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Scientific Requirements for the Rebuilding Plan of Southern Gulf of St. Lawrence (NAFO Division 4T and 4Vn November to April) Atlantic Cod (*Gadus morhua*)

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The Atlantic Cod (*Gadus morhua*) stock in the southern Gulf of St. Lawrence (NAFO Division 4T-4Vn (November-April)) is below its limit reference point (LRP) and in the Critical Zone of the Precautionary Approach. The new Fish Stocks Provisions and the amended Fisheries Act legally require Fisheries and Oceans Canada (DFO) to develop a rebuilding plan for this stock. A rebuilding plan comprises several elements that require DFO Science sector advice including: (i) stock status, (ii) causes of stock decline, (iii) rebuilding target and timeline, (iv) additional measurable objectives, (v) likelihood of management measures meeting rebuilding objectives, (vi) how to track rebuilding progress, and (vii) frequency of the periodic review of the rebuilding plan.

Southern Gulf of St. Lawrence (sGSL) Cod stock size going back to 1917 was estimated using a surplus production model. Cod biomass exceeded B_{MSY} until the late 1940s. Biomass relative to B_{MSY} started to decline in the 1950s as catch started increasing from stable values. The sGSL Cod biomass in 2018 was 2.4% of the biomass in 1917. The source of serious harm and cause of decline for sGSL Cod is fishing mortality higher than F_{MSY} in 1955 and onwards. Other sources of serious harm, and likely consequences of the overfishing, include a lasting state of low production and low biomass, recruitment overfishing, high natural mortality and a predation-driven Allee effect, low growth and body condition, and a decrease in age-at-maturity.

A review of the biomass reference points generated a new LRP using the statistical catch-at-age model; initial $0.25B_0$. Its value is estimated at 210,000 t of SSB. With this new LRP, the stock is now estimated to have declined into the Critical Zone in 1990.

In addition to the stock having a 75% probability of being at or above the LRP, the rebuilding target should include that the stock must be at or above this level for 4 consecutive years, and population projections must show the stock is likely to continue its positive trajectory under harvest for 4 years after the rebuilt state has been achieved.

Projections showed that the stock is unlikely to rebuild to the rebuilding target under prevailing conditions, even in the absence of fishing mortality, and that the environmental conditions that would allow to reverse the decline in Cod biomass are unlikely to occur. Projections showed that at 300 t of bycatch, the population SSB in 10 years would be reduced by 10%. At 500 t of bycatch, the population SSB in 10 years would be reduced by 16%. Additional measurable objectives for the rebuilding plan should include recovering the truncated age structure, increase size and condition at age, recover the spatial distribution in shallow waters, and promote recruitment by protecting spawning grounds.

Rebuilding progress will be tracked using the interim indicator survey and stock assessment models. The periodic review of the rebuilding plan should be set to the 4-year stock assessment cycle with an interim update at the halfway point.

1. REBUILDING PLAN CONTEXT

Under the Fish Stocks Provisions (FSP) section 6.2 in the amended *Fisheries Act (2019)* and section 70 of the *Fishery General Regulations*, it is a legislated requirement to develop and implement a rebuilding plan for a prescribed major fish stock, within 24 months of the day on which the Minister first has knowledge the stock has declined to or below its limit reference point (LRP). If a stock is already at or below its LRP when it is prescribed under the FSP, the 24-month timeline to develop a rebuilding plan for the stock starts the day the stock is prescribed in regulation, which occurred April 4, 2022 for Atlantic Cod (*Gadus morhua*) in the southern Gulf of St. Lawrence (hereafter; sGSL Cod).

The management unit for the sGSL Cod stock consists of the Northwest Atlantic Fisheries Organization (NAFO) Division 4T as well as subdivision 4Vn from November to April (Figure 1). This stock has been fished since the sixteenth century or earlier. Following the stock collapse in the 1990s, the fishery was closed from September 1993 to May 1998, re-opened as an index-fishery in 1999, to be closed again since 2009. A total allowable catch (TAC) of 300 t remains to allow for bycatch in other groundfish fisheries, catch in a limited recreational fishery, catch for scientific purposes and Indigenous food, social and ceremonial fisheries.

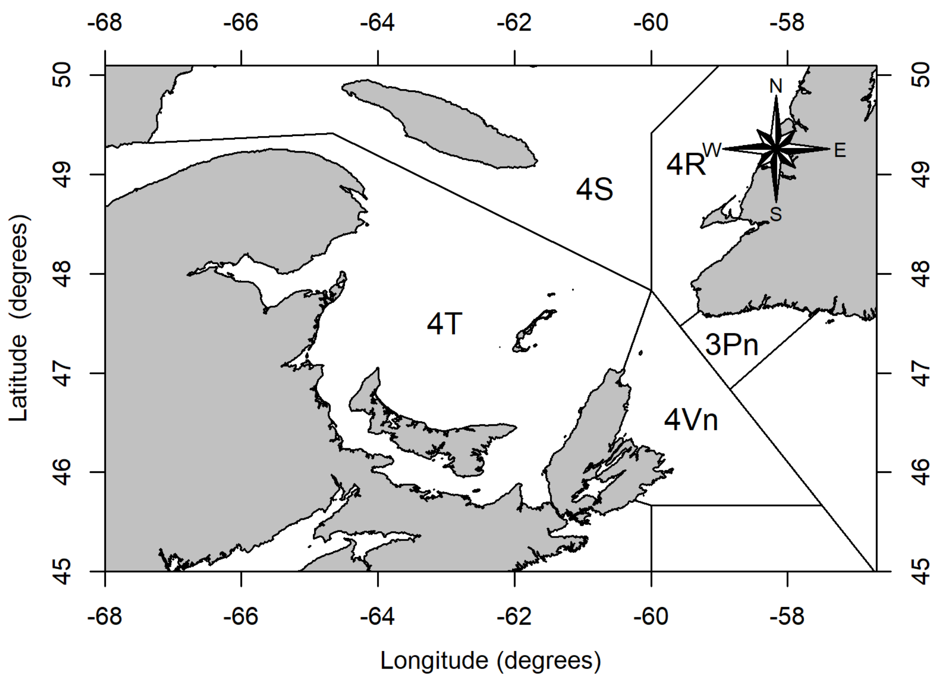

Figure 1: NAFO Divisions in the Gulf of Saint Lawrence and Cabot Strait.

In its 2003 assessment of Atlantic Cod, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) designated the Maritimes Designatable Unit (DU) Special Concern. The sGSL stock was part of this DU. In April 2010, COSEWIC re-assessed Atlantic Cod and split the previous Maritimes DU into two populations, the Laurentian South DU and the Southern DU. The Laurentian South DU, which includes the sGSL Cod stock, was designated Endangered, a higher risk category than Special Concern, due to a 90% decline in abundance over three generations (COSEWIC 2010). In response to the COSEWIC assessment, a recovery potential assessment (RPA) of the Laurentian South DU was conducted in 2011 based on data to the end of 2009 (DFO 2011; Swain et al. 2012). This RPA concluded that the sGSL Cod stock was expected to continue to decline, even with no fishing, if productivity of the stock remained at its current low level.

The last full assessment of the sGSL Cod stock was completed in March 2019 (DFO 2019a; Swain et al. 2019). As part of the multi-year assessment cycle for sGSL Cod stock, an interim year update was provided mid-way in the four-year assessment cycle in 2021, using data up to 2020 (DFO 2021a).

Both the last assessment and the interim update confirmed that the stock has remained below the LRP and in the Critical Zone of the Precautionary Approach (PA) since 2005. Therefore, a rebuilding plan must be developed. Section 70 of the *Fishery General Regulations* sets out the required content of rebuilding plans, which involve several key requirements that are defined and/or supported by advice from DFO Science Sector. Scientific advice for some of the requirements are already available in peer-reviewed material through primary publications or other CSAS processes. For example, the stock status, trends, and probable causes of stock decline, and low likelihood of the stock rebuilding under prevailing environmental conditions are available in recent assessments and published literature (Neuenhoff et al. 2019; Swain et al. 2019). This document will provide a summary of the published scientific information; however, the peer-review will focus on the new scientific analyses performed to inform the development of the sGSL Cod rebuilding plan. The specific objectives of this document are i) to review and update the current LRP and establish the stock status with respect to the recommended LRP, ii) to provide advice on the selection of a rebuilding target, iii) to calculate and evaluate the likelihood of achieving the rebuilding target in a specified timeline under various environmental and fishery management scenarios, iv) to propose additional measurable objectives, v) to identify indicators for tracking rebuilding progress, and vi) to provide guidance on the frequency of the periodic review of the rebuilding plan.

2. REFERENCE POINTS

The LRP represents the upper bound of stock states that should be avoided to prevent serious harm to the stock and is the boundary between the Critical and Cautious Zones of DFO's PA Policy (DFO 2023a). Stocks at a level below their LRPs (i.e., in the Critical Zone) are considered to be at an unacceptable risk of impaired reproductive capacity or other serious harm (Shelton and Rice 2002). The LRP should be defined at a point before serious harm is observed and not at the point when serious harm is observed (Kronlund et al. 2018). At this stock status level, there may also be resultant impacts to the ecosystem, associated species and a long-term loss of fishing opportunities. Several approaches for calculating a LRP exist, they may be refined over time, and their individual suitability for specific stocks are dependent on the nature and quality of the data and stock assessment methods and results. The LRP is based on biological criteria and established by DFO Science through a peer reviewed process (DFO 2009).

The current LRP for this stock, 80,000 tonnes (t) of spawning stock biomass (SSB), was established in 2003 using the SSB below which the probability of poor recruitment is high (according to the 2003 model-based stock-recruit relationships), as well as Brecover (Chouinard et al. 2003). As noted in the last assessment (Swain et al. 2019), there have been many model changes since 2003, making the absolute value of the LRP incorrect. Thus, the LRP should be revised. For example, based on the change in model scale, $B_{recover}$ is now estimated to be 107,000 t of SSB (Swain et al. 2019). The Upper Stock Reference (USR) for this stock is 200,000 t (Mohn and Chouinard 2004). There is no agreed upon Target Reference Point (TRP) or Removal Reference (RR) for this stock.

Deriving reference points for stocks with time-varying productivity, especially for stocks with steadily declining productivity such as sGSL Cod, is complex. The use of dynamic reference points can lead to the progressive lowering of a conservation threshold, such that risk can be underestimated (Cox et al. 2019). Moreover, the equilibrium results of fishing mortality (F) based reference points (such as F_{MSY} or $F_{0.1}$) can suggest that stocks with high natural mortality (M) and/or maturity schedules positioned to the left of selectivity schedules can be fished at high rates and maintain high values of depletion, which is inconsistent with the evidence from the stock reconstructions from assessment models (DFO 2017a; Turcotte et al. In prep.[1]). Cox et al. 2019 found that, for a stock with very similar productivity dynamics to that of sGSL Cod, a theoretical LRP should be fixed over time and that potential empirical LRPs (e.g. based on previously observed stock or biomass index levels) should not reflect worst-case scenarios. When using dynamic or empirical LRPs based on periods of harmed states, the probability of breaching both the dynamic and empirical LRPs was usually near or equal to zero, failing to indicate risks in situations where risks could be significant. These considerations limit the methods that can be used to derive an LRP that can be applied to sGSL Cod and still be precautionary.

To review the current LRP and explore alternative LRPs for sGSL Cod, it is first necessary to identify the point where serious harm has occurred. Here, a brief review of the literature and stock assessment estimates of population dynamics, processes, and stock status were used to inform the evaluation of the point where serious harm occurred. Multiple candidate LRPs estimated using different methods were then evaluated to identify the best candidate LRP. Evaluating multiple candidates is informative as it can provide confidence in selecting a LRP when estimates agree but can also identify potential risks when estimates do not agree (DFO 2023a). Indicators, LRPs, and stock status metrics should consider reliability, plausibility and uncertainty (DFO 2023a). Here, a weight-of-evidence approach was used to evaluate and select the best candidate LRP, which was compared to the best practice principles for indicators, LRPs and stock status metrics (DFO 2023a).

2.1. A DEFINITION OF SERIOUS HARM

In the context of fisheries, serious harm can be defined (DFO 2023a) as an undesirable state that may be irreversible or only slowly reversible over the long-term. It may be directly or indirectly due to fishing, other human-induced impacts, or other natural causes, and occurs at states before extirpation is a concern. These states can be associated with impaired productivity or reproductive capacity, resulting from changes to biological processes such as recruitment, growth, maturation and survival, and may lead to a loss of resilience, defined as an impaired ability to rebuild, exceed replacement or to recover from perturbation. These states can be associated with an elevated risk of depensation or Allee effect (i.e., negative density dependence, in which the intrinsic rate of increase for a stock decreases, rather than increases, as abundance declines) and are states where population dynamics are generally poorly understood. When a stock is estimated to be at risk of serious harm, there may also be resultant impacts to the broader socio-ecological system, such as the ecosystem, associated or dependent species, or a long-term loss of fishing opportunities. However, economic inefficiencies such as growth overfishing or reduced yield do not in and of themselves constitute serious harm to the stock.

[1] Turcotte, F. and McDermid, J.L. Scientific Requirements for the Rebuilding Plan of Southern Gulf of St. Lawrence (NAFO Division 4TVn) Spring Spawning Atlantic Herring. DFO Can. Sci. Advis. Sec. Res. Doc. In preparation.

2.2. SERIOUS HARM IN SGSL COD

2.2.1. Biomass

sGSL Cod SSB generally declined over the 1950 to 2018 period, except for a 10-year period in the mid-1970s to late 1980s (Swain et al. 2019). SSB peaked in the mid-1950s and declined to very low levels in the mid-1970s. SSB then rapidly recovered in the late 1970s, reaching a peak in 1981. SSB then collapsed equally rapidly between about 1987 and 1993, when the directed fishery was closed. SSB has been declining since 2001 and crossed the current LRP (80,000 t), into the Critical Zone, in 2005. Estimated SSB at the start of 2018 was 13,947 t (95% CI: 10,700 to 18,500 t), an 88% decline since 2000 and a 96% decline since 1985, which represents 17% of the LRP.

Atlantic Cod has been exploited for centuries in the Northwest Atlantic Ocean. Reconstructions of the size of other Cod stocks going back centuries have been made using logbook catch and effort data (Rosenberg et al. 2005) and surplus production models (Rose 2004; Schijns et al. 2021). Especially for stocks that experienced centuries of exploitation, integrating information from the past, even if only landings data, broadens the view of the stock dynamics, earlier states, potential productivity. More importantly, it can help counteract the shifting baseline syndrome, which results in a gradual accommodation of the creeping disappearance of resource species and inappropriate reference points and rehabilitation targets (Pauly 1995).

Atlantic Cod stocks off Newfoundland were estimated to currently be approximately at 5% of their historical biomass (between 1500 and the mid-1900s) by Rose (2004), while the NAFO Division 2J3KL Northern Atlantic Cod stock off Newfoundland and Labrador coasts were found to likely be below 1% of their original biomass at present according to Schijns et al. (2021). The contemporary Scotian Shelf (NAFO Division 4VsW) Atlantic Cod biomass is estimated to be only about 4% of what it was in the 1800s (Rosenberg et al. 2005). The maximum biomass observed in the modern 4VsW Cod assessment period is five times smaller than the level estimated in 1852 for that stock, about 240 kt in the early 1980s (DFO 2015). If Cod densities in the sGSL were similar in earlier periods, the sGSL biomass would have been approximately 735 kt based on the relative sizes of the two ecosystems (Neuenhoff et al. 2019). This approximation, while highly uncertain in absolute terms, is a reasonable one because the Cod stocks are thought to have experienced similar historical exploitation. The historical decline of these Cod stocks has been attributed to overfishing. It is likely that sGSL Cod experienced similar historical levels of exploitation, which could have resulted in similar declines in biomass over the past few centuries.

The consequences of depleting a stock to a small size can be important for their vulnerability and capacity for rebuilding. Depleted stocks may exhibit greater vulnerability to stochastic environmental changes and increased variability in mortality (Minto et al. 2008), while the greater the depletion of the population, the longer and more uncertain the recovery period (Neubauer et al. 2013).

2.2.2. Productivity

The occurrence of low production-low biomass (LP-LB) states over time is evaluated by inspecting the relationship between surplus production and population or spawning stock biomass. Persistence of such states may be an indicator of serious harm to the ability of a fish stock to grow to target levels of SSB (Kronlund et al. 2018). Annual sGSL Cod production was estimated by Swain et al. (2019). Cod production averaged 59,000 t between 1950 and 1985. Since the beginning of the first moratorium in 1994, annual production has averaged -4,000 t (i.e., a production deficit). The average production deficit since 2001 is estimated to be -7,000 t.

Among 15 Cod stocks in the North Atlantic, sGSL Cod was found to be the least productive (Dutil and Brander 2003). For sGSL Cod, a LP-LB state has occurred since 1993, when SSB was 110,000 t.

The per capita rate of population growth (e.g., production per unit of biomass) is expected to increase as population size decreases due to decreases in intraspecific competition at low population size (Nicholson 1933). However, in some instances, per capita population growth decreases as population size decreases below some threshold. This is termed an Allee effect (Courchamp et al. 1999). Allee effects increase the risk of extinction at low population sizes. The relationship between the rate of Cod population production and population biomass has exhibited positive density dependence between 1991 and 2017 (Swain et al. 2019). The current production deficit of sGSL Cod appears to be due to a predation-driven Allee effect, a demographic effect caused by the decline in Cod abundance to very low levels due to overfishing and an emergent effect due to increasing predator abundance (Neuenhoff et al. 2019). Cod in the sGSL appear to have crossed the Allee threshold in 1993 when SSB was estimated to be 112,000 t (Swain et al. 2019). Thus, the LRP should be set well above 112,000 t.

2.2.3. Recruitment

Cod recruitment (abundance of age-2 fish) generally co-varied with SSB, increasing from the 1960s to the early 1980s to reach a peak of 569 million fish in 1982 (Swain et al. 2019). Recruitment then gradually declined over time and was at the lowest level in the 69-year time series in 2014 to 2018 with an average of 27 million fish. Recruitment rates (age-2 abundance divided by the SSB that produced them) stayed relatively stable over the assessment period, but were unusually high for the 1973 to 1977 year-classes and were also slightly above average in recent years.

The unusually high recruitment rates In the 1970s fueled the rapid recovery of this stock from its earlier collapse. The recruitment rate in this period is thought to be abnormally high, potentially reflecting reduced predation on Cod eggs and larvae following the collapse of pelagic fish stocks in the sGSL in the early 1970s (Swain and Sinclair 2000). This negative effect of pelagic fish biomass on Cod recruitment success in the sGSL was estimated using data and model outputs from 1963-1994. However, using recent Cod, Atlantic Herring (*Clupea harengus*), and Atlantic Mackerel (*Scomber scombrus*) population size estimates, the relationship between pelagic fish biomass and Cod recruitment success seems to be less apparent (Appendix 1). Perälä et al. (2017) did find evidence for regime shifts in the stock-recruit relationships parameters of sGSL Cod (and other groundfish) that coincides with changes in pelagic fish abundance (and assumed consumption of Cod eggs and larvae), supporting the top-down explanation for Cod recruitment dynamics. However, few studies have examined the effect of bottom-up drivers in sGSL Cod, which have been shown to be strong drivers of recruitment in other systems.

In North Sea Cod, fluctuations in plankton have resulted in long-term changes in Cod recruitment where survival of larval Cod is shown to depend on mean size, seasonal timing and abundance of prey (Beaugrand et al. 2003). The modification in the plankton ecosystem in the North Sea and the resulting reduction in survival of young Cod has been linked to rising temperature since the mid-1980s (Beaugrand et al. 2003). Similar rising temperatures and changes in copepods community composition have been observed in the sGSL, along with concomitant decrease in recruitment success in Atlantic Herring (Turcotte 2022). In a meta analysis of data on nine Cod stocks, Planque and Frédou (1999) demonstrated the existence of a significant temperature–recruitment relationship in stocks at the limit of a species' spatial distribution. This finding could potentially be transferable to the yearly variability in water temperature and long-term warming trends and their potential effects on recruitment success. Overall, the conditions required for recruitment success in sGSL Cod should be further investigated, but the lack of readily available temperature and plankton data from the 1970s precludes analysis of potential drivers of the high recruitment rates in that decade, for now.

2.2.4. Reproductive capacity and maturation

Age and size at maturity of sGSL Cod declined sharply over time in cohorts produced in the 1950s and 1960s, but has changed little since (Swain et al. 2012; Swain et al. 2019). When mortality is high, fitness tends to be greater for individuals that mature early. The decline in age and size at maturity between the late 1950s and early 1970s is thought to reflect an evolutionary response to the high fishing mortality of the 1950s and 1960s (Swain et al. 2012). The persistence of early maturation after the sharp reduction in fishing mortality in the early 1990s is thought to be the consequence of the current high natural mortality.

McIntyre and Hutchings (2003) found that sGSL Cod life histories are characterized by relatively high size-specific fecundity, high gonadosomatic index and large eggs when compared to adjacent Atlantic Cod stocks (Sydney Bight (4Vn), eastern Scotian Shelf (4VsW) and Georges Bank). The higher reproductive allotment of sGSL Cod may represent a selection response to slower growth and later maturation, resulting in higher pre-reproductive mortality and fewer lifetime reproductive events. The same study found that size-specific fecundity did not differ significantly between years (1955-1999), except for relatively low fecundity at length in 1998.

2.2.5. Survival

Overfishing has been identified as the principal cause of the collapse of Atlantic Cod and other exploited groundfish in the Northwest Atlantic (e.g., Myers and Cadigan 1996; Sinclair and Murawski 1997). Fishing mortality for sGSL Cod aged 2-4 years was negligible over the assessment period. Fishing mortality for ages 5+ was high during most of the mid-1950s to the mid-1970s period, and again in the mid-1980s to the early 1990s (Swain et al. 2019). High fishing mortality was the main factor ultimately leading to the sGSL Cod collapse in the early 1990s (Myers and Cadigan 1996). F values around 0.45 to 0.5 for 3 to 5 consecutive years led to a decline in SSB twice in the time series (Swain et al. 2019). The high F values caused harm to the stock, especially in the late 1980s to early 1990s when M started increasing concurrently. However, the impact of high F is dependent on the ecosystem state and its impacts on the productivity of the Cod stock; high productivity in the 1970s related high recruitment rates versus low productivity due to high Grey Seal abundance in the 1990s (Swain et al. 2019).

Natural mortality of juvenile Cod (ages 2-4) fluctuated without trend near or slightly below 33% annual mortality over the assessment period (Swain et al. 2019). M of older Cod increased gradually between 1971 and 2000 (33% to 55% for ages 5 to 8 and 28% to 46% for ages 9+). M continued increasing until 2010 for both age groups to reach values between 55% and 61% and has since remained at elevated levels. Earlier studies obtained M estimates for sGSL Cod ranging from 0.07 to 0.1-0.2 in the 1970s and earlier (Dickie 1963; Beverton 1965; Myers and Doyle 1983). The low estimates of total mortality (Z) in the 1970s relative to the high estimates of relative fishing mortality also suggest that M was very low in this earlier period (Swain et al. 2012).

A comprehensive suite of hypotheses has been examined to determine which factors are most likely to be important causes of the elevated M of 5+ Cod (Swain et al. 2011). The factors examined were unreported catch, emigration, disease, contaminants, poor fish condition, life history change, parasites, and predation by Grey Seal. The conclusions, based on the weight-of-evidence, were that a predator pit caused by the predation on Cod by Grey Seal was the cause of this high M.

Predation by Grey Seal (*Halichoerus grypus*) has been identified as an important source of mortality for sGSL groundfish (Swain and Benoît 2015; Neuenhoff et al. 2019) and Atlantic Herring (*Clupea harengus*; Benoît and Rail 2016; Turcotte et al. 2021). Increases in Grey Seal predation have been linked to widespread rises in mortality rates for adults of large-bodied groundfish in this ecosystem (Benoît et al. 2011; Swain and Benoît 2015). Distribution shifts of Cod, White Hake (*Urophycis tenuis*), and Thorny Skate (*Amblyraja radiata*) were also found to be strongly related to the risk of predation by Grey Seal, with groundfish shifting their distribution into areas of lower risk as predation risk increased in their traditional areas (Swain et al. 2015). This shift in spatial distribution appears to incur the cost of reduced food availability, reflected in poor body condition of cod in deep waters (Swain and Wade 1993, Chouinard and Swain 2002).

High M was identified as the main factor preventing sGSL Cod recovery (Swain et al. 2019; Neuenhoff et al. 2019). Population models relating Cod mortality to Grey Seal abundance have forecasted a high risk of extirpation for this population unless Grey Seal presence in the sGSL is reduced by at least 65% (Neuenhoff et al. 2019; Swain et al. 2019). The most recent modeling exercise using the most up-to-date Cod and Seal data suggests that seal quotas required to sufficiently reduce predation mortality on Cod to allow for the chance of Cod survival were significantly higher than current removal levels and would likely collapse the grey seal herd in the Gulf of St. Lawrence (Rossi et al. 2024).

2.2.6. Growth

Weight-at-age of southern Gulf Cod decreased rapidly in the late 1970s and early 1980s, reflecting a density-dependent decline in growth rate as Cod abundance increased during this period (Swain et al. 2012), combined with a change in the direction of size-selective fishing mortality (Hanson and Chouinard 1992; Sinclair et al. 2002a,b). Weight-at-age has remained low since the mid-1980s, despite better conditions for growth in some parameters (i.e. less density dependence with low Cod abundance and relatively warm water temperatures) and a severe reduction in size selection due to fishing. The continued small size-at-age may be partly due to a genetic response to size-selective fishing in the 1980s and early 1990s (Swain et al. 2007). Declines in weights-at-age over the last decades, especially for older fish, have been documented for multiple commercially harvested fish stocks, irrespective of taxonomic order (Charbonneau et al. 2019).

sGSL Cod condition was relatively high in the early to mid-1970s, low from the late 1970s to the mid-1980s, near the long-term average from the late 1980s to the mid-2000s but declined to lower levels in recent years (Swain et al. 2019). The high condition in the mid-1970s followed by low condition in the mid-1980s may reflect density-dependent effects in intra-specific competition for resources as abundance increased. However, Cod condition would be expected to increase with the low Cod abundance of the last decades. This lingering low condition could be the result of predation risk by Grey Seal. Cod have shifted out of their traditional foraging grounds into deeper waters where predation risk is low (Swain et al. 2015), but where historical values of condition was lower than other areas of the sGSL (Chouinard and Swain 2002). Hence, the shift in distribution might have reduced the predation risk but might also have resulted in a decrease in condition in an unfavorable habitat.

2.2.7. Serious harm

The sources of serious harm to sGSL Cod are multiple, including overfishing, a lasting state of low production-low biomass, recruitment overfishing, high natural mortality and predation-driven

Allee effect, low growth and body condition and a decrease of age at maturity. As a result, identifying a single point where serious harm occurred is not straightforward.

A low production-low biomass state began in 1993 when SSB was 110,000 t and has continued since. The Allee effect threshold suggests a minimal serious harm level of 112,000 t, however this point should be avoided at all costs since biomass levels below this threshold result in a high risk of extinction for the stock. Consequently, the LRP should be set at a higher level than the Allee effect threshold. Unfortunately, there is no guidance on how much higher than the Allee effect threshold the LRP should be set, particularly given the various time-varying productivity components for a stock such as sGSL Cod. It seems highly plausible that this stock has been depleted for most of the period covered by the stock assessment, that the available information on productivity of the stock is based on a period of mostly harmed state and that the serious harm state was reached before the assessment period.

2.3. METHODS

Southern Gulf of St. Lawrence Cod population estimates were obtained from the population model output produced in the last assessment (Swain et al. 2019).

2.3.1. LRP based on a stock-recruit relationship

2.3.1.1. LRPs from biomass at 50% maximum recruitment

The SRR were modelled using three parametric models: Beverton-Holt, Ricker and Hockey Stick (code was adapted from Duplisea and Fréchet 2010). The Beverton-Holt and Ricker models were fit to the data using the nls function in the R statistical software (R Core Team 2021). The Beverton-Holt (BH) model was of the form:

$$R = \frac{aS}{(b+S)}$$

where R is the number of recruits in a given year class, S is the SSB that produced that year class, a is the asymptotic recruitment, and b is the SSB needed to produce, on average, recruitment equal to half of the maximum (50%R_{max}).

The Ricker (RK) model was of the form:

$$R = aSe^{-bS}$$

where R is the number of recruits in a given year class, S is the SSB that produced that year class, a is the recruits per unit of spawner biomass at low stock levels and b relates to the rate of decline in the recruits per unit of spawner biomass as S increases. R_{max} is obtained by:

$$R_{max} = \frac{a}{b}e^{-1}$$

The Hockey Stick (HS; also named segmented or change-point regression) models the SRR in two segments, one being a flat line at maximum recruitment and the other a straight line from the origin to a point intersecting the flat segment. The intersection of the two lines is determined by an iterative grid search method using Julious's algorithm (Julious 2001; O'Brien et al. 2003).

A non-parametric (NP) fit of the data was performed using a cubic spline in the smooth.spline function of the R statistical software. Various degrees of freedom (df) were used in a sensitivity analysis and the best fits to the data are presented. NP SSB50%R_{max} was calculated as the average SSB50%R_{max} from the three best fits.

The LRP derived from SRR will be dependent on the functional form of the relationship and the type of dynamics observed. The LRPs derived from these methods are the SSB at 50% R_{max}, which is the biomass associated with 50% reduction from R_{max} estimated from the SRR.

2.3.1.2. LRPs based on ICES guidance

The sGSL Cod matches two stock types description from the ICES guide to reference points (ICES 2017) where the LRP is chosen depending on the observed pattern in stock-recruit relationships:

Type 2: Wide range in SSB with evidence of impaired recruitment at low SSB. The LRP can be change point from a segmented regression of a hockey-stick stock-recruit curve (B_{lim}).

Type 3: Same as Type 2, but no clear asymptote in recruitment at high SSB. The estimate depends on an evaluation of the historical fishing mortality. If F has been high, the LRP could be highest SSB observed.

The candidate LRPs were calculated as the change point from the HS SRR (ICES Type 2 stock; B_{lim}) and the SSB in year 1981 (ICES Type 3 stock; max SSB).

2.3.1.3. LRP from replacement line analysis

Annual values of survival per recruit were calculated using annual natural mortality vector for ages 2-12+.

The survival per recruit was calculated using a survivorship analysis:

$$l_a = \ l_{a-1}e^{(-(M_{a-1})}$$

And for the plus group:

$$l_a = \ l_{a-1}\frac{e^{-(M_{a-1})}}{1-e^{-M_a}}$$

where a is age, l_a is the survival at age and M_a is natural mortality at age.

Annual values of SSB per recruit (Φ_0) were calculated by multiplying annual vectors of survival per recruit, weight at age and maturity at age, and doing the sum over ages. Annual replacement lines of slope 1/ Φ_0 were compared to a Beverton-Holt SRR. Years were the replacement line did not cross the SRR were identified as years were the stock would not replace itself. The candidate LRP from this method would be the SSB in a year were the stock would not replace itself.

2.3.2. LRP based on B_0

B_0 is here the mean long-term equilibrium spawning stock biomass of the stock in the absence of fishing. The per-recruits methods require equilibrium to derive reference points, so that their outcome adequately represent the average state of the stock. However, these methods assume stationary productivity parameters. Over the years of the Cod assessment, M increased, weight-age-age declined, maturity at age changed and the stock-recruit relationships do not display an equilibrium recruitment (see 2.4.1). These are all conditions violating the assumption of equilibrium over time. Hence, a year where the stock was in its best productivity state over the assessment period was selected to perform the calculations. The year 1950 (initial assessment year) was selected to represent a productive period (high weight-at-age, low M at age and higher age at maturity).

B_0 was calculated in the initialization function of the population model. The population was initiated with one recruit, and a vector of unfished spawners per recruit was calculated using M at age in the year 1950. SSB per recruit (Φ_0) was then calculated by summing the products of the spawner per recruit, weight-at-age and maturity-at-age vectors from 1950. To identify the year 1950 used in calculations the candidate LRPs will be identified as initial X%B_0.

20 to 30% B_0 has been suggested as an LRP that would avoid recruitment overfishing, with higher thresholds needed for lower productivity stocks (Beddington and Cooke 1983, as cited in Mace (1994); Sainsbury 2008). Productivity has been negative for most years since the early 1990s and among the 15 Cod stocks in the North Atlantic, sGSL Cod was found to be the least productive (Dutil and Brander 2003). To account for the potential low production of this Cod stock, values of 0.2, 0.25 and 0.3 B_0 were calculated as candidate LRPs.

2.3.3. LRP based on MSY_{proxy} from the DFO Precautionary Approach guidelines

Estimates of biomass that produce maximum sustainable yield (B_{MSY}) are typically used to derive LRPs from population models. However, they require stationarity in demographic productivity parameters. The absence of equilibrium in growth, natural mortality, and recruitment for this stock and the lack of historical stable stock states at stable fishing pressure precludes the ability to use these methods within the population model used in the sGSL Cod stock assessment.

In the absence of an estimate of B_{MSY} from an explicit model, the PA framework provides guidance to identify reference points and harvest rules (DFO 2009). The provisional estimate of B_{MSY} could be taken as follows (select the first feasible option): (1) the biomass corresponding to the biomass per recruit at F0.1 multiplied by the average number of recruits; or (2) the average biomass (or index of biomass) over a productive period; or (3) the biomass corresponding to 50% of the maximum historical biomass (DFO 2009).

The LRP, USR and stock status zones can be defined as follows (DFO 2009): (1) the stock is considered to be in the Critical Zone if the mature biomass, or its index, is less than or equal to 40% of B_{MSY}, i.e., biomass ≤ 40% B_{MSY}; (2) the stock is considered to be in the Cautious Zone if the biomass, or its index, is higher than 40% of B_{MSY} but lower than 80% of B_{MSY}, i.e., 40% B_{MSY} < biomass < 80% B_{MSY}; and (3) the stock is considered to be in the Healthy Zone if the biomass, or its index, is higher than 80% of B_{MSY}, i.e., biomass ≥ 80% B_{MSY}.

1. The biomass corresponding to the biomass per recruit at F0.1 multiplied by the average number of recruits.

To obtain the F0.1 value, a yield per recruit analysis was performed using the ypr function of the fishmethods package (Gabriel et al. 1989) in the R statistical software. A weight-at-age vector, a gear selectivity vector and a natural mortality vector for ages 2-12+ in the initial assessment year (1950) were used for the reasons stated in the section 2.3.2, while the same limitations apply to this use of per-recruit calculations. The oldest age was set to 20 and maxF was set to 2.

The survival per recruit at F0.1 was calculated using a survivorship analysis:

$$l_a = l_{a-1} e^{(-(M_{a-1} + F * sel_{a-1})}$$

And for the plus group:

$$l_a = l_{a-1} \frac{e^{-(M_{a-1} + F * sel_{a-1}}}{1 - e^{-M_a + F * sel_a}}$$

where a is age, l_a is the survival at age, M is natural mortality at age, F is fishing mortality and sel is selectivity at age. The F value was set to F0.1.

To obtain the SSB per recruit at F0.1, the survival per recruit multiplied by the weight-at-age and maturity at age vectors was summed over all ages. The SSB per recruit at F0.1 was multiplied by the average number of recruits estimated for years 1981 to 1984, as described in section 2.4.2. The LRP derived from this $BMSY_{proxy}$ was calculated as 40% of its value (named $40\%PA1BMSY_{proxy}$).

2. The average biomass over a productive period.

Stock production was calculated as:

$$P_t = C_t + B_{t+1} - B_t$$

Where P_t is the stock production in year t, C_t is the fishery catch in year t, B_{t+1} is the stock biomass for ages 2+ in year t+1 and B_t is the stock biomass for ages 2+ in year t. Productive periods were identified by finding uninterrupted periods of 5 years during which stock production and stock biomass were simultaneously near their highest values. The $BMSY_{proxy}$ was calculated as the mean SSB in the identified years. The LRP derived from this $BMSY_{proxy}$ was calculated as 40% of its value (named $40\%PA2BMSY_{proxy}$).

3. The biomass corresponding to 50% of the maximum historical biomass.

50% of the highest SSB in a single year was used to derive a $BMSY_{proxy}$. A candidate LRP was calculated at 40% of its value ($40\%PA3BMSY_{proxy}$).

2.3.4. LRP from a surplus production model using a longer catch time series

BSM is a Bayesian state-space implementation of a traditional surplus production model which derives its estimates from catch and abundance or effort data (Tsikliras and Froese 2019). The main parameters of the underlying Schaefer model are the “intrinsic” rate of population growth (or resilience; r) and the carrying capacity of the ecosystem (K; Schaefer 1954, 1957).

As was done for an adjacent Cod stock (NAFO Division 2J3KL; Schijns et al. 2021), a modified formulation of the Schaefer model was used here. This formulation accounts for depensation when a stock is depleted (biomass below 0.25K or $0.5B_{MSY}$), which is known to occur for sGSL Cod (Neuenhoff et al. 2019). The BSM framework allows the of a longer time series of catch estimates, providing a view of the historical stock dynamics when catches were more stable (prior to 1950; Figure 6), and the stock was presumably also more stable.

The goal here was not to perform a full assessment using catch and index data with the BSM tool, as the Cod assessment is already performed with the SCA population model. Rather, the goal was to extend the historical dynamics of the stock backwards using the longest time series of catch data available, as performed in other Cod stocks (Rose 2004; Schjins et al. 2021). The detailed length and age sampling required by the SCA assessment model was not conducted in earlier years, curtailing the use of the SCA over this longer time period. Cod landings statistics for the sGSL Cod stock dating back to 1917 were obtained from the annual Fisheries Statistics Bulletins for the period 1917-1949 (Chouinard and Fréchet 1994). Statistics for the period 1917-1949 do not include the French catches, but there is no indication that these were significant (Chouinard and Fréchet 1994).

To obtain MSY estimates that scale to assessment model results, the DFO Gulf Region bottom-trawl RV survey age-aggregated (ages 2-11) trawlable Cod biomass was used as biomass index in the BSM model inputs, with q priors tightly defined around 0.7, as estimated by the SCA model (Swain et al. 2019). The priors on the bounds for q were set as ~U(0.70, 0.72).

The analysis also requires to inform the model with priors on the bounds for the r and B/K parameters. The priors were set as broad ranges in order to let the estimation method find the most likely value for these parameters. Based on productivity information from adjacent Cod stocks, priors on bounds for r were set as at 0.095 and 0.4 $year^{-1}$ for the lower and upper bounds, respectively (Myers and Fowlow 1997; Hutchings 1999; Rose 2004; Schjins et al. 2021). Sensitivity runs were performed with slightly narrower and wider bounds, with similar posterior probability estimates.

The trends in catch and biomass estimates from the RV survey time series were used to infer potential ranges in the depletion of biomass from the start to the end of the time series. These ranges translated into priors on bounds of biomass relative to unexploited biomass (B/K). The sGSL Cod stock was already exploited at the beginning of the catch time series, but at lower annual landings than observed in the assessment period (post-1950). The average yearly catch from 1917 to 1949 was 33,683 t, while the average catch for 1950 to 1992 was 58,369 t. Hence, it was assumed that the level of exploitation in 1917 (initial model year) was not extremely low or high, and that the level of stock depletion in that year was accordingly not extremely low or high. Evidence shows that for Atlantic Cod stocks, biomass levels were higher prior to 1950 (Rosenberg et al. 2005; Rose 2004; Schjins et al. 2021). At the start of the time series, the B/K prior bounds were set as ~U(0.4,0.8), corresponding to a medium/low depletion (BSM user guide). The sGSL Cod stock assessment shows that in 1985, the stock was declining from a peak in biomass, but not yet collapsed (Swain et al. 2019). Therefore, the priors for bounds of B/K in an intermediate year, 1985, were set as ~U(0.1,0.5), corresponding to medium-strong depletion. The priors for bounds of B/K for the end of the time series were set as ~U(0.01,0.1), corresponding to very strong depletion. A sensitivity analysis on the values of the priors on the bounds was performed by switching off the intermediate and end priors. The empirical built-in default priors gave similar ranges as the expert-based priors.

The candidate LRP from this method was derived by directly calculating B_{MSY} using model estimates: $B_{MSY} = 0.5K$. The candidate LRP was defined at $0.4B_{MSY}$, as recommended by the DFO PA policy (DFO 2009).

2.4. RESULTS

2.4.1. LRP based on the stock-recruit relationship

2.4.1.1. LRPs from biomass at 50% maximum recruitment

The BH SRR model fit to the data was acceptable (Figure 2), the a parameter was significant, but the b parameter was not (a = 814,849,134, p = 0.048, b = 518,444, p = 0.176). The RK SRR model fit to the data was acceptable (Figure 2), the a parameter was significant, but the b parameter was not (a = 1,436.26, p = 0.00000156, b = 0.0000011910, p = 0.0812). Given that SRRs parameters are used as a guidance tool, the significance level may be less stringent (e.g. 0.25 rather than 0.05) than in other applications (Myers et al. 1994). Hence, the b parameters of the BH and RK SRRs are credible. The HS model fit set the inflexion point of the regression at a very high level of SSB, where higher than the predicted average number of recruits per SSB are present and the number of points supporting the inflexion point position is low (Figure 2). The diagonal regression section of the relationship fit to the data was acceptable. For the three modeled SRRs, the fitted values generally over-estimated the number of recruits of the major cluster of points, likely showing the influence of the minor cluster of higher number of recruits (above 400 million) on the model fits. There is no clear asymptote at high SSB in either of the Cod SRRs (Figure 2). The BH SRR did not produce an asymptote, even when extended beyond the range of the data (Figure 2, right panel). The Ricker SRR did not produce a maximum and descending limb with increasing SSB. The HS SRR did find an inflexion point, but its position is only supported by a small number of stock-recruit pairs.

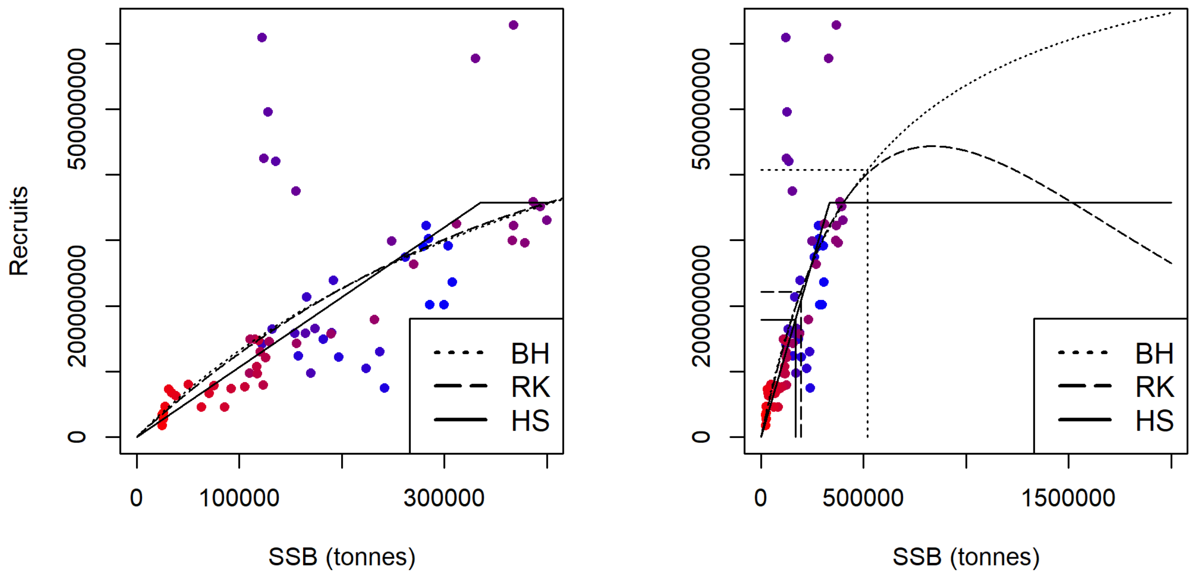

Figure 2: Southern Gulf of St. Lawrence Atlantic Cod stock-recruit relationships for years where spawning stock biomass (SSB, tonnes) and number of recruits (age-2 fish) pairs are available (left panel), and for years showing the theoretical asymptote from the models, along with dashed lines showing the 50% maximum number of recruits and the SSB producing the 50% maximum number of recruits (right panel). Circles indicate SSB and number of recruits pairs, colored lines indicate model estimates; BH: Beverton-Holt (blue lines), RK: Ricker (red lines), HS: Hockey-Stick (black lines).

The model estimated value representing 50% of the maximum number of recruits from the BH SRR was 407,424,567 recruits. The SSB producing this number of recruits (BH SSB50%Rmax) was 518,000 t of SSB. For the RK SRR, the model estimated value representing 50% of the maximum number of recruits was 221,824,758 recruits. The SSB producing this number of recruits (RK SSB50%Rmax) was 195,000 t. For the HS SRR the model estimated value representing 50% of the maximum number of recruits was 178,778,234 recruits. The SSB producing this number of recruits (HS SSB50%Rmax) was 168,000 t. The inflexion point of the SRR was 335,375 t of SSB.

The non-parametric approach provided acceptable fits to the data (Figure 3). As the SRR is almost linear, fits using two, three and four degrees of freedom provided the best fits to the data and very similar values of SSB50%Rmax between them (between 169,000 and 179,000 t of SSB). The fitted SRR did not produce an asymptote. The average NP SSB50%Rmax from the three model fits was 174,000 t of SSB.

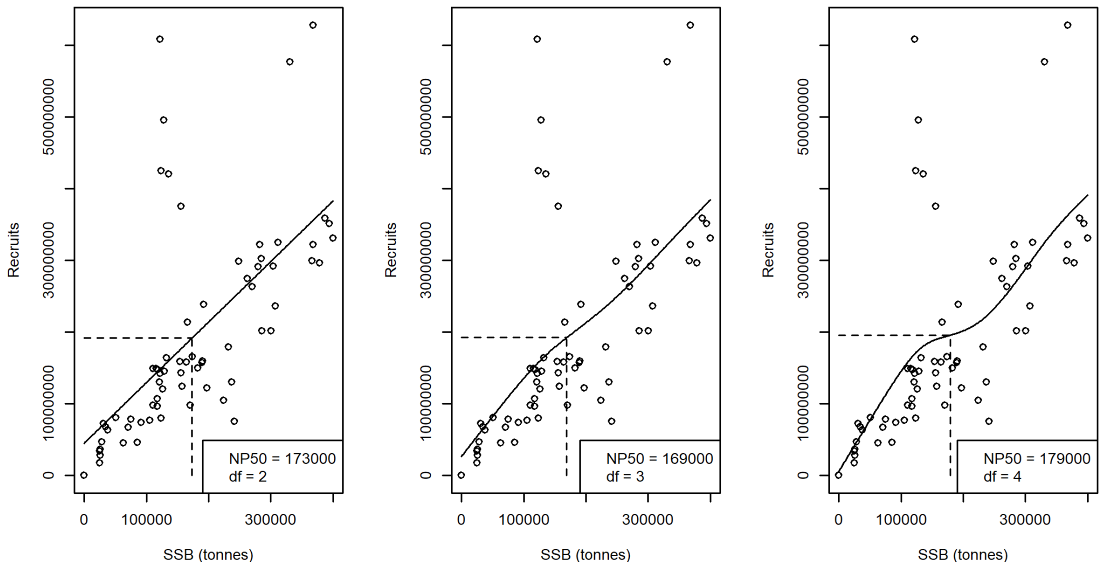

Figure 3: Non-parametric fits to the stock-recruit data using a cubic spline with two (left panel), three (middle panel), and four (right panel) degrees of freedom (df). Black lines are the fitted values, dotted lines indicate the number of recruits representing 50% of the maximum fitted recruitment and the fitted SSB (tonnes) value producing this number of recruits (NP SSB50%Rmax).

2.4.1.2. LRP from ICES guidance

The ICES type 2 stock candidate LRP (B_{lim}) was estimated at the change point of the HS SRR; 335,375 t of SSB. The ICES type 3 stock candidate LRP (highest SSB observed), was estimated at 400,038 t of SSB.

2.4.1.3. LRP from replacement line analysis

Annual replacement lines crossed the BH SRR from years 1950 to 1989 (Figure 4). 1990 was the first year were the annual replacement line did not cross the SRR and identified as the first year were the stock would not replace itself. The annual replacement lines did not cross the SRR for years 1990 to 1992, and years 2004 to 2018. The candidate LRP from the replacement line analysis is the SSB in year 1990, estimated at 190,000 t of SSB.

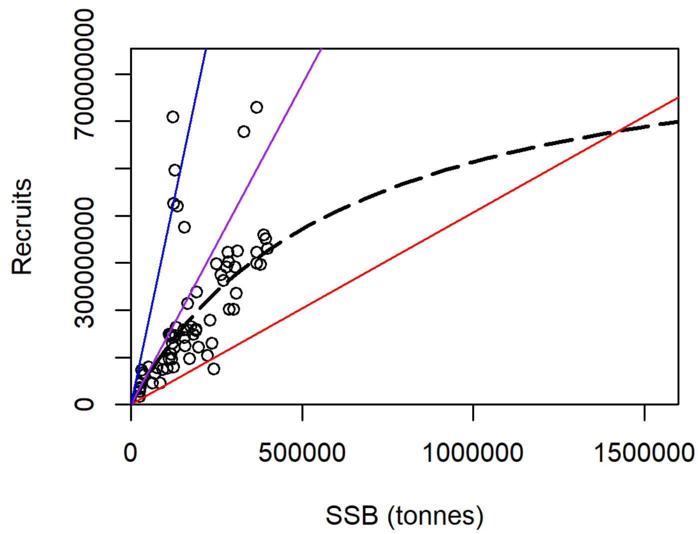

Figure 4: Southern Gulf of St. Lawrence Atlantic Cod Beverton-Holt stock-recruit relationship (black dashed line) for years where spawning stock biomass (SSB, tonnes) and number of recruits (age-2 fish) pairs are available, along with annual replacement lines for selected years (1950: red line, 1990: purple line and 2018: blue line).

2.4.2. LRP based on B_0

B_0 is usually calculated by multiplying Φ_0 by the average expected equilibrium unfished recruitment from a stock-recruit relationship. However, the BH and RK models produced equilibrium maximums outside of the range of observed data, and the HS model inflexion point is not considered credible (see 2.4.1). Hence, B_0 was calculated using the average recruitment over the highest SSB values of the linear part of the estimated SRR (years 1981 to 1984; 340,686,000 recruits) without the above-average points (see Figure 2), which is the closest metric to the equilibrium number of recruits one could obtain for that stock. This group of points represents the minimal potential position of the asymptote of the BH SRR or the maximum of the RK SRR.

The estimated Φ_0 value was 0.0025 units of SSB per recruit. The corresponding initial B_0 value was 838,363 t. Initial 0.2SSB$_0$, 0.25B$_0$ and 0.3B$_0$ values were estimated at 167,673, 209,591 and 521,509 t of SSB, respectively.

2.4.3. LRP based on MSY$_{proxy}$ from the DFO Precautionary Approach guidelines

1. The biomass corresponding to the biomass per recruit at F0.1 multiplied by the average number of recruits:

F0.1 was estimated at 0.38 for the initial year of the assessment period (1950). The SSB per recruit at F0.1 was estimated at 0.000667 t. The SSB corresponding to the SSB per recruit at F0.1 multiplied by the average number of recruits (BMSY$_{proxy}$) was 227,265 t. The associated LRP (40%PA1BMSY$_{proxy}$), was 90,096 t of SSB.

2. The average biomass (or index of biomass) over a productive period:

BMSY$_{proxy}$ was defined as the average SSB in a high biomass high production period (Figure 5; 1978-1982), and was estimated at 348,000 t. The USR, 80%BMSY$_{proxy}$, was estimated at 279,000 t. The LRP, 40%PA2BMSY$_{proxy}$, was estimated at 139,000 t.

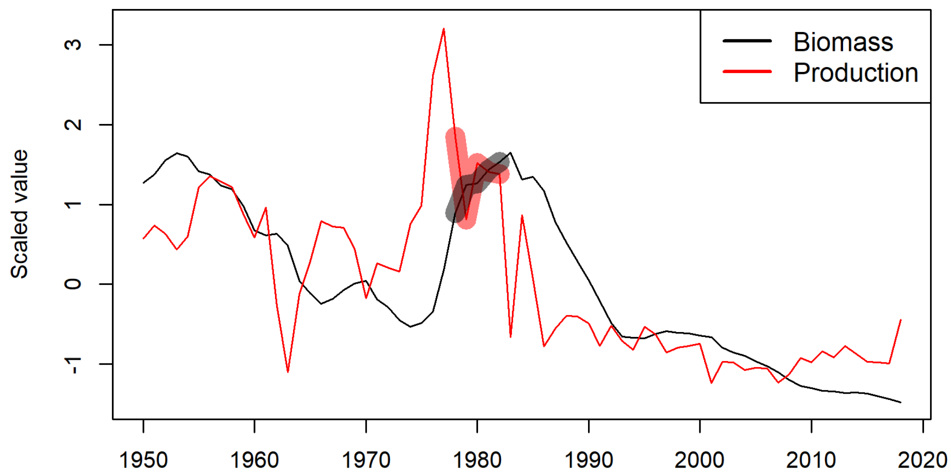

Figure 5: Scaled values of the southern Gulf of St. Lawrence Atlantic Cod stock biomass (black line and shading) and production (red line and shading) between 1950 and 2018. The shaded areas indicate the selected high-biomass high-production years (1978-1982).

3. The biomass corresponding to 50% of the maximum historical biomass:

The SSB corresponding to 50% of the maximum historical was 200,019 t. The corresponding candidate LRP was 40% of this value, 80,008 t of SSB (40%PA3BMSY$_{proxy}$).

2.4.4. LRP from a surplus production model with longer catch time series

The BSM analysis estimated a population intrinsic growth rate of r = 0.24 and a biomass carrying capacity of k = 1,007,005 t of biomass (Table 1). The q parameter for the abundance index was estimated at 0.71, which is the expected value (within the tight priors on bounds). Accordingly, the fit to the biomass data input was good (Appendix 2). The prior and posterior distributions (Appendix 2) show that posterior probability estimates are in general accordance with the prior. Uncertainty in stock size is high for the period pre-1971, which was expected as the abundance Index only starts in 1971. Hence, stock size before 1971 is only estimated from catch and the r and k parameters.

Cod biomass exceeded B_{MSY} between 1917 and the late 1940s (Figure 6), when catch averaged 31,000 t per year and F ws below F_{MSY}. The decline in biomass relative to B_{MSY} started in the 1950s as catch started increasing (averaging 57,000 t per year between 1945 to 1991; Figure 7). Catch exceeded or was close to the MSY and fishing mortality exceeded F_{MSY} in the mid-1950s until the 1990s (Figure 8). Figure 9 shows that most catch years were predicted to shrink future biomass (points above the curve). A few points at low biomass were predicted to increase future biomass (points under the curve) but did not. This is likely reflecting changes in productivity of the stock over time, which could potentially be revealed by allowing r to be estimated in time blocks. The model fit the data reasonably well (showed by the dotted line being close to the colored points).

B_{MSY} was estimated by the model at 503,528 t (LCL-HCL; 386,813-655,459 t. The candidate LRP 0.4B_{MSY} was estimated by the BSM model at 201,000 t of biomass.

Table 1: Model output for estimated parameters r, k and q, and calculated quantities MSY, F_{MSY} and B_{MSY}, with 95% lower and higher confidence limits.

Parameter	Estimate	Lower confidence limit	Higher confidence limit
r	0.24	0.16	0.36
K	1,007,055	773,626	1,310,919
q	0.71	0.70	0.72
MSY	60,949	42,522	87,361
F_{MSY}	0.12	0.08	0.18
B_{MSY}	503,528	386,813	655,459

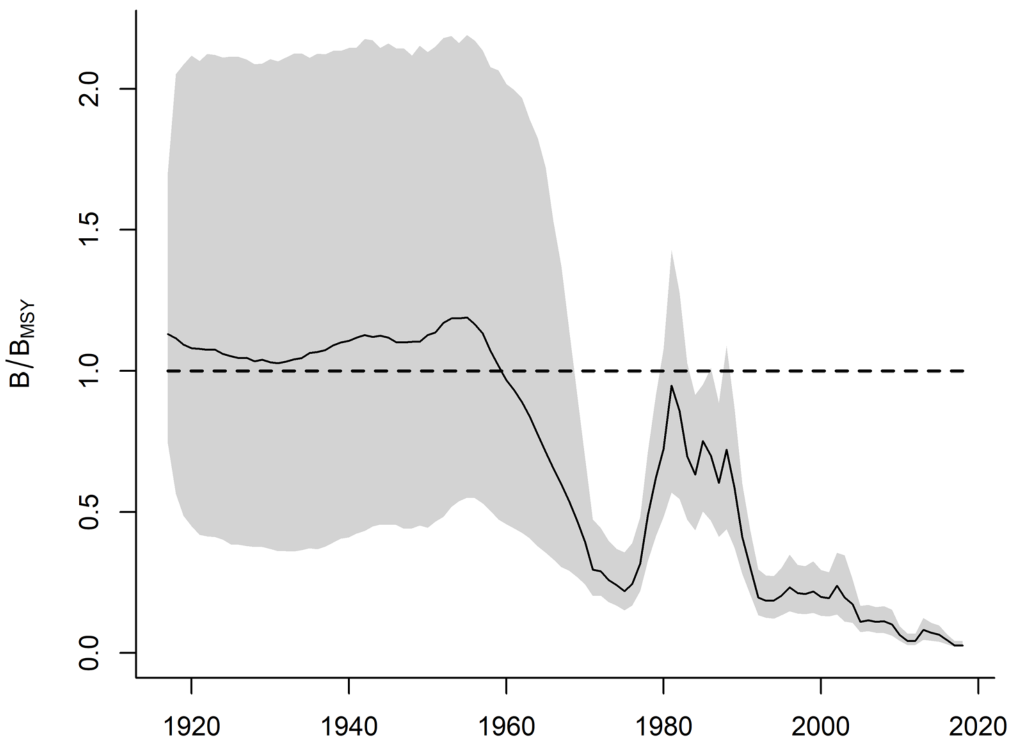

Figure 6: Southern Gulf of St. Lawrence Atlantic Cod biomass relative to biomass at maximum sustainable yield (B/B_{MSY}; y axis), between 1917 and 2018. Black line is the median estimate and grey shading is the 95% confidence interval. Horizontal dashed black line is the B_{MSY} value.

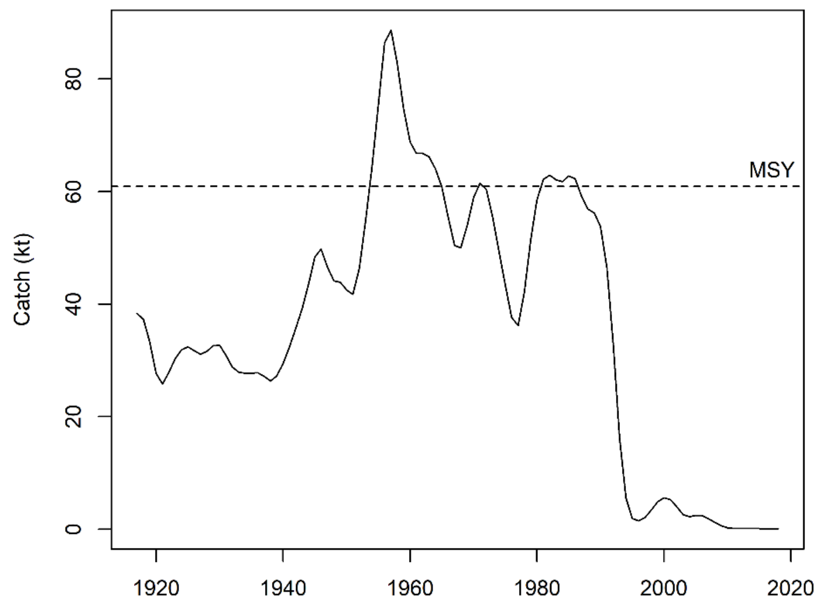

Figure 7: Southern Gulf of St. Lawrence Atlantic Cod catch (kilotonnes; kt) between 1917 and 2018 (black line). Horizontal dashed black line is the maximum sustainable yield (MSY) value.

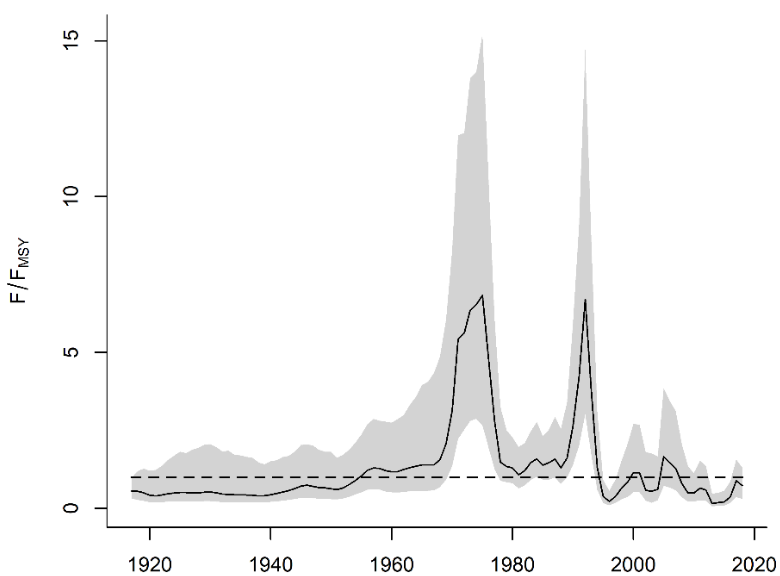

Figure 8: Southern Gulf of St. Lawrence Atlantic Cod fishing mortality relative to fishing mortality at maximum sustainable yield (F/F_{MSY}; y axis), between 1917 and 2018. Black line is the median estimate and grey shading is the 95% confidence interval. Horizontal dashed black line is the F_{MSY} value.

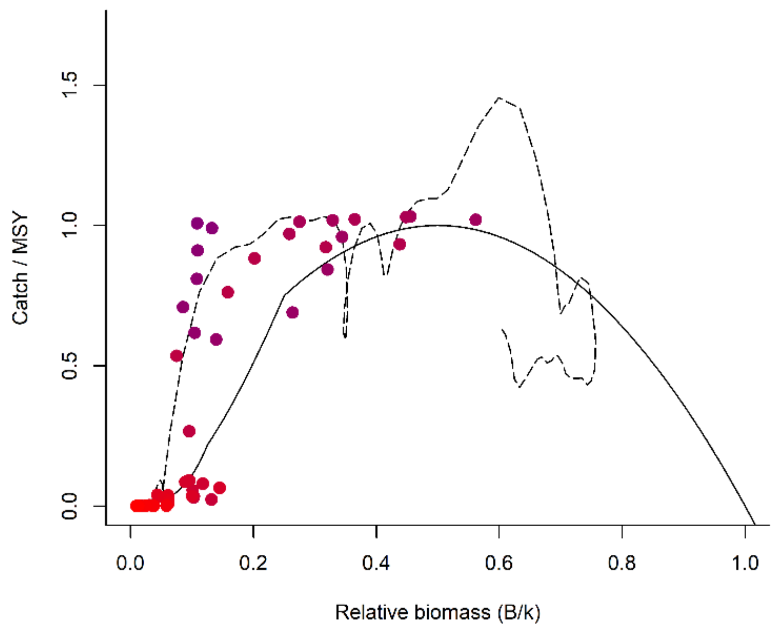

Figure 9: The Schaefer curve from the Bayesian surplus production model with catch expressed relative to MSY on the y axis and biomass relative to k on the x axis. Colored points show the observed catch relative to MSY in function of the observed biomass adjusted for catchability from the index relative to k, the color indicates the year from blue in 1971 to red in 2018. The dotted line is the catch over MSY in function of the estimated biomass over k over the whole catch time series.

2.5. BEST CANDIDATE LRP EVALUATION

2.5.1. Current LRP

The current LRP was determined around the convergence of estimates from various methods (RK_{50}, BH_{50}, $SB_{50/90}$, $B_{recover}$ and NP_{50}) at 80,000 t of SSB in the 2003 stock assessment (Chouinard et al. 2003). Many years of new data and numerous population model changes occurred since this LRP was defined, generating changes in stock scaling and parameter estimates. Furthermore, the values of 50%R_{max} do not converge with the value of $B_{recover}$ in the contemporary assessment model. The absolute value of this LRP is below the Allee threshold, and this candidate LRP is consequently not supported.

$B_{recover}$ is the lowest observed biomass that produced recruitment that led to stock recovery. For this stock, it is estimated to be the 1975 SSB level of 122,000 t (Swain et al. 2019). This candidate LRP is very close to the Allee effect threshold and the risk of reaching this threshold with $B_{recover}$ as an operationalized LRP in harvest control rules would be too high. The former higher stock productivity (lower M and high recruitment rates) allowed the stock to recover in 1975, but the stock reached $B_{recover}$ again in 1993 and has been unable to recover from this state. $B_{recover}$ is thus not supported as a candidate LRP.

2.5.2. LRPs based on the stock-recruit relationship

2.5.2.1. LRPs based on SSB at 50% maximum recruitment

The BH SRR produced a SSB50%R_{max} estimate that is larger than the largest estimated SSB for the stock. In the absence of data to support the BH estimated maximum number of recruits and associated SSB values, the BH50%R_{max} candidate LRP cannot be supported. The RK SRR curve did not produce a maximum and descending limb within the range of observed data. The modeled maximum recruitment occurs near the maximum observed SSB but is still outside of the range of the observed values. Consequently, the RK50%R_{max} candidate LRP is not supported.

The position of the inflexion point of the HS SRR is difficult to justify when analyzing the SRR. Only a few points are used to support it and higher than predicted recruitment values occur at the inflexion point. When visually analyzing the HS SRR with the theoretical horizontal part of the relationship displayed, it is not clear that the inflexion point position is correct, or that a linear relationship would not fit the data better. Hence, the HS50%R_{max} candidate LRP cannot be supported.

The non-parametric fits to the data were acceptable, although the fits were nearly linear. This was expected as the SRR is almost linear over the time series. The influence of the few data points where recruitment was higher than most of the stock-recruit pairs can also be seen in the model fits were the average relationship than to overestimate the recruitment values over the SSB range. The NP SSB50%R_{max} candidate LRP is not supported.

2.5.2.2. LRPs based on a stock-recruit relationship (ICES guidance)

Cod displayed a wide range of SSB over the assessment period, with sensitive dependence of recruitment on SSB over all the assessment period, suggesting impaired recruitment. However, the HS SRR inflexion point was not deemed credible (see 2.4.1). The candidate LRP from the Type 2 stock of the ICES definitions (B_{lim}) is not supported.

F is considered to have been high over most of the time series where an asymptote or maximum would theoretically be found in the SRR (at mid to high SSB). The ICES Type 3 stock definition would then suggest that the LRP would be the highest SSB observed, 400,038 t. However, this method is data poor and not informed by stock dynamics and production drivers. As other candidate methods are available, this candidate LRP is not supported.

2.5.2.3. LRP based on replacement line analysis

This analysis is informative as it identifies a specific year where the decline of a stock is initiated if the stock cannot replace itself for a series of years. As such, it is a good indicator of serious harm to a stock. Moreover, the method uses weight-at-age, natural mortality, recruitment and maturity values, which are all drivers of production and elements to consider when evaluating serious harm. The only caveat with this specific case is the use of a SRR, which were identified as problematic in previous sections of this document. However, the part of the SRR that is informative to this analysis is the low biomass part, which is credible for this stock. The uncertainty in the SRR lies in the high biomass part of the relationship were estimates are missing. The analysis is looking for years where the replacement line does not cross the SRR, and this is evaluated by inspecting the lower part of the SRR. In this case, the BH, RK or HS lower part of the SRR where all very similar and a linear regression would likely produce similar results, as the SRR is mostly linear over the range of SSB and recruitment estimates. With these considerations, the candidate LRP from the replacement line analysis (1990SSB) is given partial support.

2.5.3. LRPs based on B_0

$0.2B_0$ is a common rule of thumb for a threshold for recruitment overfishing (Myers et al. 1994). 0.2 to $0.3B_0$ has been suggested as LRPs, with higher thresholds needed for lower productivity stocks (Beddington and Cooke 1983, as cited in Mace (1994); Sainsbury 2008). The level of productivity of the sGSL Cod stock estimated from the surplus production model (r = 0.24) would correspond to a medium productivity stock (medium productivity = r between 0.14 and 0.35; MF 2011). Hence, the candidate LRP based on B_0 should be initial $0.25B_0$ for this stock.

As the stock-recruit relationships did not estimate a credible equilibrium unfished recruitment, the B_0 calculations are based on a proxy for it. The assumption is deemed reasonable as the K parameter from the SPM and the initial B_0 estimate are close to one another, considering the scale and uncertainty around stock size. The initial $0.25B_0$ candidate LRP is given full support.

2.5.4. LRP based on MSY_{proxy} from the DFO Precautionary Approach guidelines

1. The biomass corresponding to the biomass per recruit at F0.1 multiplied by the average number of recruits:

The derived LRP using this method is lower than the Allee effect threshold. F0.1 methods tend to allow for higher F and when M is higher than 0.2 (the default at which these per recruit methods were developed). When evidence that M increased over time for a stock is strong, a method suggesting higher F thresholds as M increases should not be used to derive biomass or fishing reference points (Legault and Palmer 2015). The $40\%PA1BMSY_{proxy}$ candidate LRP is not supported.

2. The average biomass (or index of biomass) over a productive period:

A period of high biomass and high productivity was identified. However, this period was immediately followed by a decline in SSB driven by high fishing mortality. As such, biomass in this period cannot be used as a proxy for B_{MSY}. Hence, the associate candidate LRP $40\%PA2BMSY_{proxy}$ is not supported. Another high biomass high productivity period occurred in the years following 1950, but productivity was not as high and SSB also rapidly declined immediately after.

3. The biomass corresponding to 50% of the maximum historical biomass:

This candidate LRP ($40\%PA3BMSY_{proxy}$) is under the Alle threshold, is quite data-poor, and its robustness cannot be evaluated. This candidate LRP is not supported.

2.5.5. LRP based on MSY from a surplus production model

In the case of sGSL Cod, the BSM method offers three main advantages; (1) it uses a catch time series going back to 1917 which shows stability in catches (which has not been observed in the SCA model time series), (2) surplus production models pool the overall effects of recruitment, growth, maturity and mortality (all aspects of production) into a single production function, which is informative when trying to establish a single biomass reference point where serious harm has occurred with a stock with many sources of time varying productivity, and (3) it offers a view of what the stock size could have been before the assessment period, which has been identified as a source of uncertainty for this stock.

The advantage of using this time series is that landings before 1950 were lower, more stable, and consequently more likely to have been sustainable. As estimated by the model, the biomass was stable above the B_{MSY} level and fishing mortality was stable below F_{MSY} until 1950. Although the uncertainty around the absolute values of SSB prior to 1950 is high, the stability of the catches and estimated stock size can be used to give confidence in the estimate of B_{MSY}.

Surplus production models should be considered the simplest assessment method to consider the net effects of recruitment, growth and mortality (Hilborn and Walters 1992). As shown by the model fit to the data (Appendix 2), the model fits through two clouds of points, potentially reflecting different productivity periods. Periods where productivity levels changed have been observed in other studies on sGSL Cod (Perälä et al. 2017; Swain et al. 2019).

The BSM method was used for an adjacent Cod stock using a catch time series going back to the 1500s: Northern Cod from NAFO Division 2J3KL (Schjins et al. 2021). In that stock, r was estimated at 0.25, while r for the sGSL stock was estimated at 0.24. Productivity over a long period would then be similar among adjacent stocks, which increases confidence in the results obtained here. Moreover, the estimated biomass dynamics were similar, with both stocks showing higher biomass in the early 1900s, followed by a decline, a small increase around 1980 and a collapse in the 1990s. The LRP derived from this method would be consistent with the idea that the 1950 to 2018 period represents a view of this stock in a depleted state, which is coherent with the observed declining trend in biomass, lack of recovery, and similar findings in adjacent Cod stocks. Interestingly, the 2J3KL Cod stock biomass in the 1920s was only slightly lower than the historical stable biomass going back the 1500s. If the sGSL Cod stock dynamics and exploitation were similar to this adjacent stock, it would suggest the stock size estimated here for 1917 was close to the historical stock size and that the carrying capacity would be close to the “real” (not biased by the shifting baseline syndrome) carrying capacity of the system for Cod. According to this model, the sGSL Cod biomass in 2018 (13,510 t) was 2.4% of the biomass in 1917 (569,066 t), which is consistent with the scale of depletion found for adjacent Cod stocks (2J3KL below 1%; Schijns et al 2021, Newfoundland 5%; Rose 2004, NAFO 4VsW 4%; Rosenberg et al. 2005). The potential unfished sGSL Cod biomass according to this model would be 1,000,000 t of biomass (the value of the K parameter).

This model is also useful to identify the most likely source of serious harm to the stock, and the cause of its decline. The stock was above B_{MSY} between 1917 and the 1950s, but as the annual catches increased in the 1950s, fishing mortality also increased and was above F_{MSY} by 1955. The stock biomass then started to decrease and was below BMSY by 1960. The sources of serious harm identified in section 2.2 are likely consequences of the overfishing that was initiated in the 1950s and occurred onwards.

If the stock was to recover above B_{MSY}, the results suggest that the stock could be fished up to a fishing mortality of 0.12 and the stock would then remain at a SSB around B_{MSY}. However, the caveats regarding the lack of equilibrium conditions over time and derived reference points from the SCA also apply to MSY reference points derived from a surplus production model. Again, if productivity conditions are poorer than the long-term average, fishing at F_{MSY} will not keep the stock at B_{MSY} and biomass will decline. Hence, it would be more precautionary to treat MSY as an upper limit rather than a target.

2.5.6. Best LRP

One LRP candidate (1990SSB) received only partial support, but its value is close to the fully supported SSB based LRP, initial $0.25B_0$ (Table 2).Two candidate LRPs received full support, initial $0.25B_0$ from the SCA model and $0.4B_{MSY}$ from BSM model. The absolute values of these LRPs cannot be directly compared as the $0.25B_0$ is in units of SSB, and $0.4B_{MSY}$ is in units of biomass at all ages. However, when comparing both methods, the stock status through time is similar (see below). Hence, it can be argued that the LRPs from these methods “converged”, which brings weight to their quality as best candidates.

Table 2: Candidate limit reference points (LRP), their estimated value in tonnes of SSB and the level of support for each of the candidate LRP (0 = none, 1 = partial, 2 – full).

Candidate LRP	Estimated value (SSB, tonnes)	Support (0 = none, 1 = partial, 2 = full)
Current LRP	80,000	0
$B_{recover}$	122,000	0
ICES Type 2 stock (B_{lim})	335,375	0
ICES Type 3 stock (max SSB)	400,038	0
BH SSB50%Rmax	518,000	0
RK SSB50%Rmax	195,000	1
HS SSB50%Rmax	168,000	0
NP SSB50%Rmax	174,000	0
1990SSB	190,000	1
Initial $0.2B_0$	168,000	0
Initial $0.25B_0$	**210,000**	**2**
Initial $0.3B_0$	252,000	0
$40\%PA1BMSY_{proxy}$	90,096	0
$40\%PA2BMSY_{proxy}$	139,000	0
$40\%PA3BMSY_{proxy}$	80,000	0
$0.4B_{MSY}$	201,000	2

To show how the two fully supported LRPs compare within their respective frameworks, the $0.25B_0$ LRP was plotted over the SSB estimates from the SCA, and the $0.4B_{MSY}$ was plotted over the biomass estimates from the BSM. Both representations show similar stock status estimates through time (Figure 10). Moreover, the biomass at all ages estimated from the SCA was plotted along the biomass estimated from the BSM and the estimates are in general accordance over the time series (Figure 11). Hence, the two frameworks can be considered as equivalent with respect to their estimated stock size, LRPs, and estimated stock status.

For a symmetrical Schaefer surplus production model, DFO's PA Policy provisional default LRP of 0.4 B_{MSY} is equivalent to 0.2 B_0 (DFO 2023a). Here, the units are different (SSB vs biomass at all ages) between the B_{MSY} and the B_0 estimates, who are generated from different models. Consequently, the ratio is not expected to follow this standard. Here, the ratio of $0.2B_0$ to $0.4B_{MSY}$ is 0.8.

Compared to $0.4B_{MSY}$ from the surplus production model, initial $0.25B_0$ was deemed more practical as it is easier to estimate directly from the assessment model, is highly unlikely to change as new years of data are added to the assessment and is easier to understand. The LRP meets the best practice principles identified in DFO 2023a:

Principle 1: Selected based on the best available information for the stock. The selection of LRP was performed using the stock assessment data and outputs, and stock information from a literature review of the sources of serious harm.

Principle 2: Consistent with objective to prevent serious harm. The LRP is conceptually linked to the concept of serious harm as it is linked with depletion, is a proxy for recruitment overfishing, and is a proxy for B_{MSY}, which relates to the loss of surplus production.

Principle 3: Should be feasible and relevant. The LRP is a SSB directly obtained from the assessment model and can be estimated at every assessment update. Hence, future assessments SSB estimates can be compared to the LRP. The LRP can be transferred to harvest control rules.

Principle 4: Should take account reliability, plausibility and uncertainty. The LRP is reliable as addition of data is not expected to generate changes in scale or parameters. The LRP is plausible, a weight-of-evidence approach was used to select the most plausible LRP and the two best candidate LRPs converged around similar values and adjacent Cod stocks dynamics and productivity.

The best candidate LRP for sGSL Cod is initial $0.25B_0$. Its value using the statistical catch-at-age model up to 2018 was 210,000 t of SSB. Stock status should be communicated as a ratio of indicator to LRP instead of absolute estimates, especially where estimated stock status is sensitive to changes in scale in successive assessments. Hence, the LRP should be communicated as initial $0.25B_0$.

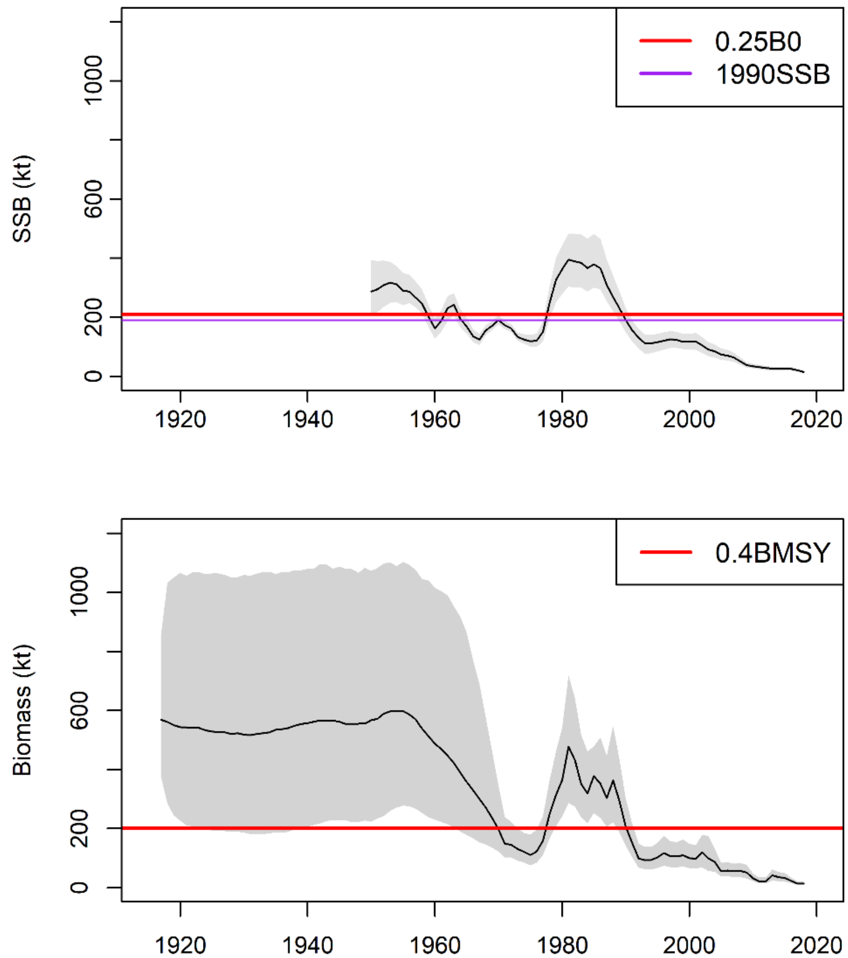

Figure 10: Upper panel: SSB based candidate limit reference points for sGSL Atlantic Cod where at least partial support was received; 0.25B_0 (full support, red solid line) and 1990SSB (partial support, purple line). Lower panel: Biomass based candidate limit reference point for sGSL Atlantic Cod from the BSM model (0.4B_{MSY}). Black line is the median SSB estimate (kt) and grey shading is the 95% confidence interval.

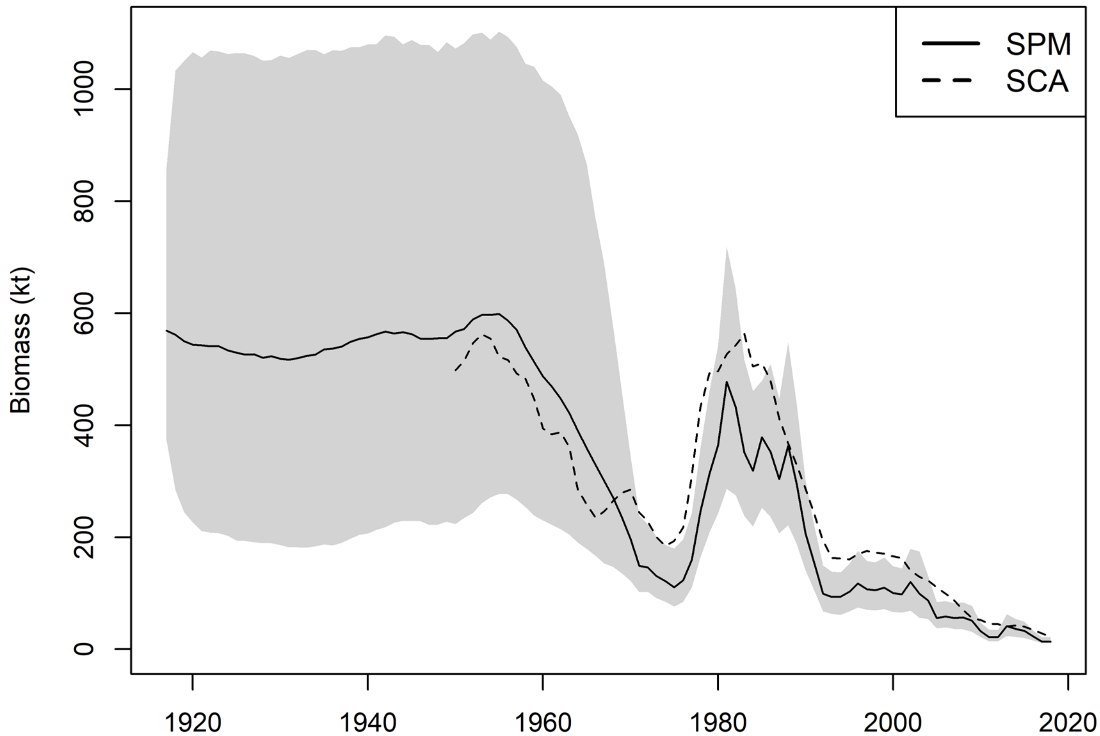

Figure 11: sGSL Atlantic Cod biomass (kt) estimated from the BSM model (solid black line) and from the statistical catch at age model (dashed black line). Black lines are the median biomass estimates and grey shading is the 95% confidence interval from the BSM, confidence intervals from the statistical catch at age model are not shown for clarity.

2.5.7. Cod LRPs from other stocks

An LRP was recently adopted for the Northern Gulf of St. Lawrence Cod stock (3Pn4RS;DFO 2023b), with the explorations of methods finding similar conclusions to that found here. The lack of stock-recruit relationship and lack of generally stationary demographic parameters precluded the derivation LRP candidates based on the most common methods. Hence, historical states where exploitation levels were stable and stock size was in response stable at a sustainable level were used as proxies for MSY derived points.

In NAFO Division 2J3KL, the low SSB levels since the 1980s have only produced poor recruitment, indicative of serious harm occurring on the stock, a conservation LRP (B_{lim}) established for Northern Cod was then determined to be the average SSB of the 1980s (DFO 2019b).

With similar concern over using MSY points with a stock experiencing variations in natural mortality, Wang and Irvine (2022) used the SSB corresponding to the intersection of the 50th percentile of the recruitment observations and the replacement line for which 10% of the stock-recruit points are above the line as an LRP for NAFO Division 4X5Y Cod.

2.5.8. Upper and target stock reference points

The initial $0.25B_0$ LRP (210,000 t) is above the current USR (200,000 t), thus generating a need for a redefinition of the USR. Using the default suggested by the PA, a USR and TRP can be calculated from B_0 when considered a proxy for B_{MSY}. Assuming $0.2B_0$ is a proxy for 0.4Bmsy, the USR ($0.8B_{MSY}$proxy) was estimated at 336,000 t of SSB and the TRP (B_{MSY} proxy) was estimated at 420,000 t of SSB (Figure 12). While determining the LRP is the role of the DFO Science Sector, the USR and TRP definitions are DFO Fisheries and Harbour Management's role. Here, the calculated default PA framework USR and TRP can be proposed as interim candidates for these reference points.

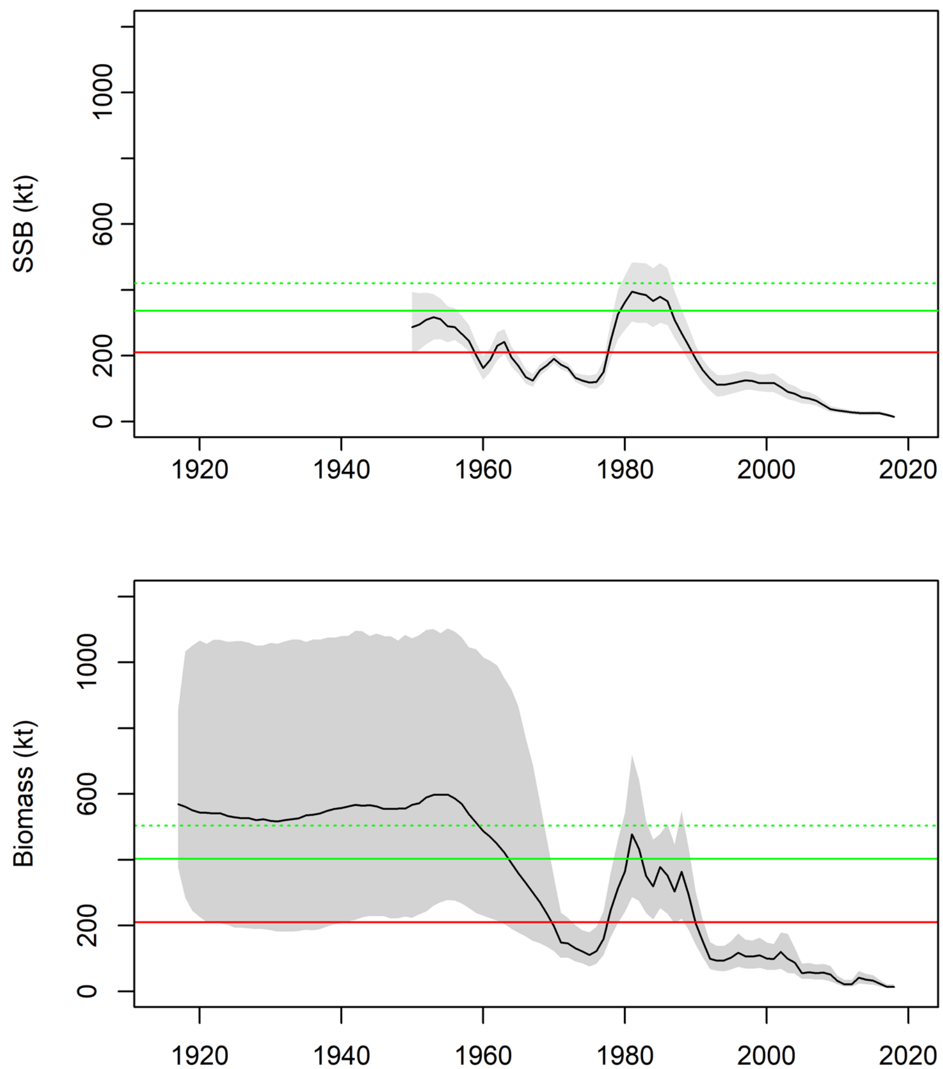

Figure 12: Upper panel: SSB based candidate limit reference points for sGSL Atlantic Cod (Limit reference point $0.25B_0$, red line; Upper stock reference $0.8B_{MSY}$proxy, green full line; Target reference point B_{MSY}proxy, green dashed line). Lower panel: Biomass based candidate limit reference point for sGSL Atlantic Cod from the BSM model (Limit reference point $0.4B_{MSY}$, red line; Upper stock reference $0.4B_{MSY}$, green full line; Target reference point B_{MSY}, green dashed line). Black line is the median SSB (upper panel) or biomass (lower panel) estimate (kt) and grey shading is the 95% confidence interval.

2.5.9. Stock status and trends

Using the newly defined LRP and interim USR from this study, the 2018 stock status remains in the Critical Zone (no change from previous assessment). The most recent year when the stock crossed the LRP to the Critical Zone is now estimated to be 1990, whereas it was 2005 with the former LRP.

With the $0.25B_0$ LRP, the stock was in the Cautious Zone at the beginning of the time series (1950) and crossed the LRP into the Critical Zone in 1959. The stock fluctuated in the Critical Zone (except for 1962 and 1963 where it was low in the Cautious Zone) until 1978 when the stock quickly recovered. The stock reached the Healthy Zone in 1980, where it stayed until 1987 when the stock rapidly declined. The stock crossed the LRP in the Critical Zone in 1990, where it remained until 2018.

The sources of harm to the stock are many, as identified in section 2.2. However, the probable cause of the sGSL Cod stock decline, along with that of other exploited groundfishes in the Northwest Atlantic, has been identified as overfishing (Myers et al. 1994; Sinclair and Murawski 1997). Fishing mortality for ages 5+ was high in most of the mid-1950s to the mid-1970s, and again in the mid-1980s to the early 1990s (Swain et al. 2019), likely the main factor ultimately leading to the Cod collapse in the early 1990s. Predation-driven high natural mortality is now the main factor preventing the Cod recovery (Swain et al. 2019; Neuenhoff et al. 2019).

3. REBUILDING TARGET AND TIMELINE

3.1. REBUILDING TARGET

For a prescribed major fish stock subject to the FSP, the legal obligation of a rebuilding plan under section 6.2 only applies while the stock is at or below its LRP. However, to increase the likelihood that a stock will not decline back to or below its LRP and to be consistent with the 2009 PA Policy intent to grow depleted stocks to healthier levels, a rebuilding plan will remain in effect until the stock reaches its rebuilding target. Once the stock reaches its rebuilding target, the rebuilding plan will come to an end and the stock will be subject to the Integrated Fisheries Management Plan (IFMP) or other management plan.

DFO guidelines on rebuilding plans state that the rebuilding target must be set at a level above the LRP so that there is a very low to low likelihood of the stock being below its LRP (< 5-25% probability). Consequently, DFO Fisheries and Harbour Management defined the rebuilding target for this stock as having been reached when there is at least a 75% probability that the stock is at or above the LRP. The sGSL Cod stock is assessed using a SCA model, therefore determining when the rebuilding target is achieved and monitoring the performance of the rebuilding plan should be accomplished using the accepted model and the estimated uncertainty from the model. As such, the value of the target is model-dependent and will change with every assessment as years of data are added and/or as model changes are implemented. Hence the target should be defined as “the SSB where there is a very low to low likelihood of the stock being below its LRP (< 5-25% probability)”, and not as a fixed number.

The science guidelines to support development of rebuilding plans for Canadian fish stocks states that the rebuilding target should be set far enough above the LRP so that there is a low probability of falling below the LRP in the short to medium term (DFO 2021b). The current rebuilding target proposed for this stock is being at or above the LRP with 75% certainty, and particularly as the uncertainty in SSB estimates for this stock are relatively small this means that the rebuilding target is very near the LRP. As such, this target theoretically offers a higher probability of the stock falling below the LRP than a target set closer to the USR or the TRP for example. If this rebuilding target is retained, it may be important to consider including additional considerations to the target such as; the stock must be at or above this level for 4 consecutive years, and population projections must show the stock is likely to continue its positive trajectory under harvest for 4 years after the rebuilt state has been achieved. Four years was selected since a rebuilding timeline could not be calculated or used to inform the choice of the number of years of growth that would minimize the probability of the stock falling below the LRP in the short to medium term. The number of years has consequently been set to the multi-year assessment cycle and projections timeline for advice for this stock. This is also the frequency of review of the rebuilding plan (see below).

3.2. REBUILDING TIMELINE

A rebuilding plan also requires that the timeline to rebuild be identified in order to track rebuilding progress with respect to the objectives and management measures. The international standard and the approach recommended by DFO (2021b) is to estimate the time to reach the rebuilding target in the absence of all fishing (T_{min}). As seen in the last stock assessments, the stock was unlikely to rebuild to the previous LRP (Swain et al. 2019), which was lower than the new LRP. Hence, the stock is unlikely to rebuild to the rebuilding target under prevailing conditions, even in the absence of fishing mortality (Swain et al. 2019). If T_{min} cannot be calculated, an estimate of an alternative such as generation time provided by DFO Science can be used by Fisheries and Harbour Management to define a rebuilding timeline. The generation time for sGSL Cod is 12 years (Swain et al. 2012). However, since the stock is unlikely to rebuild under prevailing conditions, and a rebuilding timeline cannot be calculated, the rebuilding timeline is instead set to correspond with the periodic review of the rebuilding plan. During each review, the factors limiting the stock's potential for growth will be re-assessed to determine if they are still influencing the stock and whether a rebuilding timeline can be calculated.

4. LIKELIHOOD OF ACHIEVING THE REBUILDING TARGET UNDER VARIOUS ENVIRONMENTAL AND/OR MANAGEMENT SCENARIOS

4.1. ENVIRONMENTAL SCENARIOS

In the absence of fishing, natural mortality and recruitment are the two main drivers of the sGSL Cod population. The objective of the following analysis was to identify the contribution of each process to the likelihood of stock rebuilding, and what levels of each process are necessary for rebuilding. Objectives of number of recruits and natural mortality levels to reach can then be set against potential management measures aiming to improve these processes. To estimate the minimum time for the stock to reach the rebuilding target (i.e. at or above the LRP with a 75% probability) in the absence of fishing (T_{min}), scenarios of future natural mortality and recruitment rates were modeled using the projection function of the assessment model. The population was projected forward during the Markov chain Monte Carlo (MCMC) sampling by the population model, considering uncertainty in parameter estimates. The probability of SSB being above the LRP each year was calculated by finding the proportion of MCMC samples that were above the LRP in that year.

4.1.1. Natural mortality scenarios

The future natural mortality scenarios were developed by examining historical natural mortality levels experienced by the stock. For the age group 2-4, the natural mortality rate varied without trend around 0.40 over the 1950 to 2018 period. Hence, M for this group was projected as the average of the last 5 years of the assessment, at a value of 0.42.

For the two older Cod age groups, natural mortality gradually increased between 1972 and 2018 from a value of 0.19 to 0.84 in the 5-8 age group, and from a value of 0.35 to 0.86 for the 9-12+ age group. The increase in M was mostly attributed to the increase in Grey Seal abundance in the sGSL (Benoît et al. 2011; Swain and Benoît 2015; Swain et al. 2015). Neuenhoff et al. (2019) found that using Cod data up to 2010, a 65% reduction in Grey Seal abundance was necessary to stop the decline of Cod SSB in the sGSL. However, since 2010, Cod SSB has declined even further and M for the age group 5-8 has increased (Swain et al. 2019). Here, the estimated reduction in natural mortality that is necessary to stop, reverse the decline or rebuild the stock of sGSL Cod is updated using the stock assessment population model.

Three future M scenarios were modeled to examine the role of natural mortality on the rebuilding potential of this stock (Figure 13):

1. Recent M: In this scenario, current estimates are assumed to be representative of futures estimates, which is the method used to project the population forward in the stock assessment. Projected M for age groups 5-8 and 9-12+ were set as the average M values in the last 5 years of the assessment (2014 to 2018). Projected M values were 0.42 for the age group 2-4, 0.77 for the age group 5-8 and 0.85 for the age group 9-12+.
2. Natural M decline: In this scenario, M was gradually decreased over time at the same rate it was estimated to have increased between the years 1980 and 2018. Projected M for age groups 5-8 and 9-12+ were set as a declining trend, using the 2018 value as the initial value. Projected M in the next year t+1 was calculated as 0.9867875 of M in the previous year t. Projected M values were 0.42 for the age group 2-4, decreased from 0.77 to 0.27 for the age group 5-8 and decreased from 0.85 to 0.50 for the age group 9-12+.
3. Rapid M decline: This scenario was developed to investigate the effect of many years of lower M. However, M was allowed to decrease gradually to the low level, as a sudden massive reduction in M from one year to the next is unlikely to occur. Projected M for age groups 5-8 and 9-12+ were set as a segmented trend: an initial 10% yearly decline in M for the first ten years of projections, followed by a stable M value. Projected M values were 0.42 for the age group 2-4, decreased from 0.77 to 0.27 in 10 years, then remained at that level until 2059 for the age group 5-8 and decreased from 0.85 to 0.29 in 10 years, then remained at that level until 2059 for the age group 9-12+.

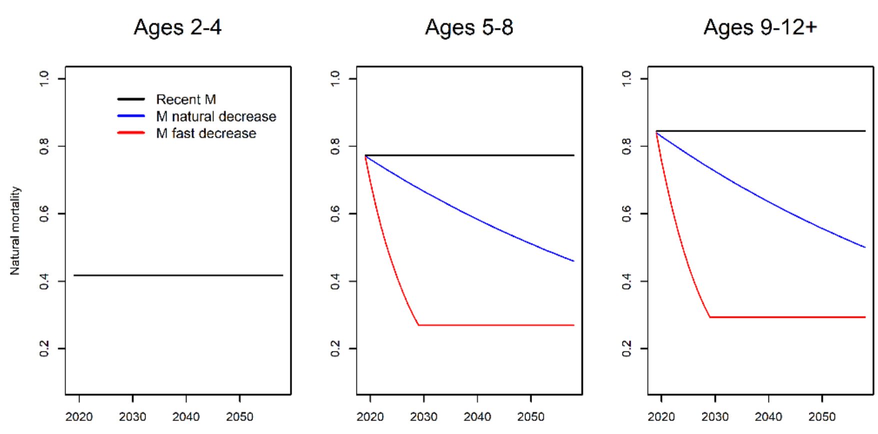

Figure 13: Projected natural mortality rates for years 2019 to 2059, for age groups 2-4 (left panel), 5-8 (middle panel) and 9-12+ (right panel), for three natural mortality scenarios: average natural mortality from the last 5 assessment years ("Recent M", black lines), a natural mortality decrease rate similar to the historical increase rate ("M natural decrease", blue lines) and a fast natural mortality decrease of 10% per year for ten years followed by a stable level ("M fast decrease", red line).

4.1.2. Recruitment scenarios

Recruitment rates for sGSL Cod did not vary greatly over the assessment period. Recruitment rates were relatively stable with a mean of 1,205 recruits per t of SSB (SD = 795 recruits). Exceptionally high recruitment rates occurred between the years 1973 and 1977 where one t of SSB produced on average 3,553 recruits (SD = 955 recruits). For the recent period, recruitment rates have been variable between low and intermediate levels, but never reaching the high levels estimated in the mid-1970s. In the last 20 years, 1,142 recruits per t of SSB (SD = 480 recruits) were produced on average. Hence, three scenarios of future recruitment rates were modeled to examine the impact of future states of recruitment on the potential to rebuild the stock:

1. All recruitment: recruitment rates were randomly selected over the whole assessment time series, where every year has an equal probability of being selected including the extreme high recruitment rates in 1973 to 1977. For this scenario, 1,205 recruits per t of SSB were produced on average (SD = 795 recruits).
2. Recent recruitment: recruitment rates were randomly selected from the last 20 years of the assessment period. This scenario did not include the extremely high recruitment rates from the years 1973 to 1977 to be selected. This scenario therefore was most similar to prevailing recruitment conditions. For this scenario, 1,142 recruits per t of SSB were produced on average (SD = 480 recruits).
3. High recruitment: recruitment rates were randomly selected from the years 1964 to 1979, allowing for an overall higher frequency of higher recruitment rates years to be selected for the projections. For this period, 1,873 recruits per t of SSB were produced on average (SD = 1,292 recruits). This scenario allowed the population to be projected under conditions where high recruitment rates would often occur. It is very unlikely that this scenario would occur, nevertheless the scenario is informative as to what processes drive the population and what conditions would be required to enable rebuilding.

4.1.3. Population projections

All projections were performed for 40 years, a time span corresponding to slightly over three generations for this population (approximately 36 years; Swain et al. 2012). Projections used maturity at age from the terminal year and weight at age vectors randomly selected over the last 20 years, which is consistent with the sGSL Cod stock assessment (Swain et al. 2019). The projections shown here are not forecasts of likely future stock states. The intent is to show the levels of future stock process needed to allow for rebuilding, based on what was observed in the past.

In the absence of fishing mortality and under current recruitment and natural mortality conditions, the stock is not expected to recover, and is expected to continue to decline. Irrespective of the combination of natural mortality and recruitment scenario, the stock was unable to exceed the LRP with a probability of 75%. The highest probability of being above the LRP in 40 years was at 3% chance of being above the LRP with the High recruitment-Rapid M decrease scenario (Figure 14). The stock decline continued until 2058 in all scenarios except the “High R” with the two versions of the decreasing M scenarios. However, these scenarios only allowed for the SSB decline to stop and stabilize at a low level. Even without fishing mortality, the stock is unlikely to rebuild to the rebuilding target under prevailing conditions or even under scenarios of the highest recruitment or lowest natural mortality. The rebuilding timeline can therefore not be calculated. Considering the history Cod exploitation, this result was expected. In a meta-analysis of overfished stocks, Neubauer et al. 2013 found that prolonged intense overexploitation, especially for collapsed stocks, not only delays rebuilding but also substantially increases the uncertainty in recovery times, despite predictable influences of fishing and life-history.

Neuenhoff et al. (2019) used a Cod-Seal model with data up to 2010 to infer the effect of a reduction of the number of Grey seal on the Cod stock trajectory. The projections showed that a reduction of 65% of the abundance of Grey Seal would be enough to stop the decline in Cod SSB. This 65% decrease in Grey Seal would translate to at most a 65% decline in Cod M. Unfortunately, from 2010 to 2018 the Cod stock continued to decline. The results shown here suggest that a similar level of decline in M would no longer be sufficient to stop the Cod decline, unless the decline in M occurred simultaneously to frequent occurrences of unusually high recruitment rates. While highly unlikely, the combination of these processes are required to stop the decline of sGSL Cod.

Recent modeling using the most up-to-date Cod and Seal data suggests that that the level of Seal removals required to sufficiently reduce predation mortality on Cod to allow the stock to survive were significantly higher than current removal levels and would likely collapse the Grey Seal herd in the Gulf of St. Lawrence (Rossi et al. 2024). Grey Seal were once very abundant in the sGSL, but hunting severely reduced their abundance in the mid to late 1800s (see Lavigueur and Hammill 1993). Simultaneously, Atlantic Cod abundance also appears to have been very high (see section 2.2.1). It is then likely that healthy populations of both Grey Seal and Atlantic Cod coexisted prior to the mid-1800s, but the history of exploitation of both species has created a predator-prey relationship that is currently out of balance. The biomass and functional response from the Cod-Seal modelling in Neuenhoff et al. (2019), suggests that even at their current high level of abundance, predation by Grey Seal would be sustainable at historical levels of Cod biomass, in contrast with the current depleted levels of biomass. The most recent Grey seal assessment suggest that the sGSL population may have reached a plateau (Hammill et al. 2023).

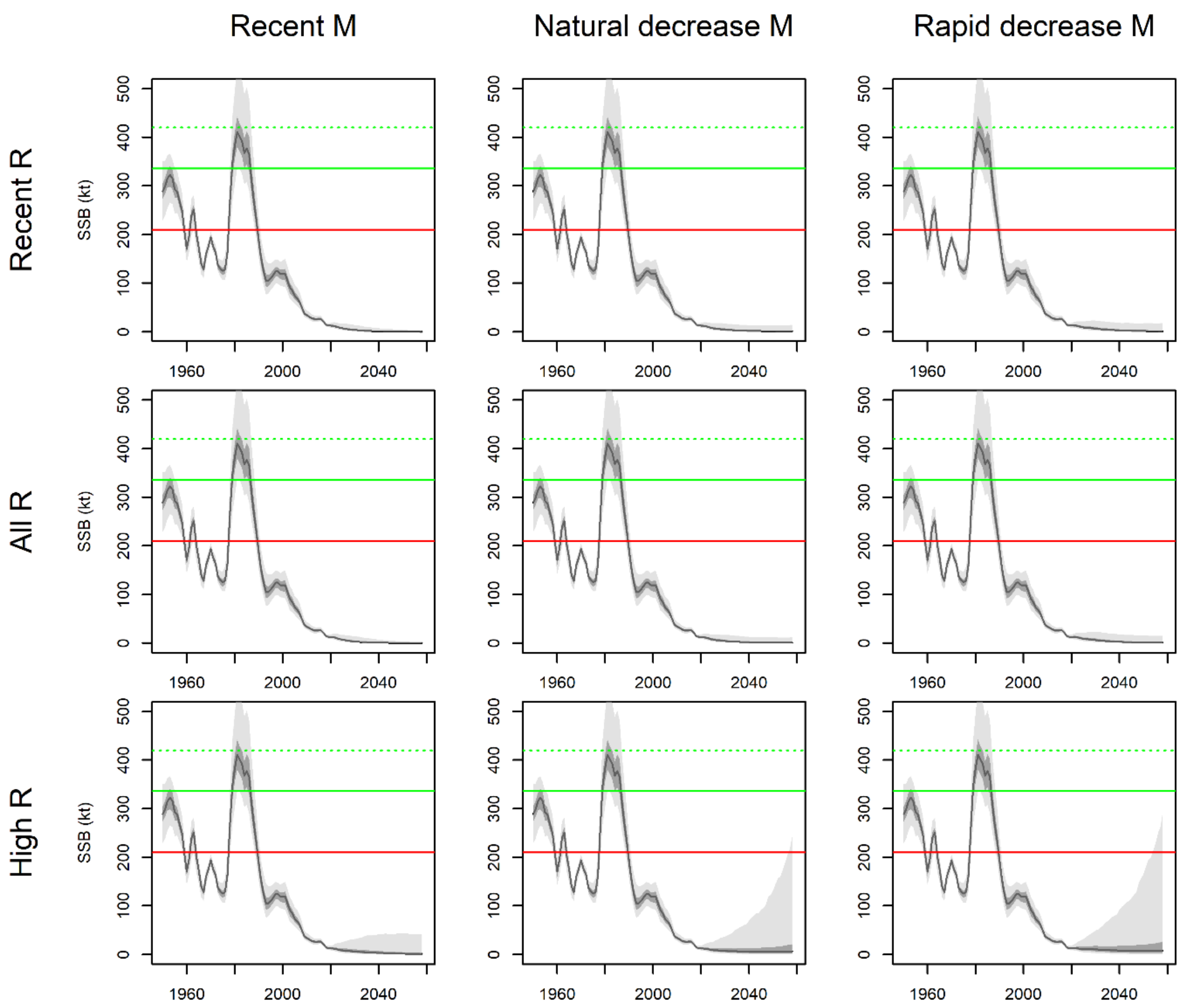

Figure 14: Projected spawning stock biomass (SSB, kt) for years 2010 to 2059, for three future recruitment scenarios: recruitment rates from the last 20 assessment years ("Recent R", top row), recruitment rates from all assessment years ("All R", middle row) and recruitment rates from a period of 15 years where the highest recruitment rates were observed ("High R", bottom row), for three natural mortality scenarios: average natural mortality from the last 5 assessment years ("Recent M", left column), a natural mortality decrease rate similar to the historical increase rate ("M natural decrease", middle column) and a fast natural mortality decrease of 10% per year for ten years followed by a stable level ("M fast decrease", right column). The red horizontal line is the limit reference point, the green horizontal line is the upper stock reference, the green horizontal dashed line is the target reference point, the black line is the median estimate from the MCMC sampling, and dark and light grey shading indicate 50% and 90% confidence intervals, respectively.

4.2. MANAGEMENT SCENARIOS

Since sGSL Cod is unlikely to rebuild under prevailing conditions, the management measures are aimed at preserving the stock such that should the prevailing conditions change, the stock retains the potential to rebuild.

4.2.1. Minimizing bycatch

As outlined in the PA framework (DFO 2009), the primary objective of a rebuilding plan is to promote stock growth above the LRP by ensuring removals from all fishing sources are kept to the lowest possible level until the stock has cleared the Critical Zone. Rebuilding plans must also include additional restrictions on catches. The primary management measure proposed in the sGSL Cod rebuilding is to keep removals to the lowest level by continuing to implement and/or develop new management measures in all fisheries that intercept sGSL Cod. An analysis of spatial overlap and bycatch potential for fisheries that intercept sGSL Cod as well as the potential impact of the emerging commercial Redfish fishery is presented in Sutton et al. (2024) and Sutton et al.*In prep*.[2]).

Reducing bycatch of sGSL Cod is unlikely to rebuild the stock, since population projections with F = 0 showed that the stock would remain in the Critical Zone in the long term under prevailing natural mortality levels. To evaluate the expected impact of bycatch on the long-term population status, the sGSL Cod population was projected forward for 10 years given bycatch levels of 0, 100, 200, 300 and 500 t, as routinely performed in the stock assessment. Projected SSB declined at all five catch levels, including no catch (Figure 15). Based on median SSB estimates, bycatch levels of 100 and 200 t did not produce different SSB trajectories compared to the 0 t catch projection. At 300 t of bycatch, the population SSB in 10 years would be reduced by 10%. At 500 t of bycatch, the population SSB in 10 years would be reduced by 16%. The median estimates of all bycatch scenarios are all within the 50% confidence intervals of each other (not shown on the figure, for clarity).

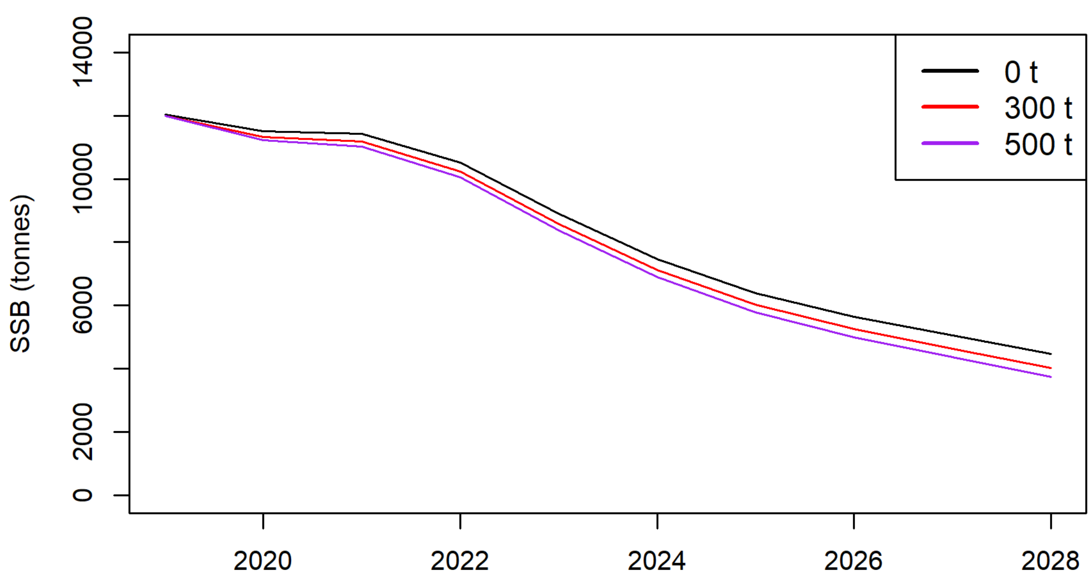

Figure 15: Projected Atlantic Cod SSB for years 2019 to 2028, with 0 (black line), 300 (red line) and 500 (purple line) annual tonnes of bycatch. Solid lines are median MCMC estimates.

[2] Sutton, J.T., McDermid, J.L., Landry, L., Turcotte, F. Mitigating Bycatch of Southern Gulf of St. Lawrence Atlantic Cod in NAFO Division 4T - 4Vn (November-April). DFO Can. Sci. Advis. Sec. Res. Doc. In preparation.

4.2.2. Legal size

Fisheries and Harbour Management requested that Science test a scenario where the small fish protocol catch size limit would be increased above 43 cm to determine if increasing this size limit for sGSL Cod could have an impact on current population trends.

The small fish protocol stipulates that if bycatch of undersized fish reaches 15%, the area is closed. However, all Cod caught in the commercial fishery has to be landed by regulations. Moreover, as the fishing gear is lethal, there would be no gain in releasing the fish back to the water.

Closing areas where bycatch of undersized fish is limited by bigger sizes would potentially limit the catch of small fish, and transfer this catch to bigger fish, as the TAC for bycatch would remain the same. In a simple scenario where undersized Cod (roughly approximated by setting the selectivity of ages 2 to 6 to zero) was completely avoided by the fishing gear, the catch would be transferred to bigger size fish and 60 t of Cod would still be removed from the population. Population projections performed using the unchanged fishery selectivity and this modified selectivity showed no impact on population processes and stock trajectory (Figure 16). The uncertainty around estimates is not shown for clarity, but as the median estimates are almost identical, it is easy to accept that there is no effect of such a management measure on the stock trajectory.

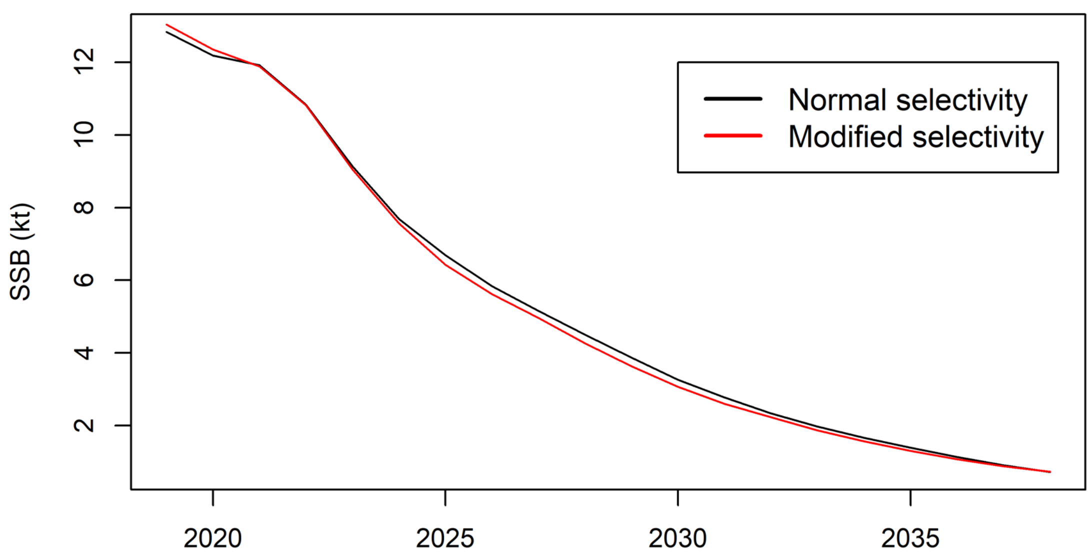

Figure 16: Projected Atlantic Cod SSB for years 2019 to 2028, with the un-changed fishery selectivity (black line) and modified selectivity where fish of ages 2 to 6 are completely exempt from the catch (red line). Solid lines are median MCMC estimates.

5. ADDITIONAL MEASURABLE OBJECTIVES

Rebuilding objectives may include other metrics beyond biomass-based measures (DFO 2021b). While setting measurable objectives for these metrics can be challenging, other considerations for sGSL Cod could include objectives of promoting recruitment and recovering the age structure, size at age, and spatial distribution.

5.1. PROMOTING RECRUITMENT

The Cod spawning ground location in Shediac Valley, especially the area east of Miscou, has still been used in the last decades (Appendix 3). The Miscou Bank area has been permanently closed by variation order to all groundfish fisheries from January 1 to December 31 where there were concentrations of sGSL Cod. A further section of Miscou Bank has a seasonal closure until the end of June to protect Cod during the spawning period (DFO 2017b).

However, as identified in Appendix 3, the closed area is not where the main aggregations of spawning Cod have been identified. Updating the coordinates of the closed area accordingly, to let fish spawn without disturbance and prevent spawning fish removals are objectives towards promoting recruitment. Moreover, research on identifying Cod recruitment drivers is recommended. The Shediac Valley spawning ground would represent the ideal location for sampling spawning Cod, eggs, larvae and primary and secondary production components of the ecosystem to study bottom-up drivers of recruitment.

5.2. AGE STRUCTURE

The RV survey catch-at-age indicates that the abundance of older Cod declined to very low levels in the 2010s (Swain et al. 2019). Older and larger cod are expected to make greater contributions to recruitment because they have been found to produce more batches of eggs, eggs of higher quality, and produce more eggs in total as a function of their body weight (Trippel 1998; Rideout et al. 2005; Barneche et al. 2018; Marshall et al. 2021). In addition, evidence from other Cod stocks have shown that stocks composed of older Cod have greater recruitment success and resilience to environmental change (Ohlberger et al. 2022; Ottersen and Holt 2022).

Provost and Botsford (2022) also found truncation of the age structure of Atlantic Cod populations resulted in an increased sensitivity of the population to environmental change and variability as well as an increased likelihood of extinction.

From the period 1971 to 2010, sGSL Cod aged 5+ averaged nearly 50% of the age composition from the RV survey, while Cod aged 8+ represented 10% of the survey catch. In the most recent period, the percentage has decreased to 32% and 5%, respectively (Swain et al. 2019). Both fishing and predation mortality have contributed to the reduction in abundance of older aged Cod.

A rebuilding plan objective could be to increase the percentage Cod aged 5+ or 8+ to averages observed historically.

5.3. SIZE AT AGE AND CONDITION

Declining size at age and poor fish condition are two factors negatively impacting SSB. Declines in length and weight-at-age of sGSL Cod occurred early in the time series between the late 1970s to the late 1980s, however it has since remained stable (Swain et al. 2019). Cod condition would be expected to have increased in the recent past as intraspecific competition decreased and environmental conditions have warmed. Unfortunately, this has not occurred perhaps due to predation risk which has shifted Cod out of their traditional foraging grounds into deeper waters (Swain et al. 2015), where historically condition was lower than other areas of the sGSL (Chouinard and Swain 2002). The shift in distribution may have reduced predation risk but might also have resulted in a decrease in condition due to poor feeding success.

Consequently, a rebuilding objective of increased size at age or condition would likely only be possible if Cod could return to their traditional forage areas.

5.4. SPATIAL DISTRIBUTION

Striking long-term shifts in the spatial distribution of sGSL Cod has been observed. During the summer feeding season, Cod were traditionally found in shallow, inshore areas of the sGSL. As predation risk increase, their distribution has shifted to the deeper waters along the southern slope of the Laurentian Channel (Swain et al. 2015). This shift in distribution to more unfavorable habitat also resulted in sGSL Cod distribution now overlapping with other active and emerging fisheries occurring in the Laurentian Channel.

A rebuilding objective could be to observe the distribution of Cod return to the shallow, inshore waters of the sGSL.

5.5. HABITAT

Section 2(1) of the Fisheries Act, defines fish habitat as "water frequented by fish and any other areas on which fish depend directly or indirectly to carry out their life processes, including spawning grounds and nursery, rearing, food supply and migration areas". For some stocks, the availability and quality of habitat may be important for rebuilding the stock when tightly linked to stock declines or rebuilding potential. With respect to this definition, habitat loss or degradation is unlikely to have contributed to the stock decline or play a role in preventing the recovery of the stock. Traditionally, sGSL Cod stock would overwinter in the relatively warm water along the southern slope of the Laurentian Channel in the Cabot Strait area and in 4Vn from November to April. In April and early May, the stock would migrate to spawn and feed in the sGSL (Swain et al. 2012). The median temperatures occupied by sGSL Cod generally vary from about 1 to 6 °C depending on season. Given the broad distribution of waters suitable for Cod in the sGSL, habitat is not considered to be limiting for this population. Furthermore, sGSL Cod do not have any known dwelling-place similar to a den or nest that may limit their recovery (COSEWIC 2010; Swain et al. 2012). The sGSL has experienced a trend towards warmer waters, shorter duration of ice season, and lower ice volume (Galbraith et al. 2021), however this has not decreased the habitat potential for Cod.

6. HOW TO TRACK REBUILDING PROGRESS

Rebuilding progress will be tracked using the sGSL Cod stock assessment model and monitoring of productivity parameters (natural mortality, recruitment, and growth) and the associated uncertainty of the model results. Projections and decision tables will be provided to monitor the progress towards attaining objectives of the rebuilding plan. Rebuilding plan progress should be tracked as part of the multi-year assessment cycle. Objectives should be revised and models should be updated as estimates of stock productivity changes.

7. FREQUENCY OF PERIODIC REVIEW OF THE REBUILDING PLAN

The periodic review of the rebuilding plan should be set to the 4 year stock assessment cycle for sGSL Cod with an interim update at the half way point. As established in the multi-year assessment cycle for sGSL Cod a full assessment would be triggered if during the interim update the stock indicator is above the LRP-proxy. Regardless of when a new stock assessment is to be initiated, at least 6-12 months lead time is required before the new stock assessment is initiated to allow for the reading of new ageing structures that will be needed for the interpretation of the population trajectory.

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APPENDIX 1: PELAGIC FISH EFFECT ON COD RECRUITMENT

Swain and Sinclair (2000) found that the period of high sGSL Cod pre-recruit survival in the early 1970s coincided with the collapse of Atlantic Herring and Atlantic Mackerel stocks. These pelagic fish are potential predators or competitors of early life history stages of Cod. The study found a strong negative relationship between the biomass of these pelagic fish and the recruitment rate of sGSL Cod. There have been many changes in the assessment models for all three stocks since the time of this study, and decades of new data are now available to update the results.

Cod recruitment and recruitment rates were obtained from Swain et al. (2019). Herring and Mackerel biomass for years 1963 to 1977 were obtained from Swain and Sinclair (2000), while Herring biomass for years 1978 to 2016 was obtained from Rolland et al. (2022). Mackerel biomass for years 1978 to 2016 was obtained from Van Beveren et al. (2023).

The highest Cod recruitment rates occurred at intermediate Cod SSB and at intermediate pelagic fish biomass (Figure 17). Lower Cod SSB and lower pelagic fish biomass produced lower Cod recruitment rates than the highest values (years 1974 to 1977).

As in Swain and Sinclair (2000), the effect of Herring and Mackerel biomass was tested on the stock-recruit relationship of sGSL Cod. A Ricker stock-recruit relationship was assumed with lognormal error. The relationships with (extended Ricker) and without covariate (standard Ricker) were fit using linear regression, with log recruit per unit of SSB as the dependent variable, and SSB and the estimates of Herring and Mackerel biomass in the year of spawning as the independent variables (Hilborn and Walters 1992). An autoregressive process of order 1 was assumed for the model error. Models were fit with the gls function in R (R Core Team 2023).

The standard Ricker formulation was as follows:

$$\log\frac{r}{ssb} = \alpha - (\beta \times ssb) + \varepsilon$$

Where r is the number of age-2 cod in year t+2 and ssb is cod spawning stock biomass in year t. The alpha parameter estimate (7.361) was significant (p<0.001), while the beta parameter (-2.00E-06) was not (p = 0.0744).

The extended Ricker was of the form

$$\log\frac{r}{ssb} = \alpha - (\beta_1 \times ssb) - (\beta_2 \times pel) + \varepsilon$$

Where pel is the biomass of pelagic fish (Herring and Mackerel) in the sGSL in year t. The alpha parameter estimate (7.892) was significant (p<0.001), while the beta1 parameter (-3.00E-06) was not (p = 0.066) and the beta 2 (-1.00E-06) was not (p = 0.062).

Using more years of data and contemporary model estimates, the addition of Herring and Mackerel biomass to the Ricker stock-recruit model did not improve the fit, and was not considered to have a significant effect on the Cod recruitment rate.

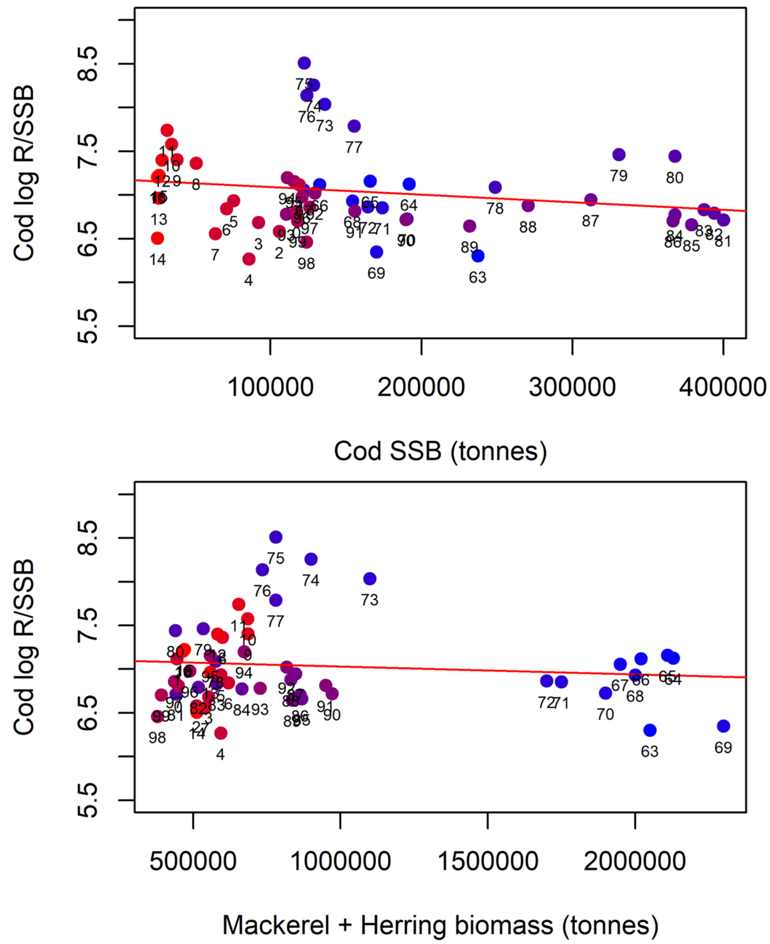

Figure 17: Relationships between cod recruitment rate (R/SSB) and cod spawning stock biomass (SSB; upper panel) or pelagic fish biomass (Mackerel + Herring; lower panel) in the southern Gulf of St. Lawrence between 1963 and 2016.

The average pelagic fish biomass in 1974 and 1975, the years with extremely high Cod recruitment rates, was 800,000 t. If this reconstructed time series of herring and mackerel biomass using various sources can be considered a reasonable representation of reality, it can be argued that pelagic fish biomass in the sGSL have remained below the level that allowed the extreme high Cod recruitment rates in 1974 and 1975 (Figure 18). Hence, it does not seems plausible that a low pelagic fish biomass is the trigger for high Cod recruitment rates. Otherwise these high recruitment rates would have persisted or at least occurred more often throughout the time series.

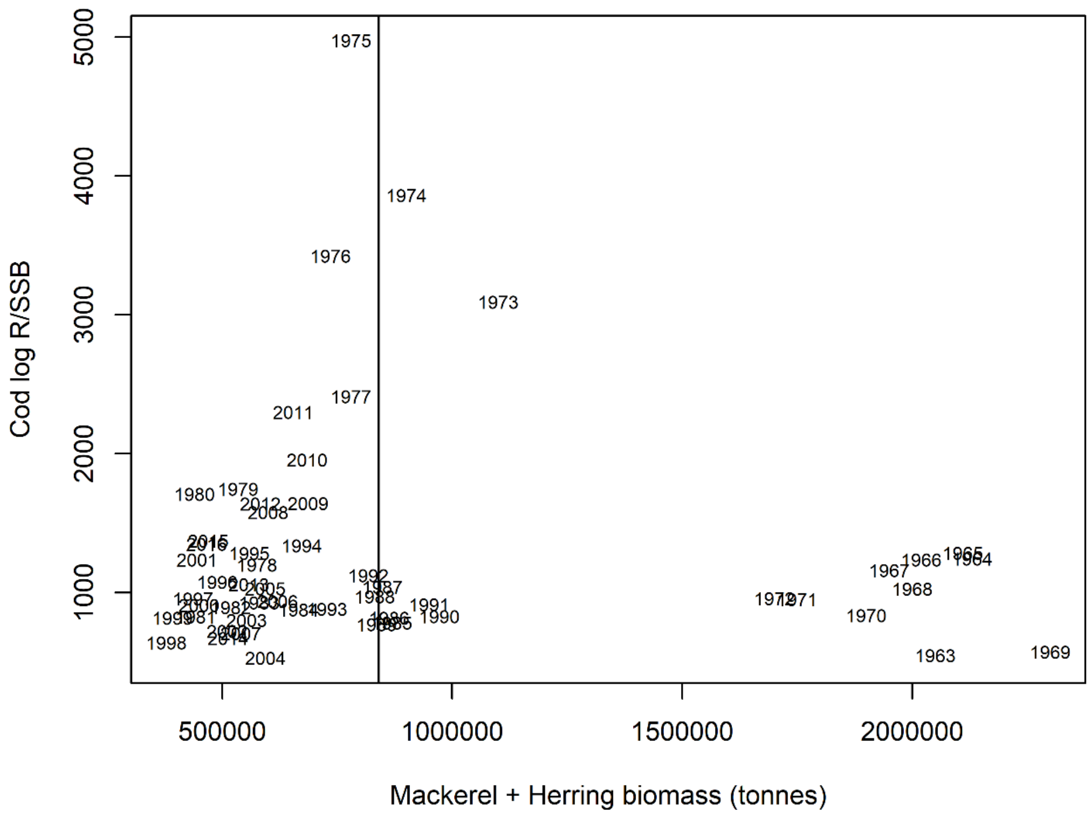

Figure 18: sGSL Cod recruitment rates (number of age-2 fish by the SSB that produced them, on the log scale) in function of the combined Herring and Mackerel biomass. The vertical black line is the mean pelagic fish biomass in years of high Cod recruitment rates.

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APPENDIX 2: SURPLUS PRODUCTION MODEL FITS, PRIOR AND POSTERIOR DISTRIBUTIONS

Figure 19 shows the viable r-K pairs identified by the Bayesian implementation of the full Schaefer model (BSM), with the red dot showing the predicted most probable r-K pair, with 95% confidence limits. The cloud of points is reasonably distributed and the confidence intervals are reasonably small and within the expected values given the priors information.

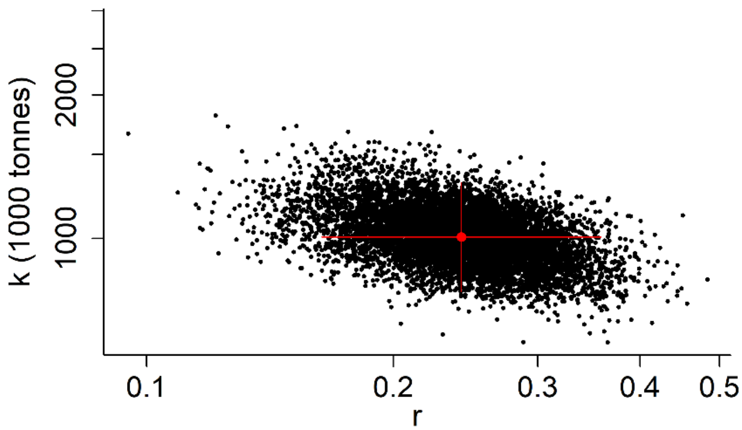

Figure 19: Viable r and k pairs estimated by the BSM model (black points). The red point is the median estimate from the MCMC sampling and the red lines are the 95% confidence intervals.

The posterior distributions of parameters overlap with the prior distributions for all parameters (Figure 20). For the B/K in 1985 and K parameters, the maximum density of the posterior distributions are at the margins of the prior distributions, showing the model had sufficient information to estimate parameter values informed by the data rather than loosely defined by priors for these parameters related to stock size and carrying capacity.

The model fits the data well (Figure 21), with the catch and index predicted values matching the observed values almost perfectly over the time series. The process variation and residuals are relatively small and the BSM autocorrelation test on the residuals showed the residuals not to be problematic.

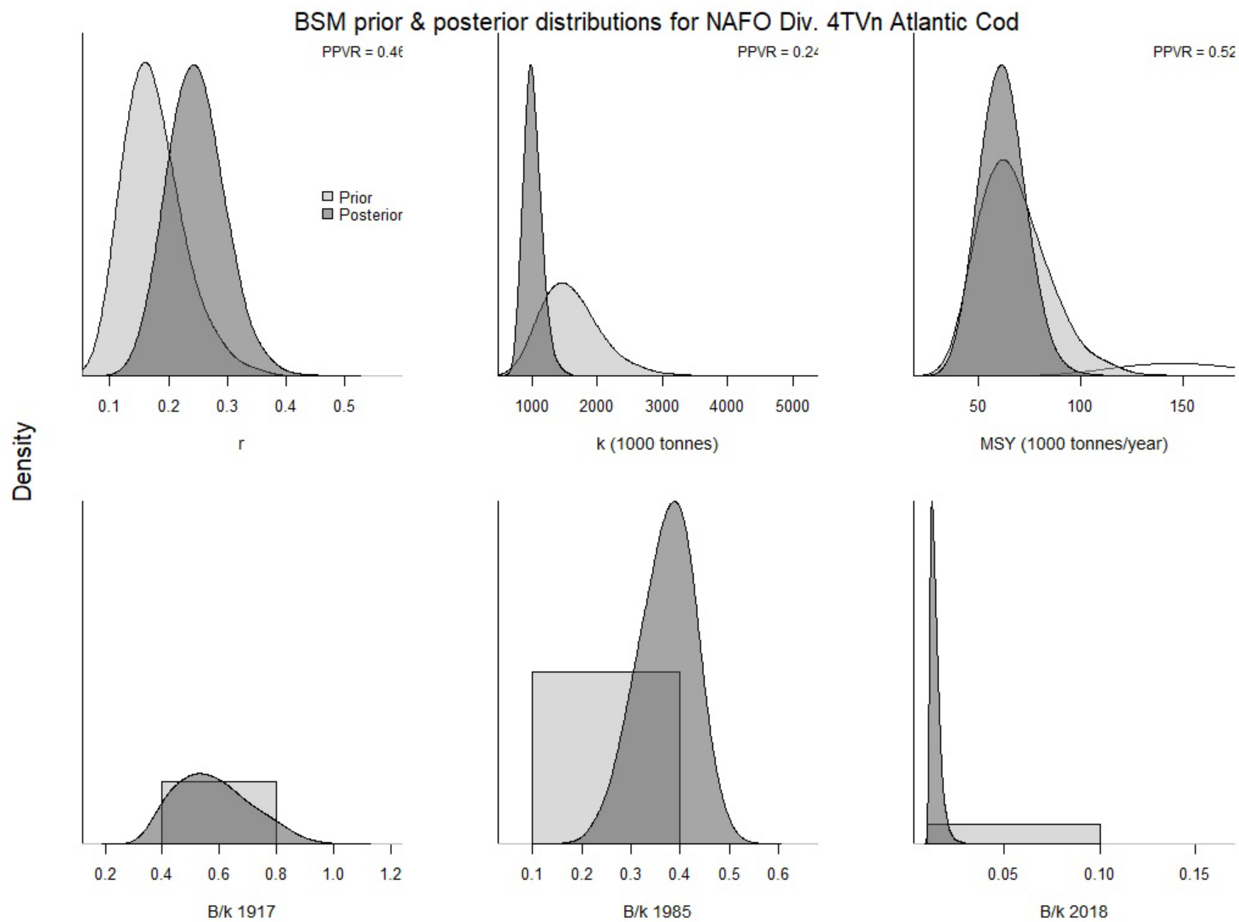

Figure 20: Comparison of prior and posterior densities (same area under curves) from the BSM analysis for productivity (r), maximum stock size (K), maximum sustainably yield (MSY), and relative stock size (B/K) at the beginning, at and an intermediate year and at the end of the available time series of catch data.

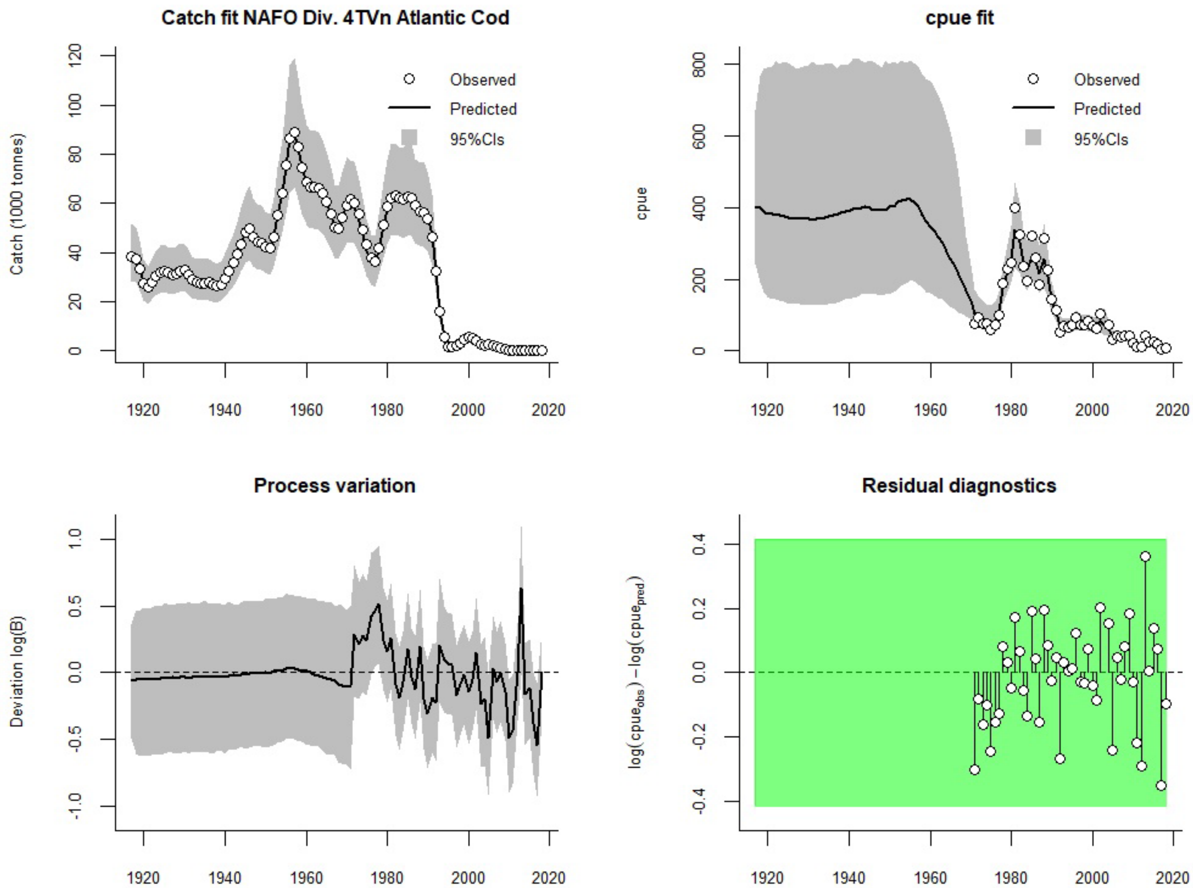

Figure 21: Bayesian state-space model diagnostics output for the fit of the predicted to the observed catch, the fit of predicted to observed CPUE, the deviations from observed to predicted biomass (process variation), and an analysis of the log-CPUE residuals, with a white or green background if autocorrelation of residuals is deemed negligible and red otherwise.

APPENDIX 3: COD SPAWNING GROUNDS LOCATION

The primary sGSL Cod spawning ground is thought to occur in the Shediac Valley area off Miscou (Swain et al. 2012). Powles (1958) reported that the spawning period of Cod in the sGSL lasted from May to September, with peak spawning in late June. Not many sampling programs target or catch Cod in the sGSL in the months of May to July. The only sampling program that satisfied these criteria was the sGSL Cod Condition Survey. However, the spatial coverage is not random over the sGSL in the sampling program database as the objective of the survey was to capture Cod so sampling was targeted towards areas of known concentrations. During the presumed spawning season, between May and July, sets were concentrated in the Shediac Valley and Baie des Chaleurs area, with some sets in the vicinity or the Cape Breton Trough and a limited number of sets in the Laurentian Channel. Despite this targeted sampling approach, the dataset can be used to confirm the presence of spawning Cod and the areas they frequent based on the maturity stages consistent with spawning.

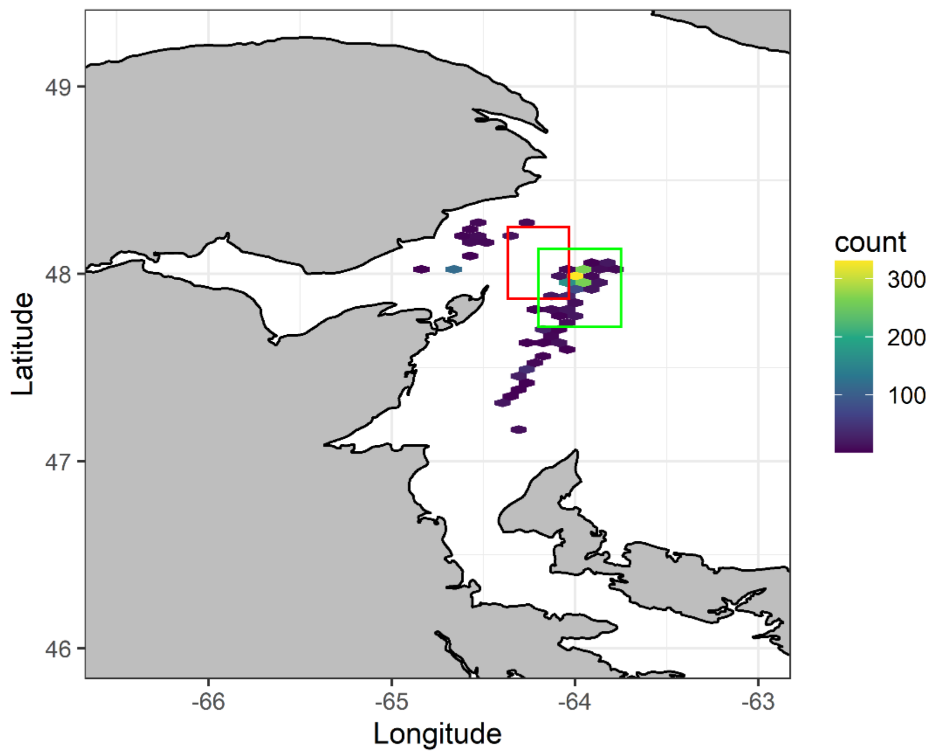

Figure 22: Count of fish in maturity stage 4-5 sampled in the months of May, June and July between 1992 and 2018 in the cod condition sampling program database. Red box is closed area, green box is proposed closed area.

The Cod Condition Survey sampling program protocol defines the maturity stage ripe and running as follows: Gonad transparent to pink-purplish in color. Large transparent eggs expressed freely by exertion of pressure on “jelly-like” mass of the ovary. Hence, the database was filtered to obtain the maturity stage 4 and 5 males and females captured between the months of May to July (In recent years protocols were revised and only stage 5 is used for spawning). The abundance per tow was then obtained for all years combined (Figure 22). There was no difference in the abundance per tow and geographic density of maturity stage 4-5 between males and females (not shown).

The location with the highest abundance per tow of stage 4-5 Cod was also the location of the highest number of fishing sets. This is explained by the opportunistic sampling design where a high number of fish were necessary to perform the Cod condition analysis, and this location was known to be an area where Cod aggregated by the sampling biologist (Éliane Aubry; personal communication). Hence, the sampling was biased towards this area, however sampling in other areas either failed to capture cod, or caught Cod that did not have a gonadal maturity of stage 4-5, or alternatively only low numbers per tow of maturity stage 4-5 were captured outside this core area. Despite the biases and caveats of this approach, this analysis allowed to confirm that the Miscou/Shediac Valley (approximately 64W, 48N) remains the dominant area for spawning Cod. Furthermore, a few sets in the Baie des Chaleurs and in the south portion of the Shediac Valley have shown a few sets with high abundance per tow of Cod with gonads in maturity stage 4-5, but not as many in with smaller abundance per tow than in the core area.

We propose an update to the closed for fishing area coordinates to align with the location of the Cod spawning aggregations (48.133; 47.716; -63.750; -64.200; Figure 23, red box is the current closed area, green box is the proposed closed area).

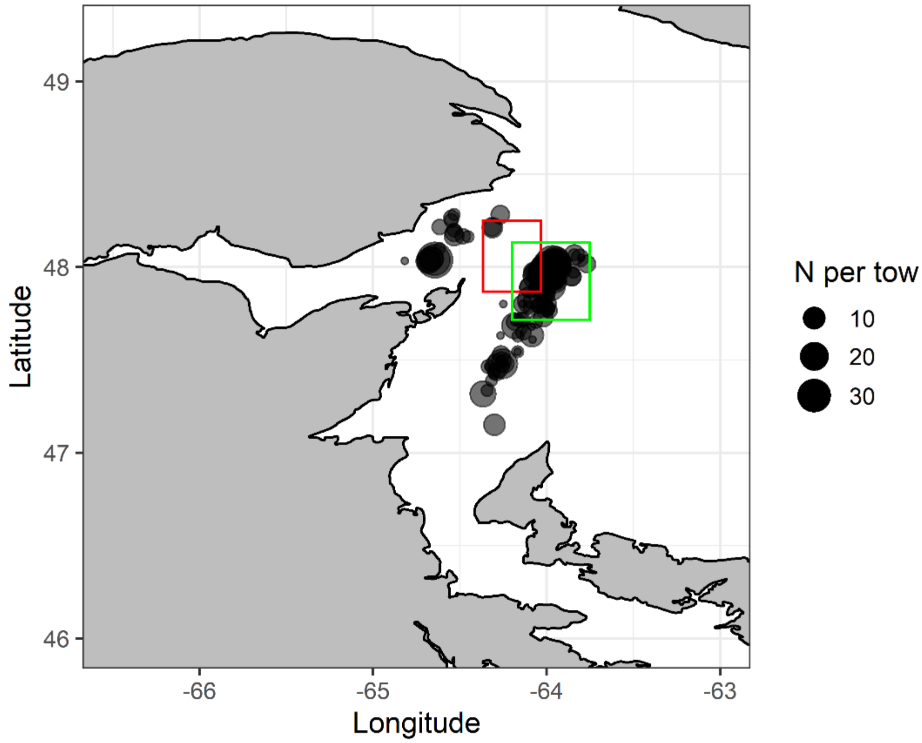

Figure 23: Abundance per tow (N per tow) of spawning Cod (gonad maturity stage 4-5) between May and July from the cod condition sampling program database. Red box is closed area, green box is proposed closed area.

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