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Canadian Science Advisory Secretariat
Maritimes Region | Science Advisory Report 2019/015

STOCK ASSESSMENT OF ATLANTIC COD (*GADUS MORHUA*) IN NAFO DIVISIONS 4X5Y

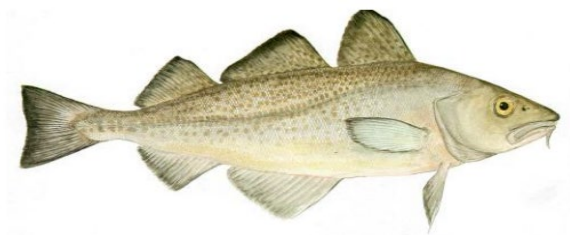

Image: Atlantic Cod, Gadus morhua.

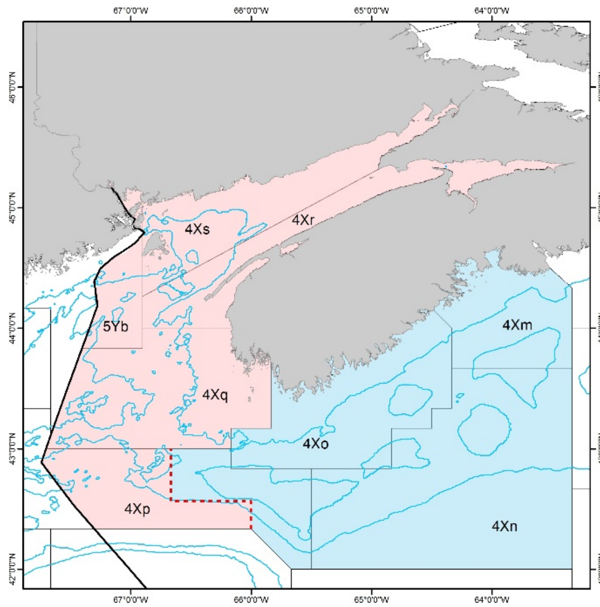

Figure 1. Management area of 4X5Y Atlantic Cod, depicting split between eastern and western components.

Context:

Atlantic Cod (Gadus morhua) ranges from Georges Bank to northern Labrador in the Canadian Atlantic. There are several concentrations of 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 (COSEWIC) assessed the southern population unit (4X5YZjm) as Endangered, and a Recovery Potential Assessment was completed in 2011. The last 4X5Y Cod stock assessment was conducted in 2008, with stock status updates provided in 2014, 2016, and 2017.

A framework assessment for the 4X5Y Cod stock was undertaken in March and November 2018, including a review of data and inputs, ecosystem information, modelling approaches, and data-limited approaches. Fisheries Management has requested that Fisheries and Oceans Canada (DFO) Science apply the modelling approach developed in November 2018 to provide catch advice and inform the rebuilding plan for this stock.

This Science Advisory Report is from the December 4, 2018, Stock Assessment of Atlantic Cod in NAFO Division 4X5Y. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- Catches have remained below the Total Allowable Catch (TAC) of 825 mt in recent years, with landings of 675 mt, 736 mt, and 746 mt, respectively, for years 2015, 2016, and 2017. The Northwest Atlantic Fisheries Organization (NAFO) Divisions 4X5Y Cod commercial fishery catch at age has shown a truncation in age structure since the 1990s. A reappearance of older fish was seen in 2016 and 2017, though their numbers remain low.
- At the 2018 peer review of the assessment framework, a Lower Reference Point (LRP) of 22,193 mt was chosen based on the $Sb_{50/90}$ method.
- Considering the stock is currently in the Critical Zone and expected to decline even in the absence of fishing under current productivity conditions, no fishing mortality reference point was proposed at the 2018 framework review.
- Following a variable but generally stable period throughout the 1980s and early 1990s, the population declined throughout the 1990s and 2000s, and has remained at low levels since 2010. The 2018 beginning of year estimate of Spawning Stock Biomass (SSB) from the 3MFfirst Virtual Population Analysis (VPA) model is 10,298 mt, remaining below the LRP of 22,193 mt.
- The levels of recruitment estimated by the 3MFfirst model for this stock have remained below 5 million fish since 2015, with the most recent estimate of the 2016 year class being the lowest on record.
- Fishing Mortality (F) shows a step-wise in all fully recruited ages after 1994, reaching series lows in the most recent time period. The most recent fully recruited F for this stock is estimated at 0.09.
- Under current productivity conditions, there is a high probability that SSB will decrease from 2019 to 2020, even in the absence of fishing.
- The most recent 5-year average of Natural Mortality (M) on Ages 5+ is 1.57, and equates to 21% annual survival. Unless natural mortality is reduced to 0.31, which is 20% of current mortality level and equates to 73% annual survival, there is a very low probability of this stock recovering to the Cautious Zone over the next 10 years.
- Although 4X5Y Cod is regarded as a data-rich stock with age-structured fishery and survey information, periods of bias in the historical catch, changing natural mortality, and stock mixing are problematic for modeling this stock.
- Lack of reliable estimates of unreported catch and discards of Cod from recreational and non-groundfish fisheries in NAFO Divisions 4X5Y restrict the model from accounting for any fishery-induced mortality besides reported catch.
- Many basic ecosystem indicators and the magnitude of their effect on the abundance and distribution of various life stages of Cod are undetermined, hindering the incorporation of ecosystem considerations into the stock assessment.

BACKGROUND

Atlantic Cod (*Gadus morhua)* have a broad distribution in the western Atlantic, with several concentrations along the Canadian Atlantic coast. Cod in Northwest Atlantic Fisheries Organization (NAFO) Divisions 4X and 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). The NAFO area 4Xp is considered a mixing area for these two components, as fish caught in 4Xp consistently exhibit characteristics of both growth curves (Andrushchenko et al. unpublished report[1]). Although the two-stock component structure within 4X5Y persists through time, they have been managed and assessed as a single unit since 1985.

FISHERY

Atlantic Cod are captured as part of a multi-species groundfish fishery in NAFO Division 4X and the Canadian portion of 5Yb. Historically part of a domestic inshore fishery, fishing intensity increased throughout the 1960s with the introduction of mobile gears by both Canadian and foreign vessels (Figure 2). The first implementation of a Total Allowable Catch (TAC) for Cod in 1975 applied only to the offshore portion of 4X, resulting in a rise in misreported catches into adjacent areas. Consequently, in 1982 a TAC was imposed on the whole 4X management area. Misreporting of catches as 5Y continued and, in 1985, Cod in NAFO Divisions 4X5Y were assessed as a single stock. The issue of misreporting throughout the 1980s necessitates the assessment of 4X5Y Cod as a single unit; assessing Bay of Fundy and Scotian Shelf Cod separately would be challenging and require starting the time series after 1990.

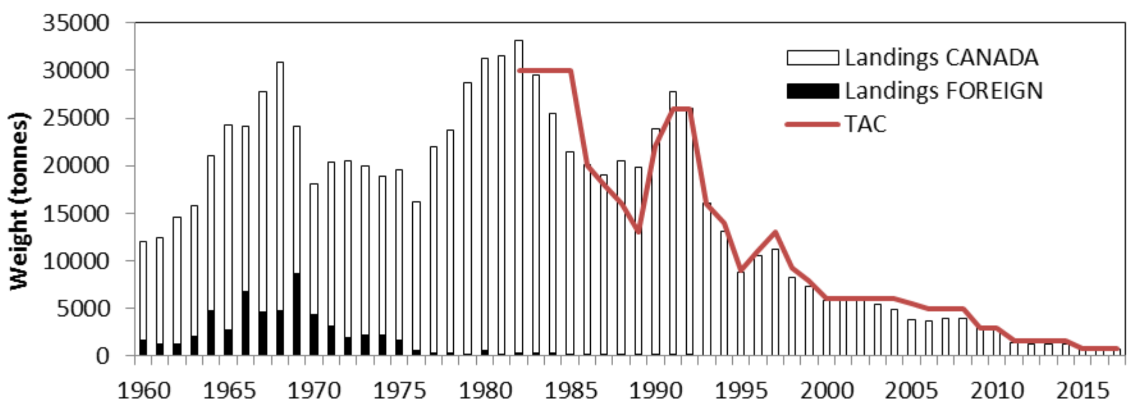

Figure 2. Landings and Total Allowable Catch (TAC) for NAFO Division 4X5Y Cod by calendar year (January 1st–December 31st). After 1999, landings and TAC are reported by fishing year (April 1st–March 31st).

Cod quotas have declined throughout the time series, with the most recent decrease taking place in 2014, when the TAC was reduced by 50% to 1,650 mt spanning two years (2015/2016 and 2016/2017). This arrangement was renewed for the 2017/2018 and 2018/2019 fishing years. Catches have remained below the TAC in recent years, with landings of 675 mt, 736 mt, and 746 mt respectively for years 2015, 2016, and 2017 (Table 1).

[1] Andrushchenko, I., D. Clark, F. Irvine, E. MacEachern, R. Martin, and Y. Wang. 2018 4X5Y Atlantic Cod Framework Data Inputs. DFO Unpublished Report.

Table 1. Total Allowable Catch (TAC) and landings by management year of 4X5Y Cod (metric tons).

Management Year	1982 – 1991 Average	1992 – 2001 Average	2002 – 2011 Average	2012/ 2013	2013/ 2014	2014/ 2015	2015/ 2016	2016/ 2017	2017/ 2018
TAC	23,500	11,821	4,615	1,650	1,650	1,650	825[1]	825[1]	825[1]
Landings	24,075[2]	11,178[2]	3,887	1,202	1,212	1,207	675	736	746

[1]Quota is 1650 mt over two years.

[2]Landings for 2001 and prior are based on calendar year, landings post-2001 are based on fishing year.

Cod are caught by a variety of fleets using both mobile (otter trawl) and fixed gear (handline, longline and gillnet). A recreational fishery for Cod also exists within the management area, but catches are not reported. Current landings are primarily from the Fixed Gear <45' and the Mobile Gear <65' fleets, with smaller contributions by the Fixed Gear 45'–65' fleet and others. Fixed gear fishing activity occurs mainly between June and December, and has generally been distributed throughout NAFO areas 4Xmnopq; however, since 2014 catches of Cod by fixed gear have shifted out of 4Xp. Mobile gear fishing activity occurs year round and generally takes place in the western portion of the management unit. Similar to fixed gear, catches of Cod by mobile gear on Browns Bank (eastern portion of 4Xp) have declined drastically since 2014. Despite the differences in fishing distribution by gear type, contribution of Cod landings from both the Scotian Shelf and Bay of Fundy remain relatively equivalent. Realized observer coverage for the area is currently estimated at 5-7% of trips (Andrushchenko et al. unpublished report). Despite several attempts to bridge knowledge gaps identified by Gavaris et al. (2010), insufficient levels of observer coverage and lack of systematic, unbiased sampling continue to be the major impediments to quantifying the magnitude of Cod bycatch in non-groundfish fisheries. Consequently, the current assessment does not account for these removals from the population.

The 4X5Y Cod commercial fishery Catch at Age (CAA) has shown a truncation in age structure since the 1990s, until 2014 when Age 6 Cod were barely detectable and Ages 8+ were completely absent (Figure 3). A reappearance of older fish was seen in 2016 and 2017 with Ages 6, 7 and 8 fish being caught in both the Bay of Fundy and Scotian Shelf, though their numbers remain low. Preliminary analyses of the most recent fishery data indicate that large fish are likely present in the 2018 CAA as well. Although fishery catch was predominantly composed of Cod Aged 2 through 5 during the 2000s, the contributions of younger fish (Ages 2 and 3) have decreased substantially since 2015 (Figure 3).

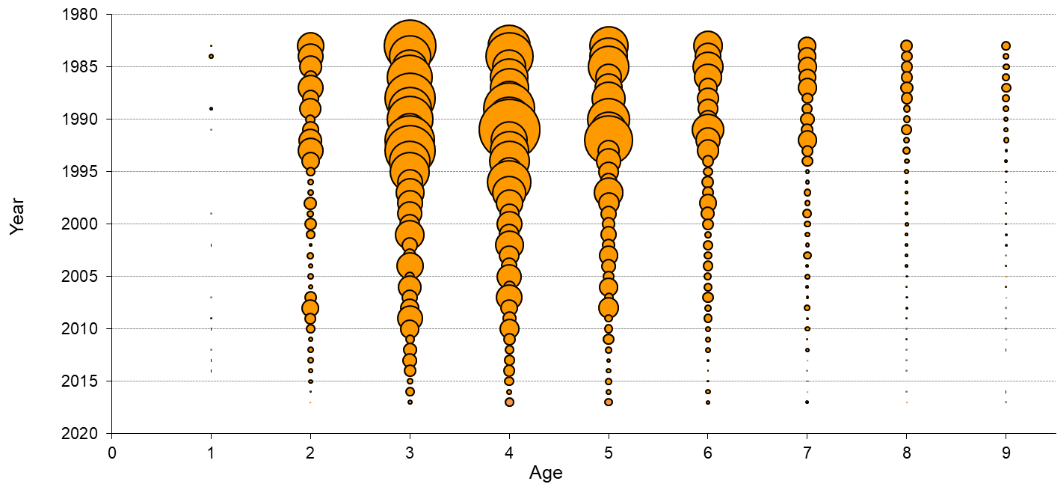

Figure 3. Commercial fishery Catch at Age (CAA) for 4X5Y Cod since 1983. Bubble area is proportional to abundance.

SURVEY

The annual bottom trawl DFO Summer Research Vessel (RV) Survey has been conducted since 1970, providing fishery-independent information about Cod in the 4X5Y management area. Sampling is generally conducted in the summer season (June–August), though periodic spring sampling (February–March) has occurred in 4X5Y. Notable shifts in the historic trends of the summer survey distribution have become evident throughout the time series, as Cod in the Bay of Fundy have receded from coastal waters and are now found primarily in deeper waters, and Cod along the Scotian Shelf have concentrated almost exclusively on the banks rather than the Shelf edge. A general decrease in weight per tow of Cod has been seen in all areas.

The total biomass index for 4X5Y Cod has been steadily decreasing since the 1990s, and has remained at a low level since 2010 (Figure 4). The trend is seen in both areas of the management unit, though a steeper rate of decline has been observed in the Bay of Fundy. Since 2010, the survey biomass has averaged 3,379 mt, ranging from 2,057 mt (2013) to 5,195 mt (2016). The 2018 DFO Summer RV Survey biomass index was estimated as 3,500 mt, though vessel issues resulted in minimal coverage of portions of 4X (DFO 2019).

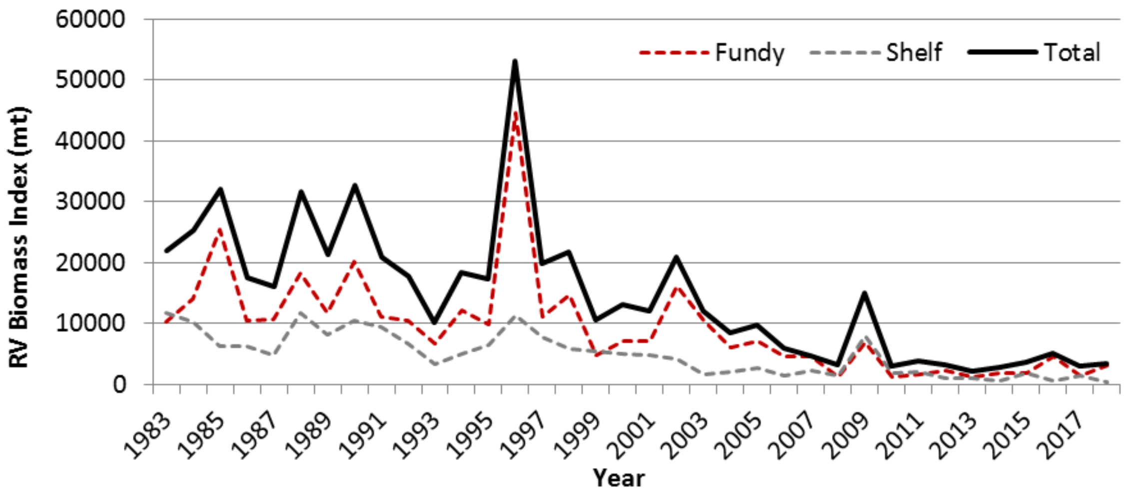

Figure 4. Total biomass index from the DFO Summer RV Survey for all of 4X5Y (solid black line), as well as Bay of Fundy (dashed red line) and Scotian Shelf (dashed grey line) stock components, since 1983.

ASSESSMENT

Reference Points

At the 2018 peer review of the assessment framework, a Lower Reference Point (LRP) of 22,193 mt was chosen based on the $Sb_{50/90}$[2]. The $Sb_{50/90}$ is one of the methodologies suggested at the 2002 DFO National Workshop on Reference Points for Gadoids (DFO 2002). It is a standardized, reproducible approach, which uses the full time series (1983-2017); however, it tends to give an optimistic perspective on recruitment (Wang and Irvine, unpublished report[3]). The $Sb_{50/90}$ LRP 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). Considering the stock is currently in the Critical Zone and expected to decline even in the absence of fishing under current productivity conditions, no fishing mortality reference point was proposed at the 2018 framework review.

Model Formulation

The 4X5Y 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. This model includes survey and fishery data back to 1983, 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, unpublished report). The 3MFfirst VPA model allows time-varying Natural Mortality (M) on three age groups (Ages 1-2, Ages 3-4 and Ages 5+), with a normal prior of mean of 0.2 ($Minit_j$) and a deviation of 0.05 ($Mdev_{j,y}$) on all ages in 1983. A normal prior for the deviation of M in the

[2] The $Sb_{50/90}$ limit is the point below which the population is unlikely to produce average recruitment under good early life-history stage survival conditions (DFO 2002).
[3] Wang, Y.W. and F. Irvine. 2018 4X5Y Cod Stock Assessment Modelling Framework. DFO Unpublished Report.

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 Fishing Mortality (F) on Age 6 is calculated as the mean of F on Ages 3 through 5 prior to 1995, and as the mean F on Ages 4 and 5 after 1995.

Since no new fishery data are available to incorporate into the 3MFfirst model since the Modeling Framework (November 6-7, 2018), the model was not re-run for the current assessment. The lack of availability of commercial aging information for the first half of 2018 introduces additional uncertainty into the advice provided from the 3MFfirst model and coordination of sample processing will be reviewed to remedy the issue moving forward. Consequently, although two-year (2019/2020 and 2020/2021) projections from the 3MFfirst model are provided, the terminal year (2020/2021) projections are subject to higher uncertainty, as recruitment for the 2017 year class (Age 4 in 2021) is assumed and not estimated.

Model Outputs

Beginning of year population biomass from the 3MFfirst model shows a declining trend throughout the time series for all ages (Figure 5). Following a variable but generally stable period throughout the 1980s and early 1990s, the population declined throughout the 1990s and 2000s, and has remained at low levels since 2010 (Figure 5). The 2018 beginning of year estimate of spawning stock biomass (Ages 4+, Spawning Stock Biomass [SSB]) from the 3MFfirst VPA model is 10,298 mt (Table A2), remaining below the LRP of 22,193 mt (Figure 5).

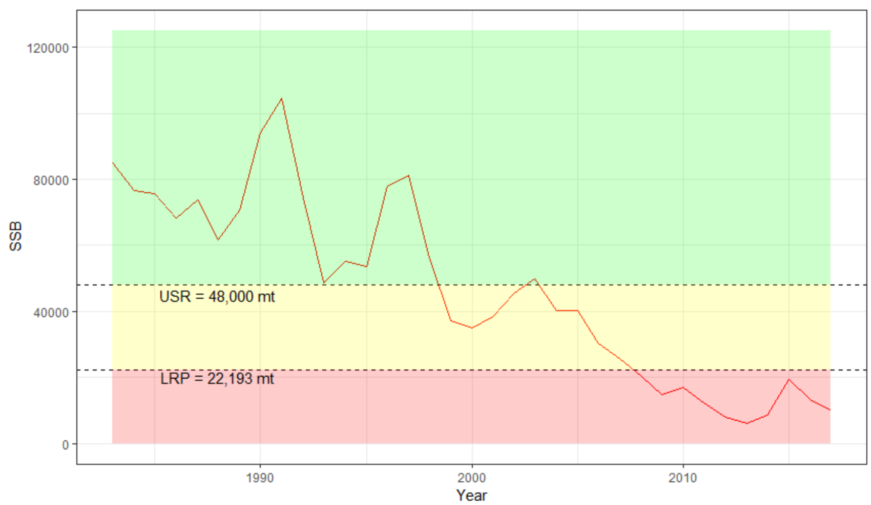

Figure 5. Spawning Stock Biomass (SSB; Ages 4+, metric tonnes) from the 3MFfirst VPA model. Colors indicate Critical (red), Cautious (yellow) and Healthy (green) zones.

The levels of recruitment estimated by the 3MFfirst model for this stock have remained below 5 million fish since 2015, with the most recent estimate of the 2016 year class being the lowest on record (1.9 million fish, Table A1).

Fishing Mortality (F) shows a step-wise reduction in all fully recruited ages ($F_{4\text{-}7}$, number-weighted average of F on Ages 4+) after 1994, reaching series lows in the most recent time period; a trend consistent across Ages 4, 5 and 6, as well as with management measures implemented since 1994 (Figure 6, Table A3). The plus group (Ages 7+) is an exception to this trend, with fishing mortality throughout the 2000s equivalent to the levels seen prior to 1994 (Figure 6). The most recent fully recruited F ($F_{4\text{-}7,\ 2017}$) for this stock is estimated at 0.09 from the 3MFfirst model (Table A3).

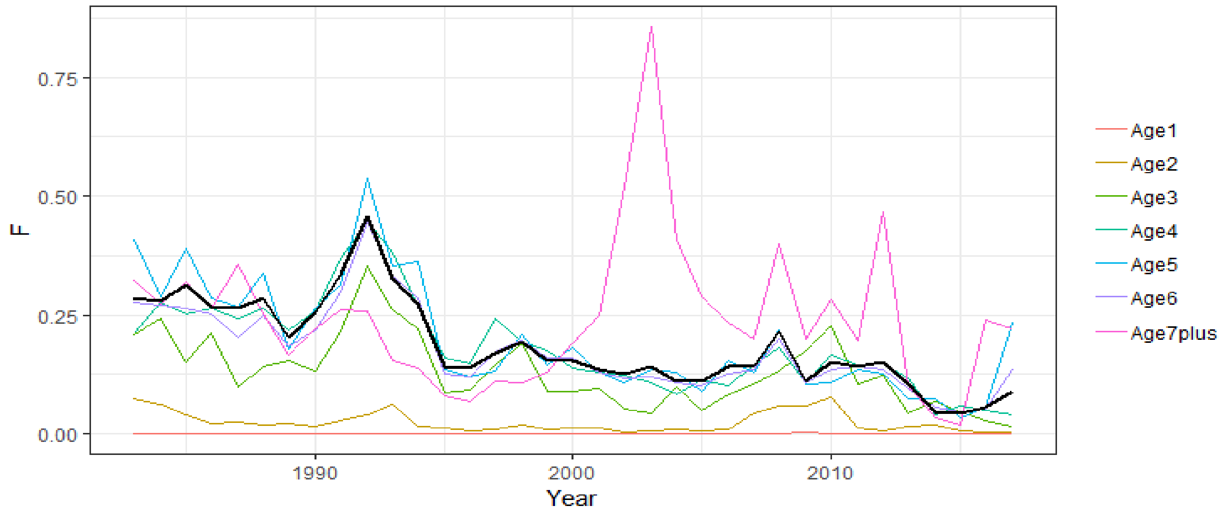

Figure 6. Fishing Mortality (F) by age from the 3MFfirst Virtual Population Analysis (VPA) model. The thick black line shows the $F_{4\text{-}7}$.

Natural Mortality (M) was estimated by the 3MFfirst model for three age groups: Ages 1-2, Ages 3-4 and Ages 5+. Throughout the time series, M marginally increased from 0.2 to 0.22 for the youngest group, and 0.22 to 0.28 for the intermediate group (Table A4). An increase in M is consistent with that of total mortality estimates on Ages 2 through 4 ($Z_{2\text{-}4}$) from the DFO summer RV survey. For the older age group, M deviated substantially from the initial prior of 0.2 in 1983 to a value of 0.37, and continued to increase throughout the time series to exceed 1.5 in the most recent time period (Table A4). Although a high M is consistent with the truncation of the age structure for this population, the disparity in M between younger and older fish in the 1980s needs to be investigated further.

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

Short-term Projections

At the framework review, it was agreed that projections provided at the stock assessment would be based on the most recent 5-year average of recruitment, the most recent 5-year average of mortality estimate by age group, and the most recent 3-year average of Weight at Age (WAA) and partial recruitment.

The projections would assume a 2018 catch of 825 mt, and be run under three harvest scenarios for 2019 and 2020:

- current TAC (825 mt annually);
- half of current TAC (412.5 mt annually); and
- no catch.

The projection outputs are summarized in Table 2 as the probability that SSB at the beginning of year 2 (2020 and 2021, respectively) is lower than the mean estimated SSB of year 1 (2019 and 2020, respectively). All projections are based on calendar year and produce January 1st biomass estimates. In the future, when Q1 and Q2 commercial samples will be completed in time for the assessment, projections will be done for mid-year. As the model only uses data up until 2017, the terminal year (2021) projections are subject to higher uncertainty, as recruitment for the 2017 year class (Age 4 in 2021) is assumed and not estimated.

Table 2. Short term projection outputs of Spawning Stock Biomass (SSB), Fishing Mortality (F) and probability of SSB change under 3 harvest scenarios. Numbers in brackets indicate the 95% Credible Interval (CI).

Harvest Scenarios	SSB (95% CI)			F (95% CI)		$P(SSB_{2020} < SSB_{2019})$	$P(SSB_{2021} < SSB_{2020})$
	2019	2020	2021	2019	2020		
825 mt	8,246 mt (4,584–15,438)	5,848 (2,452–17,942)	5,742 (2,366–20,926)	0.26 (0.13-0.49)	0.3 (0.1-0.67)	76%	52%
412.5 mt	8,246 (4,584–15,438)	6,125 (2,700–18,251)	6,134 (2,729–21,588)	0.13 (0.06-0.23)	0.14 (0.05-0.29)	74%	50%
0 mt	8,246 (4,584–15,438)	6,401 (2,954–18,556)	6,525 (3,253–22,193)	0	0	72%	48%

Long-term Projections

A 10-year projection was conducted for the modelling framework; it is reported in this document for review and discussion. Fishing mortality was set at 0 and the assumptions regarding components of productivity were the same as for the short-term projection above. This projection was used to evaluate the trajectory of SSB (Table A5) and the probability that the population will move out of the Critical Zone throughout the next 10 years under reduced M scenarios on Ages 5+ (Table A6).

The most recent 5-year average of M on Ages 5+ is 1.57, and equates to 21% annual survival. The SSB is projected to remain essentially unchanged over the 10-year time period until Ages 5+ M was reduced to below 0.63, which is 40% of current mortality level and equates to 53% annual survival. Unless natural mortality is reduced to 0.31, which is 20% of current mortality level and equates to 73% annual survival, there is a very low probability of this stock recovering to the Cautious Zone over the next 10 years.

While the stock is expected to decline even in the absence of fishing in the short-term, the recent 2013 year class in the Bay of Fundy was almost sufficient to bring the stock out of the Critical Zone. Due to the high natural mortality on older fish and a lack of persistent, above-average recruitment events, this stock will struggle to rebuild above the LRP without an increase in survival at older ages.

Assessment Schedule

Given the two-year quota management structure, it is expected that the 4X5Y Cod update would follow a two-year cycle. The update is expected to have the same format as the previous updates (e.g. DFO 2017a), with an additional section discussing whether exceptional circumstances should trigger an assessment for the following year. Given the current status of the stock, the proposed trigger mechanisms were focused on detecting a change in the current stock productivity dynamics and were defined as follows:

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 biomass index falls outside of the 95% confidence interval of the projection of 2019.
3. If the 3-year median of the Age 7+ group abundance index falls outside of the 95% confidence interval of the projection of 2019.
4. If the q-adjusted 3-year median survey biomass index exceeds B_{lim}.

Meeting at least one of the four conditions above would trigger an assessment for the following year. In addition, a model review would happen if a useable time trend on bycatch/discard of Cod becomes available, perception of stock structure changes, or a framework is developed for incorporating ecosystem information into the stock assessment.

Ecosystem Considerations

A wide range of indicators should be considered when looking at the 4X5Y Cod stock components in an ecosystem context. To date, some progress has been made in showing that spatio-temporal dynamics of Cod are partially driven by bottom temperature and depth (Irvine et al. unpublished report[4]). Despite this positive step, availability of existing data sources and substantial data gaps for key prey species continue to hinder the progress (Andrushchenko et al. unpublished report).

Although environmental factors were not incorporated quantitatively at this time, the trends in broader species groups across the region should still be considered, albeit qualitatively, when discussing changes in Cod abundance. Despite recent increases in abundance of some demersal species, the productivity, trophic interactions and structure of the Scotian Shelf ecosystem has changed since the early 1990s (DFO 2015). Increases in bottom water temperatures are accompanied by changes in groundfish landings, increases in landings of invertebrates and decreases in mean fish length from the RV surveys for many stocks (DFO 2018; DFO 2017a; DFO 2015). A dominance shift towards smaller zooplankton taxa away from large, energy-rich copepods like *Calanus finmarchicus,* has been observed since 2010, and may indicate less productive conditions for planktivorous fish (Johnson et al. 2017). In addition to these broad changes along the lower and mid-trophic groups, the abundance of Grey Seals (*Halichoerus grypus*) increased substantially on the Scotian Shelf, likely increasing the predation pressure on Cod and, consequently, contributing to higher natural mortality (DFO 2017b). Future assessments should continue considering these and other over-arching trends along the Scotian Shelf and Bay of Fundy regions, even if they cannot be accounted for quantitatively.

CONCLUSIONS AND ADVICE

The 4X5Y Cod stock has declined since the 1990s, and currently remains in the Critical Zone. Despite decreases in fishing mortality, productivity of the 4X5Y Cod stock remains low. Under current productivity conditions, there is a high probability that the SSB will decrease from 2019 to 2020, even in the absence of fishing. In keeping with the Precautionary Approach, catch

[4] Irvine, F., Y. Wang and E. MacEachern. Spatio-temporal Distribution of Atlantic Cod (*Gadus morhua*) along the Scotian Shelf and Bay of Fundy in Response to Environmental Variability. Unpublished Report.

levels of 4X5Y Cod should be kept as low as possible and monitoring of Cod bycatch/discarding in all fisheries should be improved.

SOURCES OF UNCERTAINTY

Several data gaps and uncertainties were identified during the 2018 framework review and continue to persist for 4X5Y Cod:

- Although 4X5Y Cod is regarded as a data-rich stock with age-structured fishery and survey information, periods of bias in the historical catch, changing natural mortality and stock mixing are problematic for modeling this stock.
- The apparent increases in M from the 3MFfirst model could be aliasing other factors contributing to the disappearance of Cod from the 4X5Y management unit, such as emigration of fish due to environmental changes or unreported/discarded catch of Cod from all 4X5Y fisheries.
- The treatment of older fish in the 3MFfirst model as a plus group seems to result in dynamics inconsistent with information coming from the DFO Summer RV survey (i.e. high F in the 2000s). Due to the disappearance of older fish throughout the time series, the impact of the plus group formulation is limited to the early time series and does not impact the recent trends or current stock status. Additional modifications to the 3MFfirst formulation may be required to adjust how the older fish are treated.
- Currently, any unaccounted-for fishing mortality is included under the umbrella of natural mortality. Lack of reliable estimates of unreported catch and discards of Cod from recreational and non-groundfish fisheries in NAFO Divisions 4X5Y restrict the model from accounting for any fishery-induced mortality besides reported catch.
- Fish movement, population structure and the extent of mixing between multiple spawning components both within 4X5Y and between adjacent management units are poorly understood. This information is critical to incorporating spatial dynamics of eastern and western fish into the assessment.
- Many basic ecosystem indicators (e.g. abundance indices for prey items of juvenile cod, indicators of larval Cod abundance, etc.) and the magnitude of their effect on the abundance and distribution of various life stages of Cod are undetermined, hindering the incorporation of ecosystem considerations into the stock assessment.
- Additional research is required to investigate the drivers of productivity in the 4X5Y Cod population, as well as to further examine potential sources of natural mortality on 4X5Y Cod (e.g. seal diet composition as well as research on seasonal and spatial distribution of seals in 4X5Y).

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APPENDIX I

Outputs of the 3MFfirst model, as originally reported in Wang and Irvine, unpublished report.

Table A1. 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	21,247	16,228	21,667	14,099	7,227	3,922	3,922
1984	25,359	17,360	12,336	14,179	9,197	3,332	4,035
1985	16,565	20,696	13,361	7,807	8,680	4,678	3,815
1986	45,670	13,535	16,269	9,266	4,888	3,909	4,230
1987	30,297	37,314	10,832	10,611	5,731	2,392	4,086
1988	39,675	24,751	29,706	7,918	6,715	2,798	3,066
1989	13,457	32,402	19,850	20,788	4,899	2,986	2,847
1990	19,502	10,971	25,863	13,698	13,479	2,498	2,984
1991	26,362	15,920	8,826	18,259	8,525	6,150	2,615
1992	20,283	21,517	12,642	5,733	10,163	3,589	3,782
1993	43,544	16,554	16,884	7,153	2,944	3,284	2,890
1994	16,801	35,532	12,715	10,466	3,933	1,101	2,573
1995	14,090	13,705	28,555	8,184	6,420	1,395	1,565
1996	8,686	11,487	11,051	20,998	5,603	2,691	1,285
1997	16,675	7,077	9,314	8,065	14,510	2,214	1,599
1998	11,622	13,577	5,709	6,444	5,065	5,178	1,342
1999	22,639	9,455	10,835	3,765	4,231	1,507	2,001
2000	12,707	18,403	7,621	7,873	2,512	1,210	1,004
2001	10,429	10,320	14,751	5,534	5,441	623	554
2002	18,935	8,461	8,271	10,610	3,848	1,319	270
2003	5,289	15,346	6,838	6,192	7,387	909	352
2004	16,811	4,282	12,359	5,148	4,369	1,643	243
2005	6,110	13,602	3,435	8,763	3,704	976	417
2006	7,174	4,938	10,934	2,547	6,103	892	314
2007	10,234	5,790	3,948	7,830	1,791	1,407	278
2008	4,649	8,248	4,474	2,755	5,246	430	398
2009	2,449	3,741	6,256	3,015	1,771	1,162	171
2010	3,975	1,963	2,836	4,026	2,071	428	317
2011	12,670	3,192	1,458	1,723	2,598	467	154
2012	5,980	10,169	2,529	996	1,131	520	122
2013	2,540	4,798	8,100	1,695	651	205	109
2014	7,341	2,037	3,793	5,865	1,142	116	55
2015	4,102	5,886	1,605	2,679	4,261	205	31
2016	2,773	3,288	4,691	1,158	1,910	867	48
2017	1,925	2,222	2,629	3,438	831	405	193
2018	-	1,542	1,778	1,953	2,490	150	115

Table A2. Population biomass (metric tonnes) estimated from the 3MFfirst Virtual Population Analysis (VPA) model. Dashes indicate absent values. Terminal year uses 3-year average Weight at Age (WAA) to estimate biomass. Spawning Stock Biomass = SSB.

Year	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Age 7+	Total	SSB (4+)
1983	254	3,471	16,176	21,948	19,794	15,577	27,670	104,890	84,989
1984	565	2,689	10,130	23,823	19,313	10,821	22,529	89,871	76,487
1985	939	4,170	11,384	13,651	25,132	16,221	20,710	92,208	75,714
1986	3,584	2,837	15,480	15,708	12,980	14,272	25,286	90,147	68,245
1987	1,095	9,186	6,828	21,910	16,252	9,940	25,635	90,845	73,737
1988	1,706	5,924	20,989	8,541	20,194	12,246	20,751	90,349	61,731
1989	895	7,387	17,101	31,173	9,163	12,792	17,412	95,924	70,540
1990	1,626	3,095	21,806	23,459	36,875	11,040	22,462	120,363	93,836
1991	2,053	4,469	7,495	31,989	24,527	27,670	20,210	118,412	104,396
1992	808	6,638	9,459	8,902	28,120	12,153	25,111	91,190	74,285
1993	2,268	3,749	16,300	10,794	6,674	16,078	15,062	70,926	48,608
1994	1,137	8,404	11,382	22,320	11,300	3,728	17,956	76,227	55,304
1995	440	2,726	22,917	13,832	22,961	6,099	10,666	79,640	53,558
1996	433	2,127	7,278	37,661	17,320	14,191	8,711	87,721	77,883
1997	523	1,050	6,476	13,058	45,244	11,922	11,031	89,304	81,255
1998	1,454	2,635	3,196	10,085	13,642	23,215	9,553	63,780	56,494
1999	803	2,503	8,798	5,888	11,170	5,848	14,313	49,323	37,220
2000	1,198	5,723	5,942	16,778	7,397	4,695	6,289	48,023	35,160
2001	374	3,470	17,749	11,939	20,077	3,027	3,440	60,074	38,483
2002	851	1,437	8,360	24,257	13,128	6,465	1,842	56,341	45,693
2003	179	4,132	5,543	13,592	28,790	4,625	2,757	59,617	49,763
2004	896	1,002	11,850	11,811	16,223	10,526	1,842	54,150	40,402
2005	83	3,032	3,211	17,531	14,187	4,910	3,623	46,578	40,252
2006	540	842	8,607	4,118	19,808	4,216	2,154	40,285	30,297
2007	384	2,357	3,383	14,661	4,198	5,482	1,440	31,905	25,781
2008	199	1,985	5,414	4,094	13,311	1,088	2,020	28,111	20,513
2009	293	1,077	5,853	6,114	3,864	4,125	779	22,104	14,882
2010	155	774	2,856	6,930	6,607	1,609	1,813	20,744	16,959
2011	603	852	1,505	3,144	7,065	1,336	858	15,364	12,404
2012	471	3,075	2,444	1,783	3,661	2,142	546	14,122	8,132
2013	105	1,885	3,930	2,954	1,723	898	662	12,157	6,237
2014	1,101	619	4,784	5,034	2,765	443	327	15,072	8,568
2015	166	2,279	1,576	6,207	12,252	728	188	23,396	19,375
2016	137	876	4,804	2,022	7,067	3,824	248	18,979	13,161
2017	154	734	2,555	5,664	2,109	1,578	947	13,588	10,298
2018	-	506	1,764	3,717	7,563	592	619	-	12,491

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	0.000	0.073	0.209	0.212	0.409	0.277	0.323	0.284
1984	0.001	0.060	0.242	0.275	0.289	0.268	0.273	0.278
1985	0.000	0.039	0.150	0.252	0.389	0.263	0.319	0.312
1986	0.000	0.021	0.211	0.264	0.284	0.253	0.264	0.266
1987	0.000	0.026	0.097	0.241	0.266	0.201	0.357	0.264
1988	0.000	0.018	0.141	0.264	0.338	0.247	0.252	0.284
1989	0.001	0.023	0.154	0.217	0.177	0.183	0.165	0.203
1990	0.000	0.015	0.131	0.257	0.264	0.217	0.220	0.253
1991	0.000	0.028	0.214	0.368	0.311	0.298	0.261	0.335
1992	0.000	0.039	0.352	0.449	0.538	0.446	0.256	0.456
1993	0.000	0.061	0.260	0.380	0.352	0.331	0.154	0.325
1994	0.000	0.015	0.222	0.270	0.362	0.285	0.137	0.272
1995	0.000	0.011	0.087	0.159	0.136	0.127	0.078	0.141
1996	0.000	0.005	0.093	0.148	0.121	0.121	0.067	0.137
1997	0.000	0.009	0.145	0.241	0.132	0.173	0.109	0.167
1998	0.000	0.019	0.190	0.194	0.210	0.198	0.107	0.193
1999	0.000	0.008	0.090	0.175	0.144	0.160	0.130	0.154
2000	0.000	0.013	0.088	0.137	0.182	0.160	0.191	0.153
2001	0.000	0.012	0.094	0.128	0.130	0.129	0.249	0.135
2002	0.000	0.003	0.051	0.123	0.109	0.116	0.518	0.126
2003	0.000	0.005	0.042	0.107	0.136	0.121	0.857	0.140
2004	0.000	0.009	0.098	0.084	0.129	0.106	0.407	0.111
2005	0.000	0.005	0.050	0.113	0.088	0.100	0.290	0.111
2006	0.000	0.009	0.082	0.100	0.154	0.127	0.233	0.140
2007	0.000	0.042	0.103	0.144	0.128	0.136	0.198	0.142
2008	0.000	0.059	0.133	0.180	0.219	0.200	0.397	0.214
2009	0.003	0.059	0.174	0.108	0.104	0.106	0.199	0.109
2010	0.000	0.077	0.226	0.166	0.107	0.137	0.284	0.152
2011	0.000	0.013	0.105	0.145	0.135	0.140	0.197	0.141
2012	0.000	0.007	0.122	0.147	0.125	0.136	0.468	0.150
2013	0.000	0.014	0.044	0.116	0.073	0.095	0.103	0.103
2014	0.000	0.018	0.068	0.040	0.072	0.056	0.033	0.046
2015	0.000	0.006	0.046	0.058	0.033	0.045	0.020	0.042
2016	0.000	0.002	0.029	0.050	0.054	0.052	0.239	0.055
2017	0.000	0.002	0.015	0.040	0.232	0.136	0.222	0.088

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	0.22	0.22	0.37	0.37	0.37
1984	0.20	0.20	0.22	0.22	0.39	0.39	0.39
1985	0.20	0.20	0.22	0.22	0.41	0.41	0.41
1986	0.20	0.20	0.22	0.22	0.43	0.43	0.43
1987	0.20	0.20	0.22	0.22	0.45	0.45	0.45
1988	0.20	0.20	0.22	0.22	0.47	0.47	0.47
1989	0.20	0.20	0.22	0.22	0.50	0.50	0.50
1990	0.20	0.20	0.22	0.22	0.52	0.52	0.52
1991	0.20	0.20	0.22	0.22	0.55	0.55	0.55
1992	0.20	0.20	0.22	0.22	0.59	0.59	0.59
1993	0.20	0.20	0.22	0.22	0.63	0.63	0.63
1994	0.20	0.20	0.22	0.22	0.67	0.67	0.67
1995	0.20	0.20	0.22	0.22	0.73	0.73	0.73
1996	0.20	0.20	0.22	0.22	0.81	0.81	0.81
1997	0.21	0.21	0.22	0.22	0.90	0.90	0.90
1998	0.21	0.21	0.23	0.23	1.00	1.00	1.00
1999	0.21	0.21	0.23	0.23	1.11	1.11	1.11
2000	0.21	0.21	0.23	0.23	1.21	1.21	1.21
2001	0.21	0.21	0.24	0.24	1.29	1.29	1.29
2002	0.21	0.21	0.24	0.24	1.33	1.33	1.33
2003	0.21	0.21	0.24	0.24	1.37	1.37	1.37
2004	0.21	0.21	0.25	0.25	1.37	1.37	1.37
2005	0.21	0.21	0.25	0.25	1.34	1.34	1.34
2006	0.21	0.21	0.25	0.25	1.31	1.31	1.31
2007	0.22	0.22	0.26	0.26	1.30	1.30	1.30
2008	0.22	0.22	0.26	0.26	1.29	1.29	1.29
2009	0.22	0.22	0.27	0.27	1.32	1.32	1.32
2010	0.22	0.22	0.27	0.27	1.38	1.38	1.38
2011	0.22	0.22	0.28	0.28	1.47	1.47	1.47
2012	0.22	0.22	0.28	0.28	1.58	1.58	1.58
2013	0.22	0.22	0.28	0.28	1.65	1.65	1.65
2014	0.22	0.22	0.28	0.28	1.64	1.64	1.64
2015	0.22	0.22	0.28	0.28	1.56	1.56	1.56
2016	0.22	0.22	0.28	0.28	1.50	1.50	1.50
2017	0.22	0.22	0.28	0.28	1.48	1.48	1.48

Table A5. Projected median Spawning Stock Biomass (SSB) values in the next 10 years under different assumed scenarios for Natural Mortality (M). The M in the table corresponds to M on Ages 5+ and is reduced from 100% to 20% of current value.

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
M=1.57	8,246	6,401	6,525	8,073	8,494	8,597	8,625	8,627	8,628	8,628
M=1.41	8,617	6,827	6,878	8,316	8,798	8,947	8,981	8,989	8,989	8,990
M=1.26	9,057	7,330	7,327	8,626	9,195	9,398	9,443	9,461	9,462	9,463
M=1.1	9,573	8,005	7,926	9,113	9,734	9,989	10,058	10,092	10,100	10,100
M=0.94	10,127	8,920	8,750	9,833	10,468	10,789	10,918	10,960	10,981	10,987
M=0.79	10,820	10,013	9,910	10,851	11,512	11,943	12,135	12,211	12,250	12,271
M=0.63	11,647	11,442	11,559	12,397	13,095	13,688	13,968	14,124	14,199	14,243
M=0.47	12,596	13,295	13,877	14,807	15,653	16,465	16,933	17,234	17,429	17,552
M=0.31	13,724	15,789	17,208	18,662	20,016	21,276	22,255	22,946	23,460	23,797

Table A6. The probability that the population will exceed the Lower Reference Point (LRP) in the next 10 years under different assumed scenarios of Natural Mortality (M). The M in the table corresponds to M on Ages 5+ and is reduced from 100% to 20% of current value.

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
M=1.57	0%	1%	3%	1%	1%	1%	1%	1%	1%	1%
M=1.41	0%	1%	3%	1%	1%	1%	1%	1%	1%	1%
M=1.26	0%	1%	3%	2%	2%	2%	2%	2%	2%	2%
M=1.1	0%	2%	3%	3%	2%	2%	2%	2%	2%	2%
M=0.94	0%	2%	4%	4%	4%	4%	4%	4%	4%	4%
M=0.79	0%	3%	4%	5%	6%	6%	6%	6%	6%	6%
M=0.63	1%	4%	6%	7%	9%	10%	10%	11%	11%	11%
M=0.47	2%	7%	11%	14%	16%	20%	22%	24%	24%	25%
M=0.31	4%	13%	21%	30%	38%	45%	50%	54%	57%	60%

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