 with wide confidence intervals of 0.32 to 0.86 (Fig. 9).

Table 1: Results of projections for catch multipliers from 0 (no catch) to 1.3 times the estimated catch in 2020 (11,816 t).

Projected Catch	Probability of growing out of the critical zone $P(B_y>B_{lim})$	Probability of growth from current levels $P(B_y>B2021)$	SSB_y/B_{lim}
-	**2022**	**2022**	**2022**
0	1%	59%	54%
0.7*$Catch_{2021}$	1%	55%	53%

Projected Catch	Probability of growing out of the critical zone $P(B_y>B_{lim})$	Probability of growth from current levels $P(B_y>B2021)$	SSB_y/B_{lim}
-	**2022**	**2022**	**2022**
0.85 *$Catch_{2021}$	1%	54%	53%
1.0*$Catch_{2021}$	1%	53%	53%
1.15*$Catch_{2021}$	1%	53%	52%
1.3* $Catch_{2021}$	1%	52%	52%

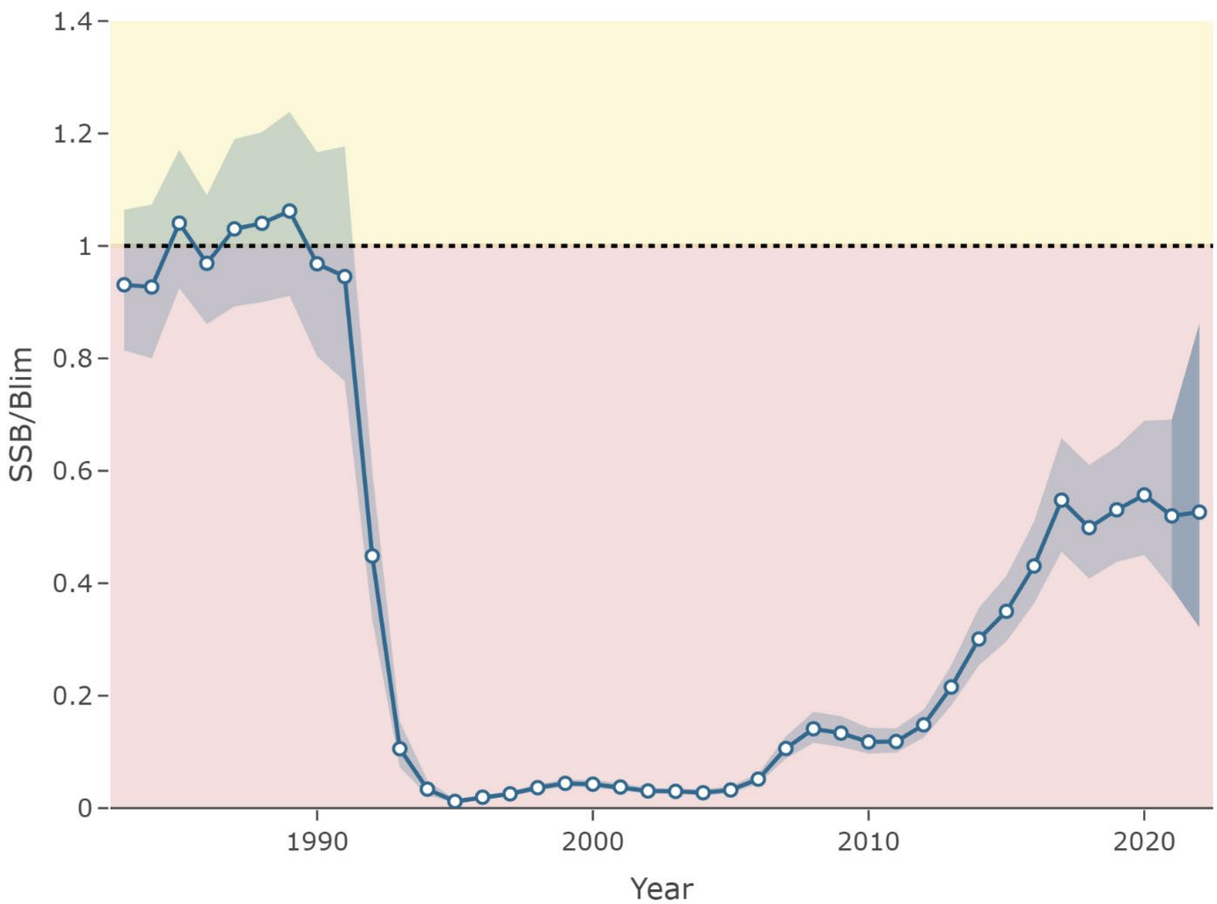

Figure 9: One year projection (to 2022) of Northern cod Spawning Stock Biomass (SSB) under status quo catch levels (11,816 t) relative to the limit reference point B_{lim}, where B_{lim} (horizontal dashed line) is defined as the average SSB during the 1980s. Solid line with circles is the model median estimate and light grey envelope is 95% confidence intervals. Dark grey envelope are 95% confidence intervals for the projection period.

Harvest Decision Rule

The Rebuilding Plan for cod (DFO 2020) had the objective of rebuilding the stock out of the Critical Zone of the Precautionary Approach framework, specifically within the range of 25% to 75% B_{lim}. A Harvest Decision Rule (HDR) was developed to keep fishing mortality low while allowing gradual changes to catch as stock size changed, with increased responsiveness when the stock was below 52% of the LRP.

The calculation of the HDR for this stock indicated removals for 2021 of 12,999 t stewardship fishery catch, based on the following equation:

$$C = C_{2017} + C_{2017}\left(1+\gamma\left(\frac{B}{B_{\text{lim}}}-0.52\right)^2\right);\ \begin{cases}\dfrac{B}{B_{\text{lim}}} < 0.52, \gamma = \dfrac{y_l - 1}{(x_l - x_{mid})^2} \\ \dfrac{B}{B_{\text{lim}}} > 0.52, \gamma = \dfrac{y_h - 1}{(x_h - x_{mid})^2}\end{cases}$$

Parameters of Rule	Value	Description
x_{mid}	0.52	Midpoint of HDR
x_l	0.25	Lower bound of b/b_{lim}
x_h	0.75	upper bound of b/b_{lim}
y_l	0.33	Catch is 33% of C_{2017} at $b/b_{lim}=x_l$ (0.25)
y_h	1.5	Catch is 150% of C_{2017} at $b/b_{lim}=x_h$ (0.75)
C_{2017}	13000	Catch value in year 2017 (tonnes)

With the above values, the equation evaluated to:

$$C = 13000 + 13000\left(1+\gamma\left(\frac{B}{B_{\text{lim}}}-0.52\right)^2\right);\ \begin{cases}\dfrac{B}{B_{\text{lim}}} < 0.52, \gamma = -9.19 \\ \dfrac{B}{B_{\text{lim}}} > 0.52, \gamma = 9.45\end{cases}$$

Additional Sources of Information

Other information reviewed at the assessment but not included in this report included the following: biological characteristics (growth, condition, maturity) obtained from analysis of catch rate-at-age in the fall surveys; recaptures of conventionally tagged cod combined with detections of acoustically tagged cod were used to estimate mortality rates and investigate migration patterns; analysis of catch rate trends from DFO-Industry Sentinel survey not used in the state space model (i.e., 3¼ inch mesh gillnet and line-trawls) from three inshore regions; logbooks from commercial vessels for post-moratorium fisheries to investigate area-specific inshore catch rate trends; information on the relative abundance of young cod (ages 0 and 1) from beach seine studies in Newman Sound, Bonavista Bay, and approximately 40 Fleming survey sites spanning the Avalon and Northeast coast of the island of Newfoundland; information on the size and/or age composition of the catch obtained from lengths and otoliths collected from cod sampled at ports and at sea during stewardship, Sentinel and recreational fisheries. Details of these sources of information may be found on the DFO Canadian Science Advisory Secretariat (CSAS) website in the Research Documents Series when available.

Sources of Uncertainty

As noted, the Sentinel and RV surveys were showing different trends in recent years. Conflicting patterns were potentially related to changes in the availability of the stock to the inshore Sentinel survey or related to differences in the selectivity of the gear (gillnets) as mean lengths-at-age changed in the stock. A thorough overview of this data source should be carried out to determine whether the current analysis methods should be revised to account for changes in the catchability of the Sentinel survey.

The relationship between reported landings and total deaths due to fishing from both commercial and recreational fisheries had some uncertainty. Total deaths due to fishing were estimated by the model based on the survey, reported landings, and tagging data; therefore the model-estimated catches could have been different from reported landings.

The range of catch bounds used in the assessment model represented a structural uncertainty. The likely range of catch (lower and upper bounds) was determined during discussions that included stakeholders present at assessment meetings.

Since 2005, there were no direct estimates of recreational landings for most years (2006, 2008, 2013–20) and available estimates in other years had some uncertainty. Although tagging could provide an estimate of recreational catch, annual estimates had wide confidence bounds and removals from all sources should be better accounted for to reduce uncertainty in the assessment model inputs.

Tag reporting rates were determined from returns of low and high reward tags. Low reporting rates led to less tagging data, which increased the uncertainty in a number of estimates and indices: assessment model estimates, the relative contributions of commercial and recreational harvest, and analyses of movement patterns and stock structure. Harvesters (recreational and commercial) should return all tags in a timely fashion to help reduce this uncertainty.

The catastrophic mortality event in the early-1990s, attributed to M in the current assessment, was controversial and a major source of uncertainty regarding the dynamics of the stock and impact of the fishery at that time.

M played an important role in projections for this stock. There was a high level of uncertainty in the projections beyond the first year due to the level of future natural mortality. If estimates for M in 2021 were appreciably different than those used, projected outcomes would differ from values reported above.

Management Considerations

Although information from tagging and the assessment model indicated that the current F was low, the recreational fishery could have been a substantial component of total removals. Recreational removals could be an important source of mortality particularly when stock size was low and the stock was not productive. Improving the management of recreational fisheries was strongly recommended so that total removals could be effectively controlled and directly measured. Work should continue to monitor catches in the recreational fishery.

Ecosystem conditions were indicative of an overall low productivity state including low levels of key forage species such as Capelin and shrimp. Capelin was a key forage species in the ecosystem at large and a driver of Northern cod dynamics in particular. Capelin was anticipated to remain at low levels to 2022. This was expected to negatively impact cod productivity and could have compromised the potential for recovery of cod. Rebuilding Capelin stocks appeared as a necessary condition for the rebuilding of cod. Low levels of Capelin should signal the need for a more cautious approach with regard to harvesting decisions. Without an adequate food source, the potential for continued stock growth was limited.

While the model output indicated that M was the driving factor behind stock size, the stock was in the critical zone, and due to low levels of forage prey and low levels of productivity in the system, harvesting decisions must be made with caution.

The NCAM estimates of actual catches could differ substantially from the reported catches and were influenced by the assumed catch bounds. In projections, catch multipliers were applied to the estimated catches from the model, not the reported landings. When accounting for the recreational fishery these removals were likely to fall at, or above, the upper range of catch scenarios examined. When setting future harvest levels, it is important to consider the proportion that is expected to be unreported (i.e., in particular, recreational fishery catches).

Projections and trends in general indicated wide confidence intervals around a point estimate. When making management decisions, it is important to take this uncertainty into account.

CONCLUSIONS AND ADVICE

A conservation LRP (B_{lim}) established for Northern cod in 2010 was determined to be the average SSB of the 1980s. The LRP was re-evaluated in 2019 and no change from the 2010 recommendation was advised. The estimated SSB has been well below the LRP since the early-1990s. Although the status of the stock has improved since the 2000s, the estimate of 2021 SSB was 52% of B_{lim} (95% CI, 39–69%) and remained in the critical zone. At current levels of SSB the stock was considered to have suffered serious harm and the ability to produce good recruitment was seriously impaired. When the stock is at such a low level, management actions should focus on promoting increases in SSB until the stock is more resilient to the effects of fishing.

A one-year projection to 2022 indicated a low probability (<1%) of reaching B_{lim} under any catch scenario. Consistency with the DFO decision-making framework incorporating the precautionary approach requires that removals from all sources must be kept at the lowest possible level until the stock clears the critical zone.

LIST OF MEETING PARTICIPANTS

Name	Affiliation
Dale Richards	DFO-NL – Centre for Science Advice
Erika Parrill	DFO-NL – Centre for Science Advice
Hilary Rockwood	DFO-NL – Centre for Science Advice
Jennifer Duff	DFO-NL – Communications
Ellen Careen	DFO-NL – Resource Management
Julia Sparkes	DFO-NL – Resource Management
Robyn Morris	DFO-NL – Resource Management
Darrell Mullowney	DFO-NL – Science
Aaron Adamack	DFO-NL – Science
Bob Gregory	DFO-NL – Science
Bob Rogers	DFO-NL – Science
Corey Morris	DFO-NL – Science
David Belanger	DFO-NL – Science

Name	Affiliation
Divya Varkey	DFO-NL – Science
Dwayne Pittman	DFO-NL – Science
Emilie Geissinger	DFO-NL – Science
Emilie Novaczek	DFO-NL – Science
Fran Mowbray	DFO-NL – Science
Fred Tulk	DFO-NL – Science
Frederic Cyr	DFO-NL – Science
Hannah Monro	DFO-NL – Science
Hannah Murphy	DFO-NL – Science
Jennica Seiden	DFO-NL – Science
Karen Dwyer	DFO-NL – Science
Keith Lewis	DFO-NL – Science
Laura Wheeland	DFO-NL – Science
Luiz Mello	DFO-NL – Science
Mariano Koen-Alonso	DFO-NL – Science
Nick Gullage	DFO-NL – Science
Paul Regular	DFO-NL – Science
Rachel Holub	DFO-NL – Science
Rajeev Kumar	DFO-NL – Science
Rick Rideout	DFO-NL – Science
Ron Lewis	DFO-NL – Science
Sana Zabini- Seissan	DFO-NL – Science
Daniel Ricard	DFO-Gulf – Science
Martha Krohn	DFO-NCR – Science
Ryan Chlebak	DFO-NCR – Fish Population Science
Sky Ann Lewis	DFO-NL – Conservation and Protection
Greg Robertson	ECCC Science and Technology
Anna Tilley	Fisheries and Land Resources
Albert Wells	Fish, Food and Allied Workers Union
Chad Strugnell	Fish, Food and Allied Workers Union
Erin Carruthers	Fish, Food and Allied Workers Union
Harrison Campbell	Fish, Food and Allied Workers Union
Keith Smith	Fish, Food and Allied Workers Union
Kris Vascotto	GEAC
Jim Baird	NLGIDC
Derrick Dalley	Innu Nation
Todd Broomfield	Nunatsiavut Government
Rob Coombs	NunatuKavut Community Council
Daniel Howell	Institute of Marine Research, Norway
Abe Solberg	Memorial University - Marine Institute
Matthew Robertson	Memorial University - Marine Institute

Name	Affiliation
Noel Cadigan	Memorial University - Marine Institute
Raquel Ruiz	Memorial University - Marine Institute
Sherrylynn Rowe	Memorial University - Marine Institute
Tyler Eddy	Memorial University - Marine Institute
Chelsey Karbowski	Oceans North
Devan Archibald	Oceana Canada
Victoria Neville	WWF Canada

SOURCES OF INFORMATION

This Science Advisory Report is from the March 23–26, 2021 regional advisory meeting on the Stock Assessment of Northern cod (Divs. 2J3KL). Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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APPENDIX I - TABLES

Table A1: Reported landings by management year in NAFO Divs. 2J3KL (nearest thousand metric tons).

Year	62-76 Avg.	77-91 Avg.	98	99	00/01	01/02	02/03	03-06 Avg.	06/07[1]	07/08[1,2]	08/09[1]	09-12[1,2]	12-15[1,2]	15/16[1,2]	16/17[1,2]	17/18[1,2]	19/20[1,2]
TAC	N/A	N/A	4	9	7	6	6	0	-	-	-	-	-	-	-	-	-
Can. Fixed	88	90	5	9	5	7	4	1	3	3	3	3-4	4-5	10	13	10	10
Can. Mobile	9	84	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Others	405	38	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Totals	502	212	5	9	5	7	4	1	3	3	3	3-4	4-5	10	13	10	10

[1] There is currently no TAC in the Stewardship fishery. Since 2016, the 2J3KL Northern cod Stewardship Fishery has been managed using variable weekly catch limits.

[2] Since 2005, there have only been estimates for Canadian recreational fisheries for 2006, 2008, and 2011–12.

Table A2: Northern cod population size and estimates of F and M from the base formulation of the 2021 Northern Cod Assessment Model (NCAM).

Year	Abundance (millions)	Biomass (000 t)	SSB (000 t)	Recruits Age 2 (millions)	Average M Age 5-14	Average F Age 5-14
1983	4555	1765	735	1925	0.39	0.22
1984	4383	1804	732	1470	0.34	0.19
1985	3739	1898	822	783	0.33	0.25
1986	3179	1857	766	710	0.30	0.24
1987	3102	1826	814	981	0.41	0.23
1988	3326	1627	822	1399	0.36	0.24
1989	3655	1591	839	1425	0.31	0.26
1990	3466	1647	765	879	0.31	0.20
1991	3209	1741	747	810	1.16	0.25
1992	1828	946	354	403	2.34	0.26
1993	494	235	83	94	2.63	0.18
1994	177	72	27	63	2.28	0.09
1995	76	26	9	34	0.34	0.04
1996	100	36	15	50	0.34	0.08
1997	117	45	20	57	0.34	0.05
1998	135	56	29	66	0.37	0.14
1999	176	67	35	98	0.44	0.21
2000	229	79	34	122	0.72	0.12
2001	253	84	30	138	0.93	0.16
2002	232	72	24	133	0.76	0.15
2003	199	62	24	115	0.82	0.06
2004	218	62	22	130	0.43	0.04
2005	229	87	25	74	0.34	0.04
2006	267	126	41	90	0.35	0.04
2007	317	167	84	115	0.48	0.03
2008	350	190	111	133	0.61	0.03
2009	379	196	105	159	0.65	0.03
2010	406	195	93	179	0.63	0.03
2011	461	203	94	226	0.41	0.03
2012	500	247	117	179	0.30	0.02
2013	670	325	170	296	0.29	0.02
2014	859	424	238	346	0.33	0.01
2015	915	510	277	279	0.32	0.01
2016	880	586	340	229	0.32	0.02
2017	920	634	433	320	0.51	0.02
2018	922	569	394	359	0.33	0.02
2019	1033	623	419	384	0.34	0.02
2020	1125	678	440	398	0.51	0.02
2021	1126	643	411	-	-	-

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