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Scientific Requirements for the Rebuilding Plan of Southern Gulf of St. Lawrence (NAFO Division 4TVn) Spring Spawning Atlantic Herring (*Clupea harengus*)

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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 spring spawning component of Atlantic Herring (*Clupea harengus*) in the southern Gulf of St. Lawrence (NAFO Division 4TVn) is below its limit reference point (LRP) and in the Critical Zone of Fisheries and Oceans Canada (DFO) Precautionary Approach framework. The new Fish Stocks Provisions and the amended Fisheries Act legally require DFO to develop a rebuilding plan for this stock. Rebuilding plans involve several key requirements, many of which are defined and/or supported by advice from DFO Science Sector. 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) Atlantic Herring spring spawners sources of serious harm include environmentally-driven recruitment failure associated with a regime shift from cold water/high recruitment to warmer water/low recruitment in the early 1990s, a sustained period of low production low biomass since 2004, reduced growth, high natural mortality, and reduced fecundity.

A review of the biomass reference points generated a new LRP using the statistical catch at age model; 40%BMSYproxy. Its value is estimated at 55,000 tonnes (t) of spawning stock biomass (SSB). With this LRP, the stock has been below the LRP and in the Critical Zone of the DFO Precautionary Approach framework since 2001 (previously 2002).

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 2 consecutive years, and population projections must show the stock is likely to continue its positive trajectory under harvest for 2 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. The environmental conditions that would allow to reverse the decline in sGSL Atlantic Herring spring spawners are the occurrence of intermediate and high recruitment events. Since 1992 recruitment has been limited due to environmental conditions which are unlikely to improve as climate change continues.

Projections showed that at 150 t of annual bycatch, the population SSB in 10 years would be reduced by 1.0%.

Additional measurable objectives for the rebuilding plan should include increasing the proportion of older and larger fish.

Rebuilding progress will be tracked using the stock assessment models. The periodic review of the rebuilding plan should be set to every 4 years, which corresponds to every other stock assessment. Objectives should be revised and models should be updated if stock productivity or external factors influencing stock dynamics change.

1. REBUILDING PLAN CONTEXT

Atlantic Herring (*Clupea harengus*) in the southern Gulf of St. Lawrence (sGSL) are found in the area extending from the north shore of the Gaspé Peninsula to the northern tip of Cape Breton Island, including the Magdalen Islands. Adults overwinter off the north and east coast of Cape Breton in the Northwest Atlantic Fisheries Organization (NAFO) Divisions 4T and 4Vn (Claytor 2001; Simon and Stobo 1983; Figure 1). The Atlantic Herring population in the sGSL consists of two spawning components: spring spawners and fall spawners (hereafter; spring Herring and fall Herring respectively). The two spawning components are genetically differentiated (Lamichhaney et al. 2017), thus considered distinct stocks and assessed separately. In addition, the sGSL Herring stocks are managed over two fishing season (spring and fall). The spring Herring stock collapsed in the 1990s. The annual fishery total allowable catch (TAC) was gradually reduced, but the stock has failed to recover. The most recent stock assessment for spring Herring was completed in March 2022 and confirmed that spring Herring has remained below the limit reference point (LRP) and in the Critical Zone of the Fisheries and Ocean Canada (DFO) Precautionary Approach (PA) framework since 2002 (Rolland et al. 2022). The bait and commercial fisheries for spring Herring were closed in 2022.

Under section 6.2 of the Fish Stocks Provisions (FSP) 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 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 NAFO Division 4TVn spring spawning Atlantic Herring.

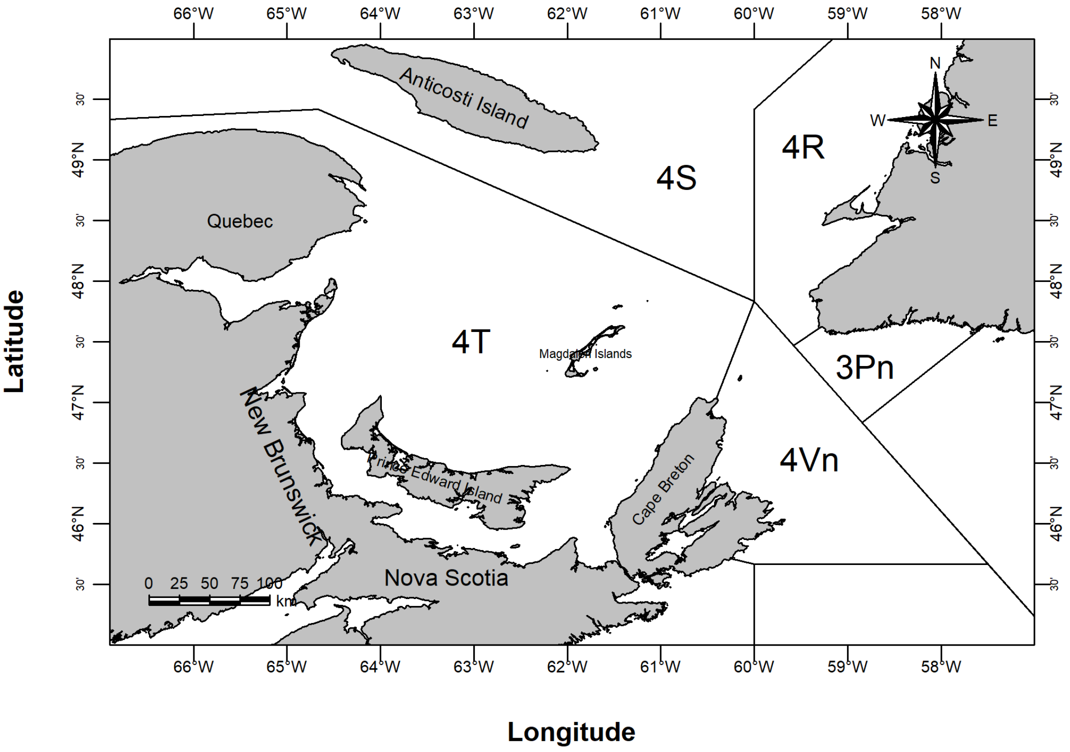

Figure 1: NAFO Divisions in the Gulf of St. Lawrence and Cabot Strait.

Section 70 of the *Fishery General Regulations* also set out the required content of rebuilding plans. The rebuilding plans involve several key elements that are defined and/or supported by advice from DFO Science Sector. Scientific advice for some of the elements are already available in peer-reviewed material through primary publications or other CSAS processes. This document will provide a summary of the published scientific knowledge, however the peer-review will focus on new analyses performed to inform the development of the spring Herring rebuilding plan. The specific objectives of this document are to review and update the current LRP and establish the stock status with respect to the recommended LRP, determine a rebuilding target, calculate and evaluate the timeline and likelihood of achieving the rebuilding target under various environmental and fishery management scenarios, propose additional measurable objectives, identify indicators for tracking rebuilding progress, and provide guidance on the frequency of the periodic review of the rebuilding plan.

2. REFERENCE POINTS AND HARVEST CONTROL RULES

The LRP represents the stock status below which serious harm is occurring to the stock. Stocks at a level below their LRPs (i.e., 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 point, there may also be resultant impacts to the ecosystem, associated species, and a long-term loss of fishing opportunities. Several approaches for calculating the LRP are in use and may be refined over time. The LRP is based on biological criteria and established by DFO Science through a peer reviewed process (DFO 2009).

The current LRP for spring Herring is $B_{recover}$, which is the lowest biomass from which the stock has been observed to readily recover. It is calculated as the average of the four lowest spawning stock biomass (SSB) estimates in the early 1980s (i.e., 1979-1982). Consequently, this value is model dependent. At every model update or modification, stock biomass may be re-scaled upwards or downwards. For the 2022 assessment, the LRP was estimated to be 46,340 tonnes (t; Rolland et al. 2022).

The Upper Stock Reference (USR) was determined in 2005 as an interim reference point (Chouinard et al. 2005) using a yield per recruit analysis assuming natural mortality of 0.2 and specific partial recruitment vectors to the fishery, a method that is not compatible with the high natural mortality estimates obtained the assessment (Turcotte et al. 2021a,b). Hence, an interim USR was estimated for the 2019 assessment at 132,546 t of SSB (Turcotte et al. 2021a). The removal reference (RR) for spring Herring was first introduced in the 1995 stock assessment (Claytor et al. 1995) and has since been used as the RR in the Healthy Zone ($F_{0.1} = 0.35$). There is no agreed upon Target Reference Point (TRP) or RR in the Cautious and Critical Zones for this stock.

Deriving reference points for stocks with time-varying productivity 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 2017). Cox et al. (2019) found that, for a Pacific Herring stock with very similar productivity dynamics to that of sGSL spring Herring, 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 actually be significant. These findings limit the methods to derive a LRP that can be applied to sGSL spring Herring and still be precautionary.

In order to review the current LRP and explore alternative LRPs for spring Herring, it is first necessary to identify the point where serious harm has occurred. Here, population dynamics processes and estimated stock status over the assessment period were used to inform the evaluation of the point where serious harm occurred. Then, an evaluation of multiple candidate LRPs will be conducted to identify the best candidate LRP. Evaluating multiple candidates is informative as it can provide confidence in selecting the LRP when estimates agree, but can also identify potential risks when estimates don't agree (DFO 2023). Examining a variety of estimation methods is warranted, as there is not a single method that can fit all cases (Myers et al. 1994; Shelton and Rice 2002). Indicators, LRPs, and stock status metrics should take into account reliability, plausibility, and uncertainty (DFO 2023). 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 2023).

2.1. A DEFINITION OF SERIOUS HARM

In the context of fisheries, serious harm can be defined as an undesirable state that may be irreversible or only slowly reversible over the long-term (DFO 2023). 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, result 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.

2.2. SERIOUS HARM IN SGSL SPRING HERRING

2.2.1. Biomass

Spring Herring SSB increased from low levels in the early 1980s to the highest levels of the time series in the mid-1980s to mid-1990s (Rolland et al. 2022). SSB declined from the mid-1990s to reach the Critical Zone in 2002, where it has since stayed. The SSB estimate for 2021 was 77% of the LRP, and represented 18% of the 1995 SSB.

2.2.2. Recruitment

Spring Herring recruitment (number of age 2 fish) was highest in the early 1980s, 1990, and 1993 (Rolland et al. 2022). Recruitment has been relatively stable at low values since 1993, with slightly higher values between 2006 and 2008. Recruitment declined to lowest values of the time series from 2008 to present, with the exception of a small increase in 2015. Recruitment rates (number of age-2 fish per kg SSB) were highest in the early 1980s and around 2005, and at the lowest between 1992 and 2000. Since 2006, recruitment rates have declined to low values except for a small peak in 2013 and 2019.

A review of the literature on Atlantic Herring recruitment drivers identified a substantial number of biotic (n = 9) and abiotic (n = 8) factors that can impact survival at the egg, early larval, late larval, and juvenile stages, thereby directly influencing recruitment of Atlantic Herring (Burbank et al. 2022a). From this review, it is evident that the wide range of factors influencing recruitment act simultaneously and interact with one another to impact and determine year-class strength. Factors include suitable spawning substrate, prey quality and abundance, intra- and interspecific competition, temperature, storms, and dominant currents.

For sGSL spring Herring specifically, the recruitment dynamics are strongly influenced by variation in environmental conditions (Brosset et al. 2019; Turcotte 2022; Burbank et al. 2023b; Sellinger et al. 2024). A regime shift analysis showed that both the sea surface temperature across the sGSL and spring Herring recruitment abruptly shifted from a cold water/high recruitment regime (1978-1991) to a warmer water/low recruitment regime (1992-2017) in the early 1990s (Turcotte 2022).

A set of zooplankton indicators was also able to predict spring Herring recruitment. These included (1) the abundance of large calanoid copepods early in the summer; an indicator of food availability to Herring larvae, (2) the *Calanus hyperboreus* copepodite ratio; an phenology indicator for the timing of availability of food for larval Herring, and (3) the warm water zooplankton abundance; a indicator of the quality of the food items available to Herring larvae, as a result of water temperature effects on the zooplankton community.

When examining the influence of a larger sets of predictors, Burbank et al. (2023b) found that a combination of biological (bottom-up) and physical ecosystem factors along with demographic factors had an effect on spring Herring recruitment. Higher recruitment was observed when the proportion of age 8 to 11+ adults were higher. Additionally, there was a significant positive correlation between the recruitment of spring Herring and the sum of weight-at-age of adults.

2.2.3. Reproductive capacity and maturation

The average fecundity of sGSL spring Herring has undergone a substantial temporal decline of approximately 47% since the 1970s and 1980s (Burbank et al. 2024). The estimated fecundity of spring spawning herring in the 1970s was of 77,764 ± 37,379 (mean ± sd) eggs per fish, while it was 40,853 ± 14,533 eggs per fish in 2022.

The length- and weight-fecundity relationships for spring Herring have remained relatively static through time, though fish are overall smaller in 2022 compared to the 1970s and 1980s. Consequently, simulations using 1 million fish representative of the size distribution of each time period highlighted a substantial reduction of approximately 32% in potential reproductive output in 2022 compared to 1970.

For spring Herring cohorts between 1972 and 2014, the age at 50% maturity increased by 0.59 years (Beaudry-Sylvestre et al. 2022). The length at maturity declined continuously over the same time period, concomitant with reductions in size at age. The observed delay in maturation would be consistent with a harvesting strategy that targets spawners, whereas Herring fisheries also harvesting juveniles mostly exhibit a shift towards earlier maturity.

2.2.4. Survival

Natural mortality estimates for the age group 2 to 6 varied between 0.24 and 0.51 (between 21% and 40% annual mortality) between 1978 and 2021 (Rolland et al. 2022). For the age group 7 to 11+, natural mortality increased gradually from 0.30 to 0.56 (between 26% and 43%

annual mortality) between 1978 and 2006, it then decreased slightly to 0.47 (37% annual mortality) in 2009. Beginning in 2010, estimates increased sharply to reach a maximum of 1.05 (65% annual mortality) in 2018 before decreasing slightly to a mean value of 0.9 (59% annual mortality) in 2020 and 2021.

Potential sources of natural mortality include: unreported catches, disease, and predation. The unreported catches of Herring are most likely to occur in the bait fisheries. Catches in these fisheries are meant to be recorded in harvester logbooks, however compliance with the requirement to complete and return logbooks to DFO is low. Catches of Herring in the bait fishery are expected to be much lower than landings in the commercial fishery and be a negligible source of natural mortality (see Section 4.2.2 Bait removals). Disease mortality is expected to be relatively small in 4TVn Herring, as no disease-related mortality event was recorded in the time period covered by the assessment. Hence, spring Herring natural mortality is likely to be mostly predation driven.

Herring is an important pelagic prey species for numerous predators in the sGSL including Grey Seal (*Halichoerus grypus*; Hammill and Stenson 2000; Hammill et al. 2007, 2014), seabirds (mostly Northern Gannets; *Morus bassanus* (Pelletier and Guillemette 2022)), cetaceans (Fontaine et al. 1994; Benoît and Rail 2016), Atlantic Cod (*Gadus morhua*; Hanson and Chouinard 2002), White Hake (*Urophycis tenuis*; Benoît and Rail 2016) and Atlantic Bluefin Tuna (*Thunnus thynnus*; Turcotte et al. 2021c; Turcotte et al. 2023). Of these major predators, Atlantic Cod, Grey Seals, Atlantic Bluefin Tuna, and Northern Gannets have undergone large changes in abundance in the sGSL in the last decades. The increasing trend in Grey Seal, Bluefin Tuna and Northern Gannet abundance are strongly correlated with the increase in older (age group 7-11+) spring Herring (Rolland et al. 2022). Their herring consumption is estimated to be at least 10 kilotonnes (kt) of herring annually for each predator (Benoît and Rail 2016; Turcotte et al. 2021c).

Fishing mortality (F; abundance weighted fishing mortality for ages 6 to 8) was high in 1979-1980, decreased until 1984 and then increased steadily to over 0.5 in 2004. F then decreased rapidly to a low value (<0.05) in 2010 and has remained at this low value until 2021. The lowest value was estimated in 2021. For a few years, F was stable around 0.2 when the stock was at high biomass in the early 1990s. F increased to high values during and after the collapse as SSB decreased and TACs remained high. Fishing mortality during and after the collapse is a source of harm to the stock.

2.2.5. Growth

The average weight-at-age of spring Herring declined by 39.6% between 1978 and 2021 (Rolland et al. 2022). Von Bertalanffy growth models also suggest that the asymptotic length of spring Herring has declined over the time series, suggesting spring Herring are not growing to be as large as they had historically (Burbank et al. 2023a). This corroborates observations that size-at-age has generally been decreasing over the last decades across eastern Canada Atlantic Herring spring and fall stocks (NAFO 4VWX, DFO 2018; 4R, DFO 2022; 4S, DFO 2021b; Newfoundland East and South coast, Wheeler et al. 2009; Bourne et al. 2023). A decrease in the size of fish can have wide-ranging negative implications, including reduced fecundity and reduced lifetime reproductive output (Barrett et al. 2022; Burbank et al. 2022b], which in turn can negatively impact population productivity and population abundance.

Declines in growth are observed in many exploited fish populations but the age-specific trends vary and causes of the declines, which can be fishing-induced, density-dependent and/or environmental, are generally not well understood or difficult to identify (Charbonneau et al. 2019). In sGSL Herring, Beaudry-Sylvestre et al. (2022) found a relationship between the temperature experienced and mean length at age 4, a pattern that was consistent in Herring populations in the northwest Atlantic. The faster declines in weight-at-age experienced by warm-water populations of the northwest Atlantic could arise from steeper increases of metabolic costs with temperature, while the intensity of exploitation-history did not seem to be a factor in the relationship between temperature and growth.

2.2.6. Serious harm

As per the definition, serious harm may lead to a loss of resilience, defined as an impaired ability to rebuild, exceed replacement, or to recover from perturbation. This stock has not recovered since it decreased below $B_{recover}$, the current LRP, it is reasonable to assume serious harm has occurred in the years leading to, or during the collapse.

The decline in survival of older fish was gradual and natural mortality increased continuously between the 1990s and late 2000s. Hence it is difficult to identify a point where serious harm occurred in this case. Similarly for growth and fecundity the observed changes were gradual and a breakpoint is not easily identifiable.

Recruitment abruptly declined post-1992 and is likely to be the source of serious harm and cause of decline of this stock. However, as recruitment is not SSB driven in this stock, deriving a biomass limit reference point directly from the process of recruitment failure is not possible.

Individual elements of the serious harm definition do not lead to a clear point where serious harm occurred to inform the definition of a biomass limit reference point. Consequently, tools to derive candidate LRPs explored in the next sections will also be used to define where serious harm occurred and how candidate LRPs compare to that point.

2.3. METHODS

The sGSL spring Herring population estimates were obtained from the population model output of the last published assessment at the time of this peer-review (Rolland et al. 2022).

2.3.1. LRP based on a stock recruitment relationship

Stock recruitment relationships (SRR) were modelled using three parametric models: Beverton-Holt, Ricker and Hockey Stick. The Beverton-Holt and Ricker models were fit to the data using the nls function in the R statistical software (R Core Team 2023). 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 maximum number of recruits produced, 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. a is an index of stock-independent mortality, and b is an index of stock-dependent mortality. R_{max} is obtained by:

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

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 regime shift in spring Herring recruitment had previously been identified, along with a regime-like shift in sea surface temperature in all regions of the GSL (Turcotte 2022). Candidate LRPs were derived from Ricker SRR models for each regime periods identified by the STARS algorithm in Turcotte 2022.

The LRP candidates derived from SRRs will be dependent on the functional form of the relationship and the type of dynamics observed. The candidate 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.

2.3.2. LRP based on B_0

B_0 is the mean long-term equilibrium SSB 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 have been developed assuming stationary productivity parameters. Over the years of the spring Herring assessment, M values increased, weight-at-age declined, and recruitment is displaying regime-like behavior. 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 initial assessment year, 1978, was selected to represent a productive state (high weight-at-age and low M at age).

The population was initiated with one recruit to get through calculations, and a vector of unfished spawners per recruit was calculated using natural mortality at age in the year 1978. SSB per recruit (Φ_0) was then calculated by multiplying the spawner per recruit, weight-at-age and maturity at age vectors from 1978.

B_0 was calculated by multiplying Φ_0 by the average expected maximum recruitment from the Ricker SRR model over years 1978 to 2019 (362,321,236 recruits). An alternative B_0 was also calculated using the average number of recruits over the assessment period to account for uncertainty in the modelled Ricker SRR. Initial $0.2B_0$ was calculated as the candidate LRP for this stock.

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

The PA framework provides guidance to identify reference points and harvest control rules (DFO 2009). In the absence of an estimate of B_{MSY} from an explicit model, 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 $F_{0.1}$ multiplied by the average number of recruits; (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): 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}. In other words: Biomass ≤ 40% B_{MSY}. 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}. In other words: 40% B_{MSY} < Biomass < 80% B_{MSY}. The stock is considered to be in the "Healthy Zone" if the biomass, or its index, is higher than 80% of B_{MSY}. In other words: biomass ≥ 80% B_{MSY}.

1. The biomass corresponding to the biomass per recruit at $F_{0.1}$ multiplied by the average number of recruits.

To obtain the $F_{0.1}$ 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. Vectors of weight-at-age, gear selectivity and natural mortality for ages 2 to 11+ in the initial assessment year (1978) were used. The oldest age was set to 20 and maxF was set to 2.

The survival per recruit at $F_{0.1}$ 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 $lage_a$ is the survival at age of age a, M is natural mortality at age, F is fishing mortality and sel is selectivity at age. The F value was set to $F_{0.1}$.

To obtain the SSB per recruit at $F_{0.1}$, the survival per recruit multiplied by the weight-at-age and maturity at age vectors were summed over all ages. The SSB per recruit at $F_{0.1}$ was multiplied by the average number of recruits estimated by the population model over the time series. The LRP derived from this $BMSY_{proxy}$ was calculated as 40% of its value (named $40\%PA1BMSY_{proxy}$).

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

Production in a fish stock is the combination of recruitment, growth and natural mortality. To define the provisional B_{MSY} level ($BMSY_{proxy}$) from the PA recommendations, the 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 in year *t*+1 and B_t is the stock biomass in year *t*. Productive periods were identified by finding uninterrupted periods of 7 years during which stock production was high and led to high stock biomass. 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 ($40\%PA3BMSY_{proxy}$).

2.4. RESULTS

2.4.1. LRP based on the stock recruitment relationship

Two extreme high recruitment events occurred in the assessment time period (Figure 2, left), in 1988 and 1991. The number of recruits produced were 961 and 989 million, respectively. The SSB producing these number of recruits were 126 and 107 kt, respectively. The next biggest recruitment events are in the 50 to 70 million recruits range. Recruitment events in this range occurred three times in the assessment period. The remainder of recruitment events gradually increase in frequency of occurrence as the number of recruits produced decreases. Three recruitment events are outliers in a boxplot of all the recruitment values and could be defined as higher than expected recruitment events (Figure 2, right). The outlier with the lowest value was for 638 million recruits, which occurred in 1980 when SSB was 41 kt.

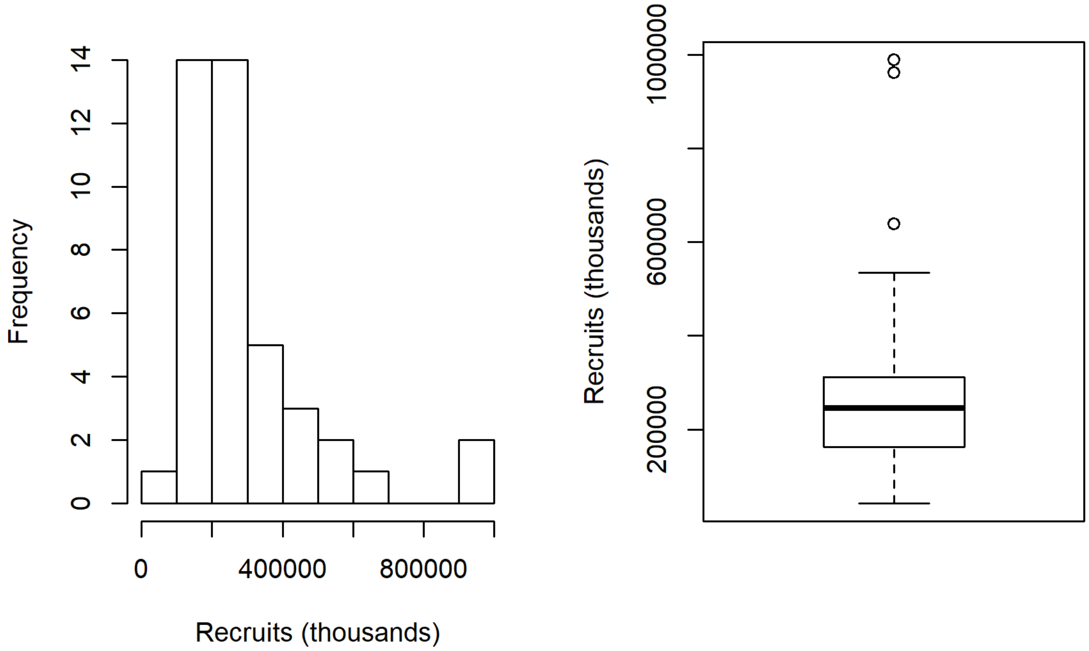

Figure 2: Frequency of occurrence of recruitment events (left panel) and boxplot of the time series of recruitment values (right panel) for Southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring.

The BH SRR model fit to the data was acceptable (Figure 3), the a parameter was significant but the b parameter was not (a = 393,187,287, p = 0.000134, b = 14,628, p = 0.391). The RK SRR model fit to the data was acceptable (Figure 3), the a and b parameters were significant (a = 10,197.28, p = 0.0000460, b = 0.00000970, p = 0.0000549). The HS model fit set the inflexion point of the regression at the lowest SSB value. Hence, no points support the estimation of the diagonal section of the curve. As such, the fit was not acceptable.

For the BH and RK SRRs, the fitted values predicted the average expected number of recruits well. However, the variation around the predicted mean was high. The model estimated value representing 50% of the maximum number of recruits from the BH SRR was 196,593,643 recruits. The SSB producing this number of recruits (BHB50%Rmax) was 14,628 t of SSB. For the RK SRR, the model estimated value of the SSB producing the maximum number of recruits was 99,000 t. 50% of the estimated maximum number of recruits was 193,282,096. The SSB producing this number of recruits (RKB50%Rmax) was 24,000 t. For the HS SRR the model estimated value representing 50% of the maximum number of recruits was 131,146,440 recruits. The SSB producing this number of recruits (HSB50%Rmax) was 14,491 t. The inflexion point of the SRR was 24,982 t of SSB.

A regime shift analysis in Turcotte (2022) found a shift in spring Herring recruitment occurring in 1992. For the Ricker SRRs modelled for the group of years identified by the STARS regime shift analysis, the fit to the data was acceptable (Figure 4). For both regimes, the a and b parameters were significant (1978-1991; a = 20,914.98, p = 0.0302, b = 0.0000138, p = 0.00408, 1992-2019; a = 8,309.98, p = 0.00000288, b = 0.0000109, p = 0.0000136). For the 1978-1991 RK SRR, the model estimated value representing 50% of the maximum number of recruits was 277,035,533 recruits. The SSB producing this number of recruits (RKB50%RmaxShift1) was 17,000 t. For the 1992-2019 RK SRR, the model estimated value representing 50% of the maximum number of recruits was 140,572,180 recruits. The SSB producing this number of recruits (RKB50%RmaxShift2) was 21,000 t.

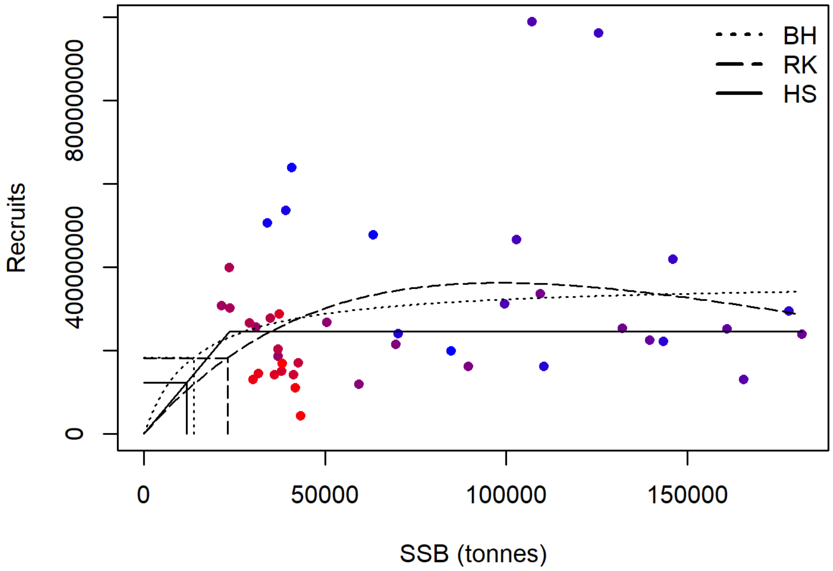

Figure 3: Southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring stock recruitment relationships for years 1978 to 2019, for three stock recruitment relationship models; Beverton-Holt (BH), Ricker (RK) and Hockey stick (HS), along with dashed lines showing the estimated 50% maximum number of recruits and the corresponding SSB producing 50% of the maximum number of recruits. Colored circles indicate SSB and number of recruits pairs, colors indicating years from 1978 (blue) to 2019 (red).

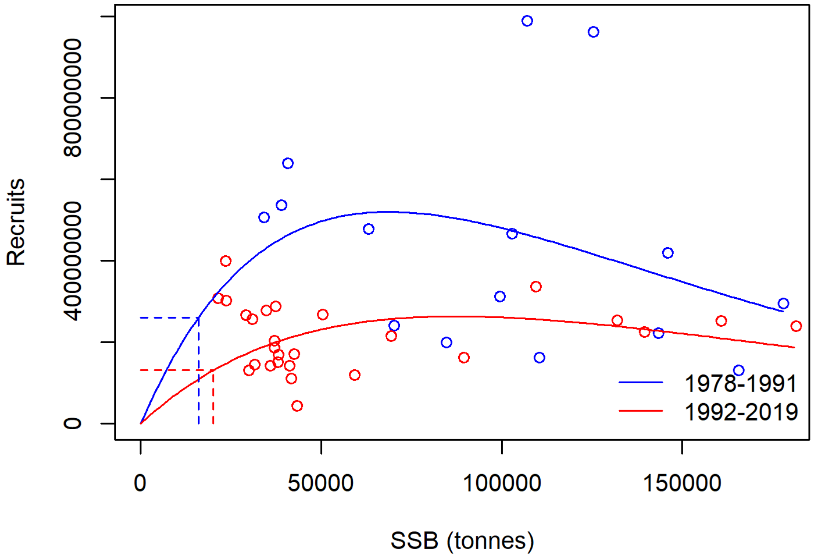

Figure 4: Southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring stock recruitment relationships from Ricker model for two year groups. Blue circles and lines are for years 1978 to 1991, red circles and lines are for years 1992-2021. Dashed lines show the estimated 50% maximum number of recruits and the corresponding SSB producing 50% of the maximum number of recruits.

2.4.2. LRP based on B_0

The estimated Φ_0 value was 0.00107408 units of SSB per recruit. The maximum average number of recruits from the Ricker SRR over the years 1978 to 2019 was estimated at 362,321,236. The calculated B_0 value was 389,162 t, and the corresponding initial $0.2B_0$ was estimated at 77,832 t.

The average number of recruits from the population model over the years 1978 to 2019 was estimated at 238,378,000. The calculated B_0 value was 256,037 t and the corresponding initial $0.2B_0$ was estimated at 51,207 t of SSB.

Since spring Herring recruitment has been shown to be mostly environment driven and not SSB dependent (Brosset et al. 2019; Turcotte 2022; Burbank et al. 2023b), the average number of recruits from the population model is preferred here over the SRRs as an indicator of an equilibrium or unfished number of recruits the stock is expected to produce over the range of environmental conditions the stock experienced over the time series. Hence, the reported candidate LRP from B_0 calculations (Initial $0.2B_0$) was 51,207 t of SSB.

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

1. The biomass corresponding to the biomass per recruit at $F_{0.1}$ multiplied by the average number of recruits:

$F_{0.1}$ was estimated at 0.68 for the initial year of the assessment period (1978). The SSB per recruit at $F_{0.1}$ was estimated at 0.153338 t. The average number of recruit over the assessment period was 238,378,000. The SSB corresponding to the SSB per recruit at $F_{0.1}$ multiplied by the average number of recruits was 25,109 t. The associated LRP (40%PA1BMSY$_{proxy}$), was 10,043 t of SSB.

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

Spring Herring production varied greatly over the 1978 to 2020 period (Figure 5). Production was low in 1978 and 1979 but increased in 1980. Production then gradually decreased until 1987. Production varied greatly between 1987 and 1992, with occurrences of high, intermediate, low and negative values. A few high recruitment years generated peaks in production around 1990, which was the highest production period the stock experienced. Production was mostly negative from 1993 and onwards except for a few years in the mid-2000s.

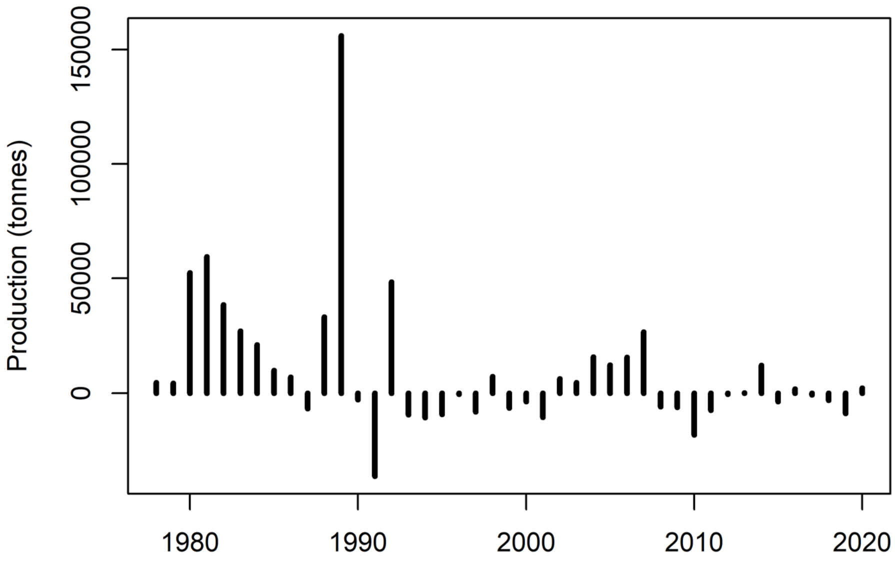

Figure 5: Southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring production (tonnes; black bars) between 1978 and 2020.

The production rate did not vary as a function of biomass over the time series (Figure 6). High and low values of production rates were estimated at high, intermediate and low values of biomass. Temporal aspects of the variation in production rates were identified, with the highest production rate values only observed in the earlier period of the time series. However, very low production rates were also observed in the same period. In recent years, biomass was low but production rates varied between low and intermediate values.

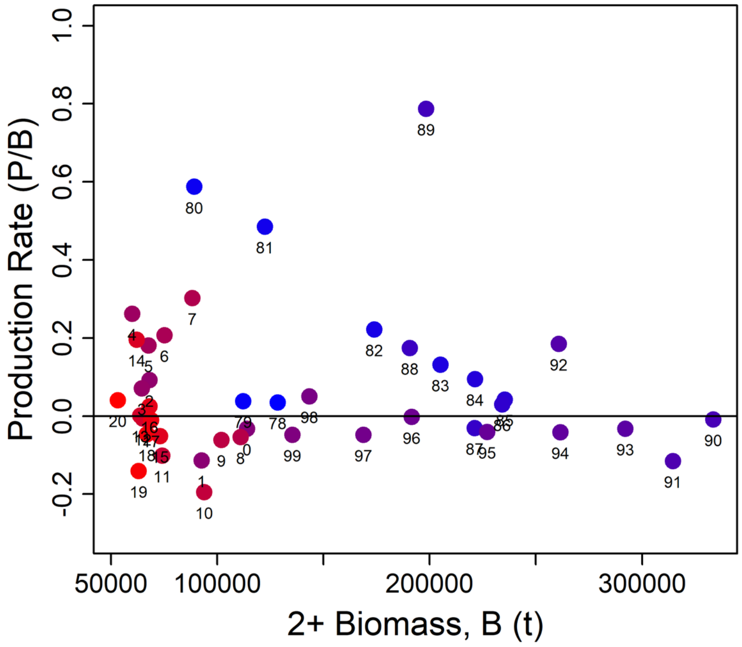

Figure 6: Southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring production rates (production per unit of biomass) in function of biomass (tonnes; t) between years 1978 and 2020. Colored points indicate years (1978; blue to 2020; red) with years labeled (e.g. 78 = 1978, 0 = 2000).

A low production-low biomass state seems to occur since the beginning of the 2000s where both biomass and production reached low levels and remained low afterwards (Figure 7). Production reached and stayed at low levels earlier, in the mid 1990s, both biomass was still high, although declining, at that time. Biomass stopped declining in 2004 when SSB reached 23 kt. Hence, the year of the onset of the low production-low biomass state can be defined as 2004.

$BMSY_{proxy}$ was defined as the average SSB in a high biomass high production period (Figure 7). The years 1988 to 1994 were selected as years with high production because of the high biomass and highest production peaks observed. The high volatility of production in this period is reflective of the high volatility in recruitment, which is typical of forage fish (Trochta et al. 2020). $BMSY_{proxy}$ was estimated from years 1988 to 1994 at 138,536 t of SSB. The corresponding candidate LRP, $40\%PA2BMSY_{proxy}$, was estimated at 55,414 t of SSB. The corresponding USR, $80\%BMSY_{proxy}$, was estimated at 110,828 t of SSB.

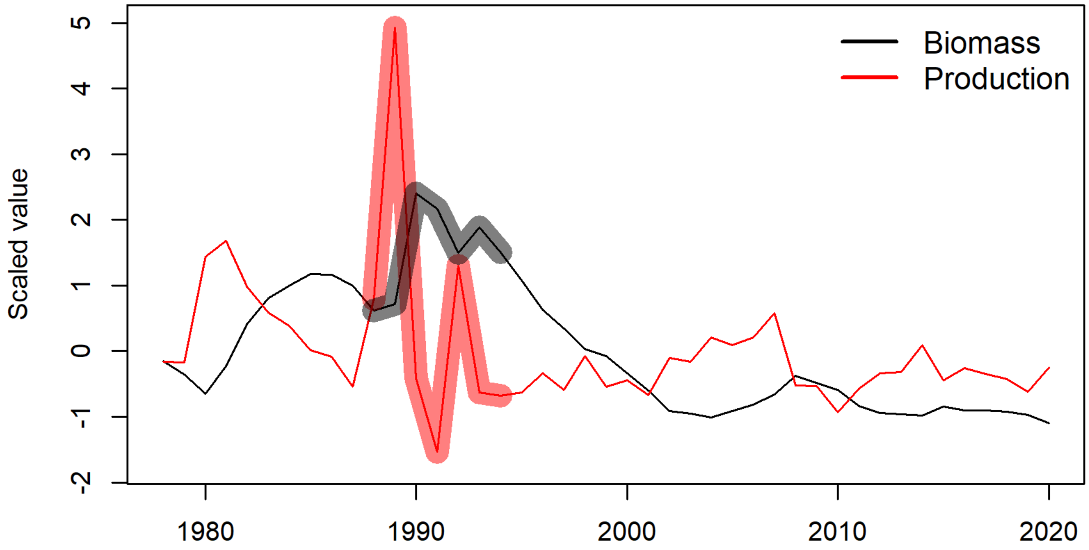

Figure 7: Scaled values of stock biomass (black line and shading) and production (red line and shading) between 1978 and 2020. The shaded areas indicate the selected high-biomass high-production years (1988-1994) used to estimate $BMSY_{proxy}$.

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

The SSB corresponding to 50% of the maximum historical biomass was 95,823 t of SSB. 40% of its value was 38,329 t of SSB ($40\%PA3BMSY_{proxy}$).

2.5. BEST CANDIDATE LRP EVALUATION

2.5.1. Serious harm

The sources of serious harm to sGSL spring Herring are multiple: environmentally-driven recruitment failure since 1992, a lasting state of low-production/low-biomass, high natural mortality, high fishing mortality during and after the stock decline, and declines in growth and fecundity.

The RK SRR suggest that spring Herring recruitment is impaired (declining number of recruits with declining SSB) when the SSB declines under 99,000 t. However, uncertainty around the

SRR parameter estimates is high, and spring Herring recruitment is environmentally driven (Brosset et al. 2019; Turcotte 2022; Burbank et al. 2023b). In Canada and other jurisdictions, recruitment overfishing is generally agreed to constitute serious harm (Myers et al. 1994; Shelton and Rice 2002). Recruitment overfishing occurs when the mature adult population is depleted to a level where it no longer has the reproductive capacity to replenish itself. The SSB at 50% of the theoretical maximum recruitment is usually used in Canada to identify a state of harm or to derive a LRP. However, these estimated values from spring Herring SRR are all below the observed SSB-recruitment pairs. As such, they cannot be used to define a credible point where serious harm occurred.

The spring Herring stock is highly recruitment driven (Turcotte 2022; this study section 4.1.3), but defining the point of serious harm or deriving a LRP when only analyzing recruitment dynamics is not well suited as recruitment is highly environment-dependent, and not biomass-dependent. Production data on the other hand, is well suited to define the point of serious harm, and in addition to accounting for recruitment dynamics, also accounts for the other sources of harm to the stock which include increased natural mortality, declining growth and decreased fecundity. As recommended in Hilborn (2001) and Walters et al. (2008), routinely conducting production analyses in stock assessments is highly informative, especially for stocks where variation occurs in various productivity metrics over time.

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 spring Herring population production and population biomass has not exhibited positive density dependence in the assessment time series. Hence, even with high natural mortality in older fish, no evidence points to the occurrence of an Allee effect for spring Herring.

The seemingly most important source of harm (and cause of the stock decline) for spring Herring is recruitment failure since 1992. However, as recruitment is mostly environmentally driven and independent of SSB, deriving a biomass state that would transfer in a biomass LRP from this source of harm would be inadequate. A more feasible option would be to define serious harm in terms of production. The occurrence of low production-low biomass (LP-LB) state over time is evaluated by inspecting the relationship between production and population 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 biomass (Kronlund et al. 2018). A LP-LB state as been identified with an onset in 2004 when SSB was estimated to be 23 kt and the stock has not recovered after reaching that level. Hence, this threshold could represent the point where serious harm occurred for spring Herring, a point to be avoided as the stock is not likely to be able to recover from. As such, the LRP should be set above it.

2.5.2. Candidate LRPs for 4TVn spring Herring

2.5.2.1. Current LRP

The current LRP, $B_{recover}$, was estimated at 46,000 t of SSB in the last assessment (Rolland et al. 2022). The stock recovered from this level of SSB in the early 1980s. However, the stock reached this same biomass in 2002 and has remained relatively stable near this level, yet has not been able to recover. Its value is above the level of serious harm.

The basis for $B_{recover}$ is stemming from a low level the stock was able to recover from, in opposition to the fraction of a reference, healthy state as B_{MSY} or B_0 LRPs are. As this stock recruitment is environmentally-driven, the biomass that produced the recruitment that allowed rebuilding in the early 1980s is not expected to produce similar recruitment in other conditions. Hence, while it is informative that the stock was once able to recover from this low level, $B_{recover}$ is only partially informative and this candidate LRP is given partial support.

2.5.2.2. LRPs based on SSB at 50% maximum recruitment

The BH and RK SRR model fits to the data were acceptable but the variability around the expected mean recruitment was very high. Recruitment was highly variable especially at the lower end of the observed SSB range, where very low to very high recruitment occurred. Very high recruitment events also occurred at mid-range of SSB, but only on two occasions. The B50%Rmax estimates from the SRRs were at the lowest of the range of the observed SSB values (RK), or lower (BH). For the RK model, very few points support the estimation of the B50%Rmax, and, the observed recruitment at the B50%Rmax are all above the expected values. Finally, the candidate LRPs from these models are all at or under the point of serious harm (the onset of the LP-LB state). Hence, there is no support for a LRP derived from the SRRs fitted to the whole time series. The RK models fitted to the two time periods identified by the regime shift analysis also displayed the same lack of support for the position of the SSB at 50%Rmax, and produced candidate LRPs that are below the point of serious harm. As such, they are also not supported.

2.5.2.3. LRPs based on the stock recruitment relationship (ICES guidance)

sGSL spring Herring matches one stock type 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 1: Spasmodic stocks – stocks with occasional large year classes.

The stock type description states: this group have unique biological characteristics which justify a specific approach. They exhibit some points well above the cloud of points in a stock–recruitment scatter plot. However, the time series are usually too short to establish the frequency of such rare events with any accuracy. Examples of such stocks are: most haddock stocks, Norwegian spring-spawning herring, and Western horse mackerel. Establishing biomass reference points for such stocks is often difficult because the population dynamic depends on the occurrence of strong year classes.

For this stock type, ICES recommends that the LRP be based on the lowest SSB where large recruitment is observed. A large recruitment event is not a unambiguous threshold, but the analysis of occurrence of recruitment events showed that the 1980 recruitment event could be considered the SSB at which a higher than usual recruitment event occurred. In that year, 41 kt of SSB produced 638 million recruits. However, the spring Herring stock has been at an SSB near or around 40 kt for most years since the early 2000s, and such a high number of recruits has not been produced in that time period. Hence, the ICES Type 1 stock LRP is not supported.

2.5.2.4. LRPs based on B0

Twenty to thirty percent B_0 has been suggested as a LRP that would avoid recruitment overfishing, with higher thresholds needed for lower productivity stocks (Beddington and Cooke 1983; Mace 1994; Sainsbury 2008). As a forage fish, spring Herring is theoretically highly productive, relying on its “boom” recruitment events to grow the population to high levels. However, productivity has been low since 1995 and recent recruitment values are all lower than either the maximum predicted recruitment from the SRR or the average recruitment estimated by the population model. Still, when compared to non-forage fish stocks, spring Herring would be considered a productive stock.

In a review of British Columbia Pacific Herring LRP methods, it was recommended that attention focus on reference points related to equilibrium unfished biomass to avoid the “ratcheting down” effect (Cox et al. 2019). Similarly for sGSL spring Herring, selecting years where production declined from the maximum or “unfished conditions”, produces continuously lower LRP as production declines. Hence, selecting initial assessment years (higher production years) as a baseline for the LRP reduces the potential for progressive lowering of conservation thresholds (Kronlund et al. 2018).

The B_0 calculations here are based on a proxy of the equilibrium number of recruits, not estimated by a SRR. Moreover, $0.2B_0$ is a proxy for recruitment overfishing and recruitment is not SSB-dependent. Hence, the support for this candidate reference point is only partial.

2.5.2.5. LRP based on MSYproxy from the DFO Precautionary Approach guidelines

1. The biomass corresponding to the biomass per recruit at $F_{0.1}$ multiplied by the average number of recruits:

$F_{0.1}$ methods tend to allow for higher F and when natural mortality is higher than 0.2 (the default at which these per recruit methods were developed). When there is strong evidence that natural mortality has increased over time, a method suggesting higher F thresholds as natural mortality increases should not be used to derive biomass or fishing reference points (Legault and Palmer 2015). The $40\%PA1BMSY_{proxy}$ candidate LRP is lower than the point of serious harm and is therefore not supported.

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

A period of high biomass and high production was identified where the catches and associated F (around 0.2) were stable and did not lead to a decline in SSB. The decline following this period was associated with reduced recruitment and decreasing weight-at-age. F values were also observed to increase, but only after SSB had already started to decline. Hence, the higher F values are a result of stable removals concurrent with declining SSB. F is not believed to be the cause of the early decline in SSB observed in 1995. As such, the 1988-1994 SSB can be used as a proxy for the SSB at maximum sustainable yield. Hence, the associated candidate LRP $40\%PA2BMSY_{proxy}$ (55,000 t of SSB) is supported.

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

This candidate LRP ($40\%PA3BMSY_{proxy}$) is not supported as: (1) the second method from the suggested PA guidelines was supported and the process should stop there as the first feasible option criteria was met, and (2) the LRP value from this method would be very low, without any reasonable biological or stock specific justification. As such, it is quite data-poor and its robustness cannot be properly evaluated.

2.5.2.6. Best LRP

Three candidate LRPs received at least partial support, with the $40\%PA2BMSY_{proxy}$, estimated using the second $BMSY_{proxy}$ method from the PA receiving full support (Table 1; Figure 8). As the $40\%PA2BMSY_{proxy}$ was the only method receiving full support, it should be selected as the LRP for spring Herring. Estimated LRP values from the supported candidate methods ranged from 46,000 to 55,000 t of SSB. The fact that the supported methods produce a similar LRP provides lends support to the selected method and best candidate LRP.

Stock status should be communicated as a ratio of indicator to LRP (or to B_{MSY}, B_0, etc.) instead of absolute estimates, especially where estimated stock status is sensitive to changes in scale in successive assessments. The supported LRP for sGSL (NAFO 4TVn) spring spawning Herring is $40\%BMSY_{proxy}$ (where $BMSY_{proxy}$ is the average SSB in years 1988 to 1994), estimated from the population model. As such, the value of the LRP is model-dependent and will change with as data is added to the assessment or the assessment model is changed. The value of the LRP estimated here was 55,000 t of SSB.

The LRP meets the best practice principles identified in DFO 2023:

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 based on a proxy for B_{MSY} which relates to the loss of surplus production, which was identified as a source of serious harm for this stock.

Principle 3: Should be feasible and relevant. The LRP is 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 (based on years 1988-1994). The LRP is plausible, a weight-of-evidence approach was used to select the most plausible LRP and the three best candidate LRPs converged around similar values.

Table 1: Candidate limit reference points (LRP), their estimated value in tonnes of spawning stock biomass (SSB; model-dependent values) 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 (Brecover)	46,000	1
ICESType1Stock	40,000	0
RKB50%Rmax	24,000	0
RKB50%RmaxShift1	17,000	0
RKB50%RmaxShift2	21,000	0
BHB50%Rmax	15,000	0
HSB50%Rmax	12,500	0
40%PA1BMSYproxy	10,000	0
40%PA2BMSYproxy	55,000	2
40%PA3BMSYproxy	38,000	0
0.2B0	51,000	1

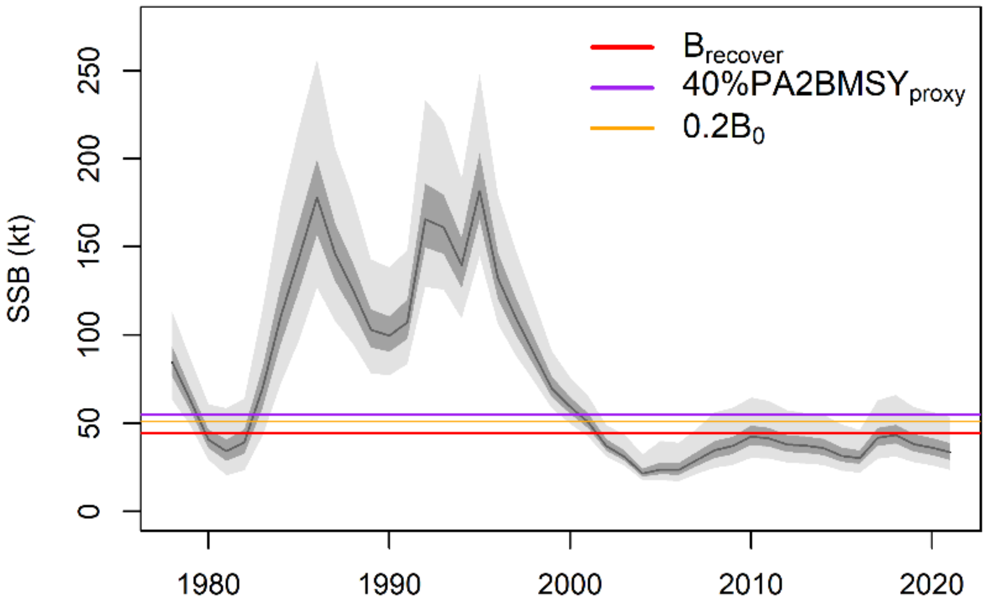

Figure 8: Current and candidate limit reference points for southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring where partial or full support was received; $B_{recover}$ (current LRP; red solid line), $40\%PA2Bmsy_{proxy}$ (purple line) and $0.2B_0$ (orange line). Black line is the median spawning stock biomass (SSB) estimate (kilotonnes; kt) and dark and light grey shading are the 50% and 95% confidence interval, respectively.

2.5.2.7. LRP in other Herring stocks

Other jurisdictions faced similar issues when exploring methods to derive a LRP for Herring stocks. The main uncertainties identified were: (i) uncertainty in the nature of the stock recruitment relationship and the poor recruitment predictability from these; and (ii) time-varying productivity and changes in growth, natural mortality, maturity, and recruitment all generate violations of equilibrium assumptions on which most reference points methods are based.

ICES uses the breakpoint of a segmented regression stock recruitment relationship as B_{lim} (ICES equivalent of the LRP) for Norwegian spring spawning Atlantic Herring. However, major concerns were expressed about the lack of fit to the data, the highly spasmodic nature of recruitment in this stock (and thus the ICES stock Type identification and suitability of associated methods), and recruitment in recent years being consistently under the stock recruitment curve (ICES 2018).

Pacific Herring assessed by DFO is under conditions very similar to sGSL spring spawning Atlantic Herring: stock collapse, decline in weight-at-age, increased natural mortality, LP-LB state, and lack of recovery. A thorough review of the applicability and suitability of methods for this stock identified similar issues as in this study, with equilibrium based methods for a stock with such highly variable productivity that violates the assumptions behind the methods. The recommendation for a LRP was to use the upper bound of the LP-LB state as a point of serious harm. $0.3B_0$ was then suggested as a LRP as it corresponded to the upper bound of the LP-LB state for the stock (Kronlund et al. 2018).

NOAA historically used a Beverton-Holt stock recruitment relationship-based LRP for Atlantic Herring, but a recent assessment found the relationship to be spurious. The assessment then used a proxy for F40%. Many issues were identified with the associated reference points as M is thought to have varied but is not estimated in the model and recruitment in the last decades has been systematically lower than predicted by equilibrium conditions (NOAA 2018).

NAFO 4VWX Atlantic Herring assessed by DFO uses the average biomass observed in five consecutive years of low biomass in an acoustic survey as the LRP (Clark et al. 2012). Other DFO Atlantic regions do not have a LRP due to the absence of population models or accepted survey-based methods for their respective Atlantic Herring stocks (Newfoundland [Bourne et al. 2023]; 4R [DFO 2022]; 4S [DFO 2021b]).

2.6. USR, TRP, RR AND HARVEST CONTROL RULES

2.6.1. Upper Stock Reference and Target Reference Point

The $PA2BMSY_{proxy}$ method allowed the derivation of a LRP, a USR and a TRP as suggested by the PA. The USR ($80\%PA2BMSY_{proxy}$) was estimated at 110,000 t of SSB and the TRP ($PA2BMSY_{proxy}$) was estimated at 138,000 t of SSB (Figure 9). While determining the LRP is the role of DFO Science, determining the USR and TRP are DFO Resource Management's role. Here, the default PA framework USR ($80\%BMSY_{proxy}$) and TRP ($BMSY_{proxy}$) are proposed as quality candidates for these reference points and can be used in the interim until other USR and TRP are adopted. As they are estimated using the method used to derive the LRP, and are based on a productive period with high SSB and stable catches where the stock did not decline, these candidates are assessed to be quality proxies for SSB at MSY and could be used to manage the stock.

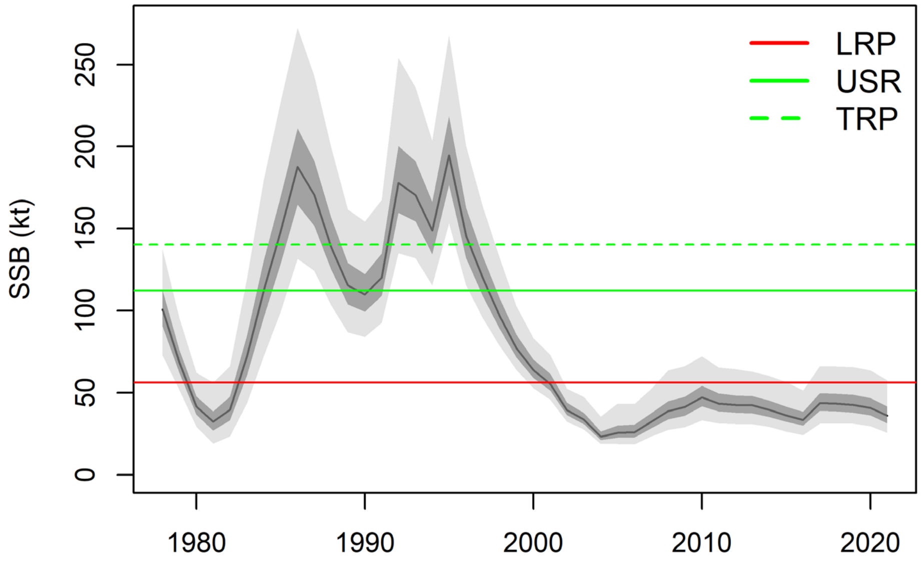

Figure 9: Southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring Precautionary Approach reference points (Limit Reference Point; LRP, red line, Upper stock Reference; USR, solid green line and Target Reference Point, TRP, dashed green line) based on the $PA2BMSY_{proxy}$. Black line is the median spawning stock biomass (SSB) estimate (kilotonnes; kt) and dark and light grey shading are the 50% and 95% confidence interval, respectively.

2.6.2. Removal Reference

The removal reference needs to be re-evaluated as $F_{0.1} = 0.35$ was calculated with a natural mortality level of 0.2, which used to be the default in most stock assessment due to the difficulty of estimating natural mortality, or time-varying natural mortality. Counter-intuitively, when natural mortality is increasing, $F_{0.1}$ methods suggest a higher removal reference to attain a given yield before fish are lost to natural mortality. Such harvest strategies pose a high risk and could lead to crashing the stock (Legault and Palmer 2015).

To illustrate how the productivity dynamics of this stock affect the $F_{0.1}$ estimation, yearly values of $F_{0.1}$ were calculated using annual vectors of natural mortality, weight, selectivity and maturity at age (Figure 10). The yearly $F_{0.1}$ values using the natural mortality values estimated by the population model are always greater than $F_{0.1} = 0.35$ (estimated using $M = 0.2$), and increases to $F_{0.1}$ values greater than 1 or 2 as M increases and the stock is collapsed post 2000s. In the 1990-1994 period, the high production high biomass period used to derive the LRP, the $F_{0.1}$ value is 0.73. This very high $F_{0.1}$ value is driven by the natural mortality values of 0.4 for the older age group for this period.

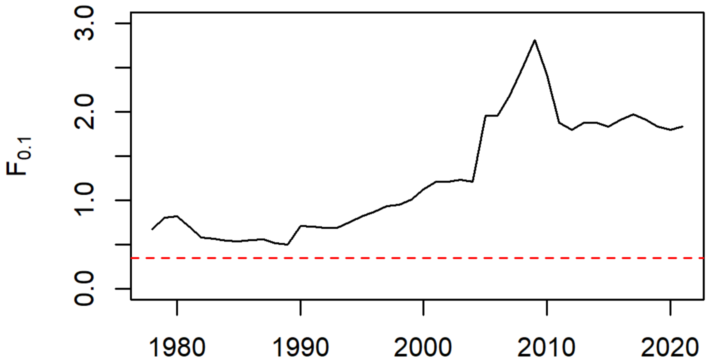

Figure 10: Annual $F_{0.1}$ values obtained using annual vector of time-varying inputs to the calculations (black line). The red dashed line shows the actual removal reference.

Using fixed parameters (weight-at-age, selectivity and maturity) from 1978 and theoretical natural mortality values between 0 and 1 illustrates the isolated effect of M on $F_{0.1}$ estimates (Figure 13). When natural mortality increases for all ages, the yield per recruit methods suggest higher fishing removal reference (Figure 13). Hence, the choice of years used to derive the removal reference point or the assumptions on natural mortality used in the methods will have a big influence on the results and is inappropriate to use when natural mortality changes (departs from 0.2) over the assessment period particularly given the magnitude of change observed in this stock.

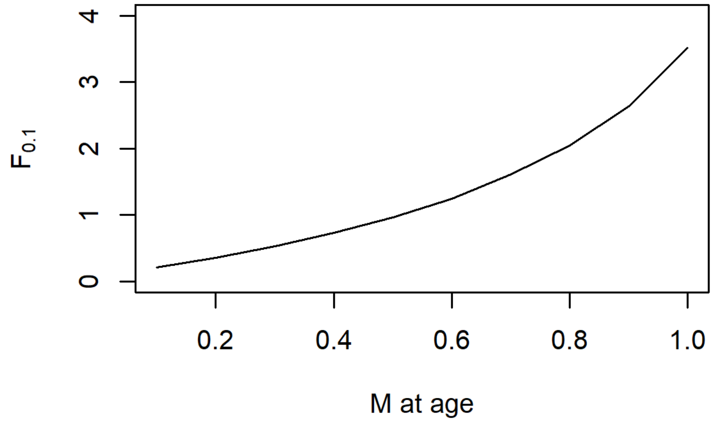

Figure 11: Theoretical $F_{0.1}$ values when natural mortality (M) for at age increases between 0 and 1 for spring spawning Atlantic Herring. Other inputs were fixed to isolate the effect of changing M on $F_{0.1}$.

If the stock was to rebuild to a biomass level that is close to a theoretical B_{MSY} level, population projections could be used to find the F level that maximizes the yield without causing the stock to crash (F_{MSY}). However the effect of this F value on stock trajectory is highly dependent on recruitment and natural mortality conditions, which cannot be predicted years ahead. The other way to estimate F_{MSY} would be to use historical stock metrics but non-stationarity in adult mortality, growth and stock recruitment in this stock violate the assumptions of equilibrium behind reference point calculation using fishing rate analyses, as stated in general by Hilborn (2002) and Hilborn and Stokes (2010).

In absence of an estimate of F_{MSY} from an explicit model, the PA provisional estimate of F_{MSY} could be taken as follows (select the first feasible option):

- the fishing mortality corresponding to $F_{0.1}$;
- the average fishing mortality (or an index of fishing mortality) that did not lead to stock decline over a productive period; or
- the fishing mortality equal to natural mortality inferred from life history characteristics of the species.

As demonstrated above, $F_{0.1}$ is not an appropriate removal reference for this stock. The second default PA option, however, is feasible. A period of stable F between 1988 and 1992 (mean F = 0.21) coincided with the period of high biomass and high production used in the LRP determination (Figure 12). The criteria for this stable F to be considered for a removal reference is that it did not lead to a stock decline. The stock did start to decline in 1996, 4 years after this period of stable F. However, the production and recruitment data clearly shows that recruitment failure since 1992 initiated this decline, not F. F increased as SSB started to decline and catch values remained high as SSB was declining, thus exacerbating the decline.

No other period of stable F was observed in the time series that did not lead to a decline. Other periods showed very high F in periods of decline or very low F in period of collapsed stock. The third option from the PA (RR = M) is also inappropriate for a stock with such natural mortality variations and extreme values. Furthermore, the second default PA option was deemed feasible hence, there is no need to explore the third option further.

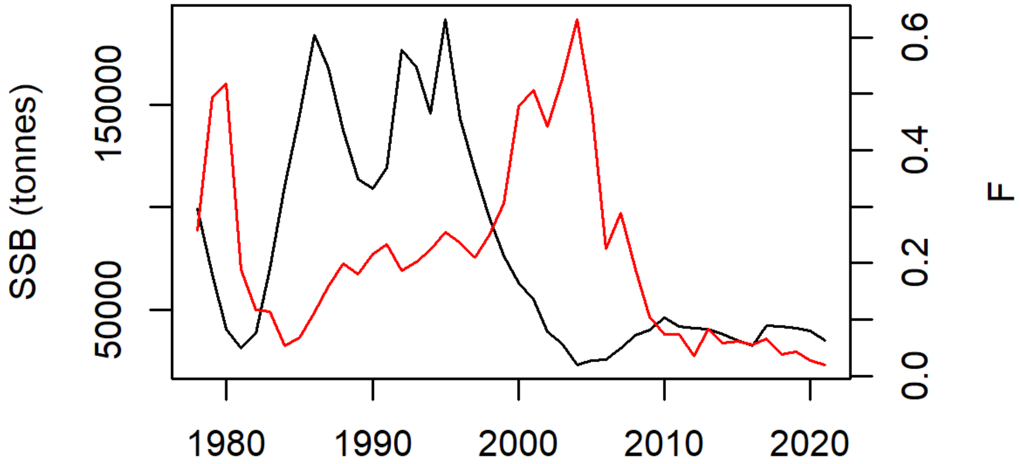

Figure 12: Spawning Stock Biomass (SSB; left axis and black line) and fishing mortality (F; right axis and red line) between 1978 and 2021 for southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring.

The suggested removal reference for spring Herring is then $FMSY_{proxy} = 0.21$. Figure 13 shows the PA harvest control rule resulting from the updated reference points presented in this document.

Overall, the PA provides a means to reduce the harvest level of a stock when the biomass is declining, based on average conditions or with respect to a fixed period of productivity. However, the stock is almost never under these conditions. Hence, making TAC recommendations based on the PA is not ideal in stocks with high variation in productivity. Population projections from the assessment model offer the predicted stock response to future harvest levels in a way where the risk associated with a future TAC is more precise as it is reflective of the conditions the stock is currently experiencing (e.g., for spring Herring projections are made using the last 5 years of M, recruitment, growth, etc.). If the stock was to reach the rebuilding target and harvesting was to resume, the projections of the population model should be used to evaluate the likelihood of attaining an objective x under various harvesting scenarios. As the advice for this stock is provided every 2 years, projections can be used to advise on which TAC provides a likelihood *x* of maintaining SSB at a desired level for *y* number of years, irrespective of the stock position relative to the PA.

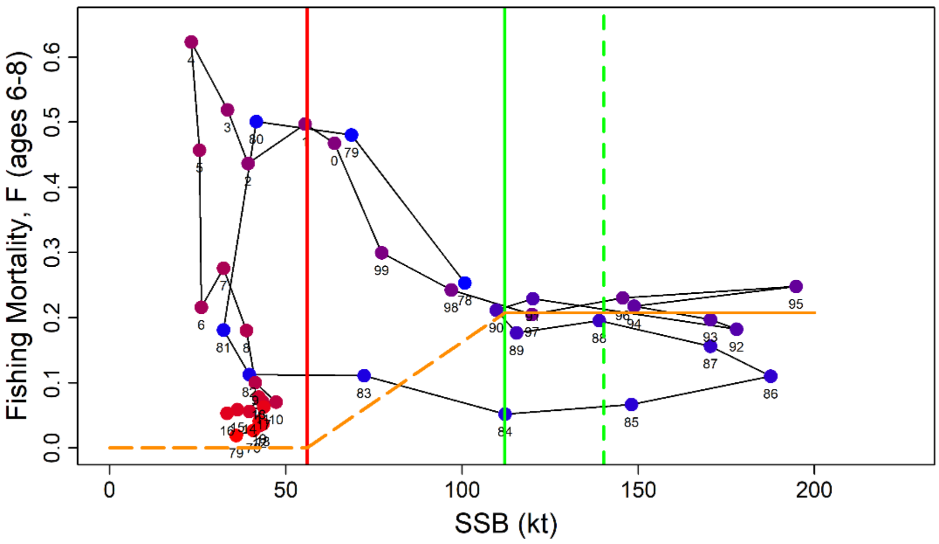

Figure 13: Proposed southern Gulf of St. Lawrence spring spawning Atlantic Herring harvest control rule. X axis is spawning stock biomass (SSB; kilotonnes (kt)) and y axis is abundance weighted fishing mortality rates (F) for ages 6 to 8 years. The red vertical line is the LRP, the green vertical line is the proposed Upper Stock Reference (USR), and the green vertical dashed line is the Target Reference Point (TRP). The orange solid horizontal line is the removal rate reference value ($FMSY_{proxy}$ = 0.21) in the Healthy Zone and the orange dashed line is the provisional harvest decision rule of the Precautionary Approach Framework in the Cautious and Critical Zones. Point labels are years (83 = 1983, 0 = 2000).

2.7. STOCK STATUS AND TRENDS

Using the proposed reference points from this study, the stock status in 2021 did not change from the previous assessment, the stock was in the Critical Zone. There was a change in the estimated year when the stock crossed the LRP to the Critical Zone which was 2001 with $40\%BMSY_{proxy}$ versus 2002 with $B_{recover}$ (Figure 9).

The stock was in the Cautious Zone at the beginning of the time series (1978 and 1979) and declined below the LRP into the Critical Zone in 1980. In 1983, the stock increased above the LRP into the Cautious Zone, before crossing the USR into the Healthy Zone only one year later in 1984. The stock remained in the Healthy Zone for 13 years before declining below the USR into the Cautious Zone in 1998. The continued to decline until it stock crossed the LRP into the Critical Zone in 2001, where it has since remained. Fishing mortality was above the $FMSY_{proxy}$ removal reference for all years except from 1984 to 1989 and years 1992, 1993, and 1997 (Figure 13).

The probable causes of stock decline are multiple, as identified in the serious harm analysis presented above. However, environmentally-driven recruitment failure since 1992 (Turcotte 2022) seems to be the main factor in the stock decline observed in the 1990s. Recruitment abruptly declined post-1992 and could be considered a point where serious harm occurred in this stock. Moreover, many stock productivity components gradually deteriorated over the assessment period, without having a clear breakpoint when the stock collapsed but these also likely contributed to the decline. Older fish survival declined and their predation-driven natural mortality increased continuously between the 1990s and late 2000s. Growth and fecundity also declined gradually over the time series. Stock production is a metric that encompasses all of the above-mentioned stock characteristics. Spring spawning Herring production was very high in 1994 when the 1990 year class entered the spawning population, but dropped to negative production in 1995 as recruitment failed. Production has since remained close to zero. Hence, the probable cause of stock decline is the lack of production since the early 1990s with recruitment failure being the likely biggest contributor.

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 spring spawning Herring stock is assessed using a statistical catch at age 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 also 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 2021a). The current rebuilding target selected for this stock of being at or above the LRP with 75% certainty is close to the LRP, as the uncertainty in SSB estimates for this stock can be considered low. 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. However, due to the occurrence of highly spasmodic recruitment events that allowed the stock to either rebuild from low levels in the early 1980s or alternatively the stock has declined drastically from high to low abundance in the 1990s, both in one to two years, it is difficult to state that high abundance is a guarantee for a low probability of a decline in the near future. Even if the rebuilding target was set very high, the probability of falling below the LRP in the short to medium term would never be considered low. If this rebuilding target is retained by Fisheries and Harbour Management, it may be important to consider including additional considerations to the target such as; the stock must be at or above the rebuilding target for 2 consecutive years, and population projections must show the stock is likely to continue its positive trajectory under harvest for 2 years after the rebuilt state has been achieved. Two 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 shown in recent stock assessments, the stock is unlikely to rebuild to the rebuilding target under prevailing conditions, even in the absence of fishing mortality (Turcotte 2022; Rolland et al. 2022). If T_{min} cannot be calculated an estimate of an alternative such as generation time, as to be provided by DFO Science can be used by Fisheries and Harbour Management to define a rebuilding timeline. The generation time of both spring and fall Herring stocks in the sGSL have recently been analyzed in Burbank et al. (2023a). The results indicate a temporal reduction in generation time of spring Herring. Over the time series, the generation time of spring Herring has decreased by approximately 1 year. The average generation time of spring Herring across the time series was estimated at 6.23 years (95% CI: 5.78–6.85 years). Generation time estimates reached a maximum of 6.99 years (6.31–8.01 years) in 1990 and then consistently declined to a minimum of 5.66 years (5.18–6.34 years) in 2003. Following 2003, the generation time estimates for spring Herring fluctuated around 6 years. 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 REACHING THE REBUILDING TARGET UNDER VARIOUS PRODUCTIVITY AND/OR MANAGEMENT SCENARIOS

4.1. PRODUCTIVITY SCENARIOS

In the absence of fishing, natural mortality and recruitment are the two main drivers of the sGSL spring Herring population and their dynamics have been identified as environmentally-driven (Brosset et al. 2019; Turcotte et al. 2021a; Turcotte 2022; Burbank et al. 2023b). The objective of the following analysis was to identify the contribution of each process to the likelihood of stock rebuilding, and to determine 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. The assessment model for spring Herring are used to project the population forward and assess the likelihood of reaching a SSB target. Scenarios of future natural mortality levels, recruitment rates and their combinations were modelled using the projection function of the assessment model. The population was projected forward during the MCMC sampling, taking into account uncertainty in parameter estimates.

4.1.1. Natural mortality scenarios

For the 2-6 age group, natural mortality decreased slightly between 1978 and 2021 (Rolland et al. 2022). For the 7-11+ age group, natural mortality increased gradually in the period covered by the assessment, to reach the highest values in the recent decade. The increase in natural mortality of older Herring was identified as likely to be predation-driven. Herring is prey to numerous predators in the sGSL (Benoît & Rail 2016), but the increased natural mortality of Herring correlated strongly with the concomitant increase in abundance of Atlantic Bluefin Tuna, Grey seal and Northern Gannet, three of the most important predators in terms of consumption (Rolland et al. 2022). The future natural mortality scenarios were developed by examining historical natural mortality levels experienced by the stock.

Three future natural mortality (M) scenarios were modelled:

1. Recent M: In this scenario, current estimates are assumed to be representative of future estimates, which is the method used to project the population in the stock assessment. Projected M for age groups 2-6 and 7-11+ were set as the average M values in the last 5 years of the assessment (2017 to 2021; 0.27 and 0.92, respectively).
2. Decrease M: projected M for the age group 2-6 was set as the average M values in the last 5 years of the assessment (2017 to 2021; 0.27). Older fish M was gradually decreased over time at the same rate it was estimated to have increased between the years 1978 and 2018 (minimum and maximum M years). Projected M for the age group 7 to 11+ was set as a declining trend, using the 2021 value as the initial value. Projected M in the next year t+1 was calculated as 0.9808434 of M in the previous year t. M values used in projections declined from 0.88 in 2022 to 0.50 in 2051. This scenario was built to assess the effect of a potential return to lower M values for older Herring, using values that were once experienced by the stock.
3. Increase M: projected M for age groups 2-6 and 7-11+ were set as a 25% increase of the average M values in the last 5 years of the assessment. As the value of M is relative to the value of SSB, it is possible that M will continue to increase as SSB declines because predator consumption is constant. Also, predator abundance could increase, their distribution could change or the predator-prey functional responses could change and increase Herring M. Projected natural mortality values were 0.34 for the group age 2-6 were 0.34 and 1.15 for the 7-11+ age group.

4.1.2. Recruitment scenarios

High recruitment events in spring Herring have occurred at both high and low SSB values, either allowing the stock to quickly rebuild (early 1980s) or to maintain high SSB (late 1980s and early 1990s). The variability in recruitment was very high over the beginning of the time series; Herring are generally more likely to have very large recruitment events than non-forage fish and overall to display greater variability in recruitment (Trochta et al. 2020). Spring Herring recruitment has exhibited less variability since 1992, with a long period of recruitment failure and few strong year classes. Spring Herring recruitment dynamics are strongly environmentally driven (Brosset et al. 2019; Turcotte 2022; Burbank 2023b), and displayed a regime-like behavior with both the sea surface temperature of the sGSL and the spring spawning Herring recruitment abruptly shifting from a cold water/high recruitment regime to a warmer water/low recruitment regime in the early 1990s (Turcotte 2022). Hence, three scenarios of future recruitment were modelled:

1. Recent R: recruitment values were randomly selected from the last 5 years of the assessment period. This scenario did not allow for the extreme high recruitment rates observed before 1994 to be selected, and is reflective of recent environmental conditions leading to recruitment. It is also the projection method used for the stock assessment. The average projected recruitment values were 133 million fish for the recent recruitment scenario (SD = 3 million fish).
2. Intermediate R: recruitment values were randomly selected over the stock assessment period, allowing for both high and low recruitment events to occur. This scenario allowed to project the population forward in a scenario were the very good recruitment conditions would occur periodically. The average projected recruitment values were 257 million fish for the recent recruitment scenario (SD = 11 million fish).

3. High R: recruitment values were randomly selected over the assessment time period were high recruitment events occurred (1978 to 1994). The average projected recruitment values were 305 million fish for the high recruitment scenario (SD = 18 million fish).

4.1.3. Population projections

All projections were performed for 30 years. Projections used weight at age vectors randomly selected over the last 5 years, which is consistent with the spring Herring stock assessment (Rolland et al. 2022). 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.

Without fishing and under current condition of recruitment and natural mortality, the stock is not expected to recover (Figure 14). If M was to increase at current recruitment conditions, SSB would stabilize at a lower state than the actual state. More interestingly, even if older Herring (ages 7-11+) M was to decline to low historical levels, the stock would not rebuild under current recruitment conditions (Table 2; Figure 14). For the stock to rebuild above the LRP with a 75% probability, recruitment needs to increase in a scenario where high recruitment events occurs more frequently (Intermediate or High R scenarios). In a scenario where recruitment increases to intermediate levels, rebuilding could occur within 6 years at current or lower M conditions. If recruitment was to increase to high levels, rebuilding would occur at all M levels, within 5 to 6 years. In all scenarios, higher recruitment levels than observed in the last decades are required for spring Herring to rebuild (Table 2; Figure 14).

High recruitment events in spring spawning Herring have occurred at both high and low SSB values, either allowing the stock to quickly rebuild (early 1980s) or to maintain high SSB (late 1980s and early 1990s). The occurrence of these high recruitment events is quite rare, as only three years of high recruitment has been observed during the 44 years of the assessment period. Moreover, these events all occurred before 1992 as spring Herring recruitment abruptly shifted from a cold water/high recruitment regime to a warmer water/low recruitment regime (Turcotte 2022). As spring Herring recruitment is highly environmentally-driven and considering the changes in oceanographic and productivity conditions of the sGSL, the conditions favoring high spring Herring recruitment are unlikely to occur again (Brosset et al. 2019; Turcotte 2022; Burbank et al. 2023b). Hence, the rebuilding scenarios that allowed the stock to rebuild (High and Intermediate R) shown in this study are highly unlikely to occur.

Changes in natural mortality had a lesser effect on the probability of rebuilding the spring Herring stock. In all natural mortality scenarios, intermediate or high recruitment was needed for the stock to rebuild to the target. Spring Herring natural mortality is mostly predation-driven, and its predators are numerous. Predator abundance is not expected to change abruptly, as population dynamics of large bodied predators is more likely to occur over a long period of time.

Table 2: Year where rebuilding target is reached for different natural mortality and recruitment scenarios from population projections starting in 2022.

Recruitment scenario	Natural mortality scenario	Years needed to rebuild
Recent	Recent	-
Recent	Low	-
Recent	Increase	-
Intermediate	Recent	6
Intermediate	Low	6
Intermediate	Increase	-
High	Recent	5
High	Low	5
High	Increase	6

Since spring Herring is prey to numerous predators, modelling the effect of changes in single predators is not feasible using the available assessment framework, or with the current available data. However, modelling changes in M is appropriate as it is largely the result of the combination of the predation pressure by all predators at once. Predator abundance, distribution, behavior and functional response can all change over time, and independently for each predator. Hence, future spring Herring M is highly uncertain and scenarios used here were only used to show the effect of changes in M and the M levels required to rebuild the stock. The scenarios do not reflects potential trends in any of the many Herring predators. However, Atlantic Bluefin tuna (Hanke 2021), Northern Gannet (Rail 2021), and Grey seal (Hammill et al. 2023) abundance in the sGSL have plateaued in recent years. Hence, an increase in spring Herring M is less likely, even though it could still occur if any of the other predator processes change, or if Herring biomass declines further. Overall, spring Herring M levels are likely to remain at current levels in the near future. Hence, the current M scenario is most likely and does not indicate the spring Herring stock will rebuild in the near future.

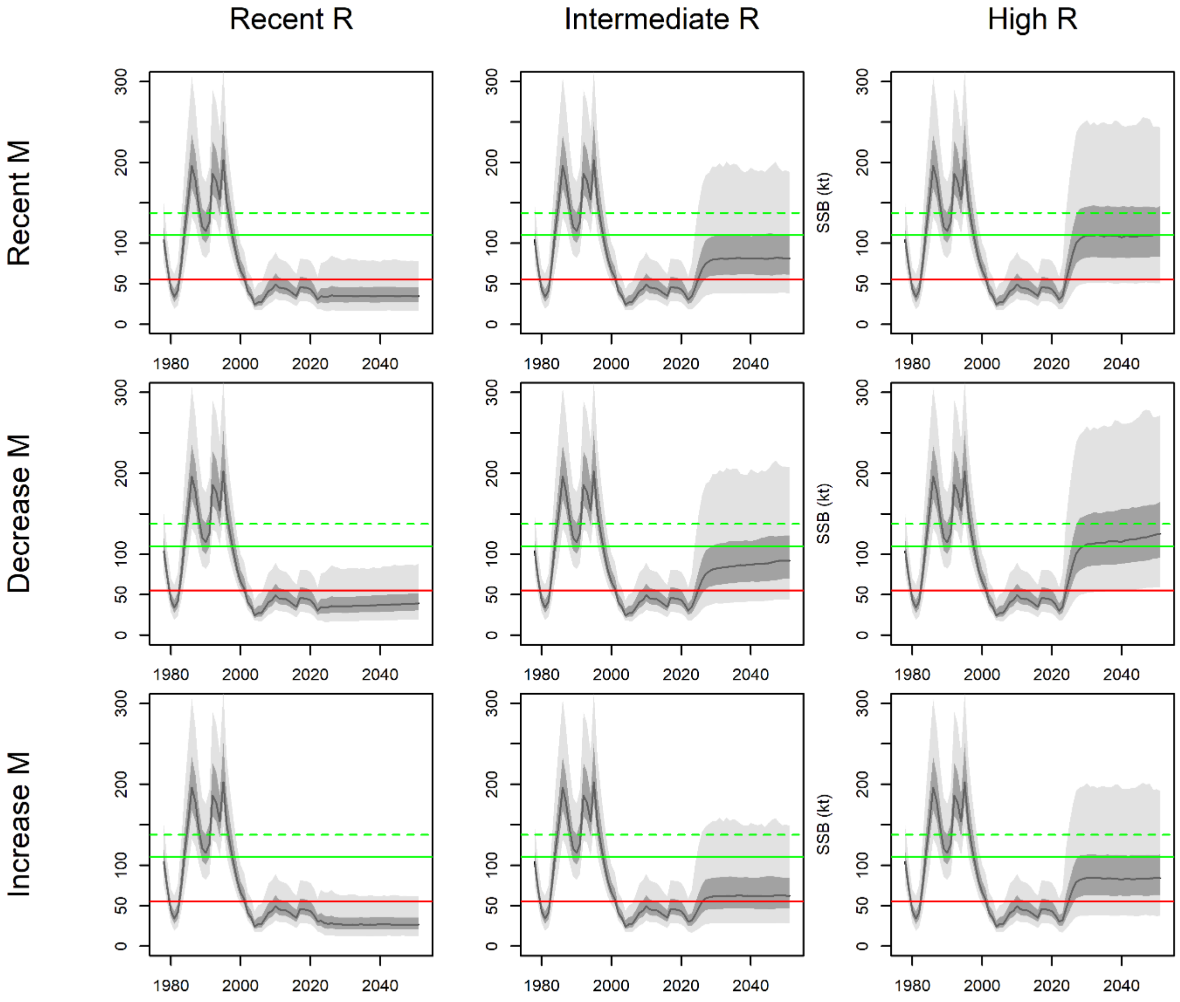

Figure 14: Estimated spawning stock biomass (SSB, kt) for years 1978 to 2021, and projected SSB for three future recruitment scenarios for years 2022 to 2051: recruitment from the first 16 assessment years ("High R", left column), recruitment from the last 5 assessment years ("recent R", middle column) and recruitment from all assessment years ("Intermediate R", right column), for three natural mortality scenarios: average natural mortality from the last 5 assessment years ("Recent M", top row), natural mortality from the first 5 assessment years ("1978-1982 M", middle row) and a 25% increase of the recent natural mortality ("Increase M", bottom row). The red line is the limit reference point, the green solid line is the upper stock reference and the green dashed line is the rebuilding target, 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 MEASURES

Since spring Herring are unlikely to rebuild under prevailing conditions, the management measures are aimed at preserving the stock such that should prevailing conditions improve, the stock retains the potential to rebuild. A TAC of 50 t remains to allow for bycatch in the seine fishery (25 t) and for scientific purposes (25 t).

4.2.1. Minimize 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 restriction on catches. The primary management measure proposed in the spring Herring rebuilding plan is to keep removals to the lowest level by continuing to implement and/or develop new management measures on all fisheries that direct for, or intercept, spring Herring. Assuming that the directed commercial fishery and the fixed gear bait fishery in the spring season remain closed, the main catch of spring Herring is bycatch from the commercial fall season mobile and fixed gear Herring fisheries as well as the presumed minor fall bait fishery (see Section 4.2.2).

Throughout the time series, bycatch from the fall season fishery catch has typically been greater in the mobile gear fishery than in the fixed gear fishery (Table 3). The fall mobile gear fleet consisted of catches ranging from a high of 12,036 t in 1988 to 7 t at the lowest in 2022 (with the exception of 2021 when the mobile gear fleet did not fish; Table 3). In contrast, bycatch in the fall fixed gear fishery has been as high as 3,181 t in 1986 and as low as 1 t in 2013 (Table 3). Spring Herring have been below the LRP since 2002 and bycatch of spring Herring in the fall fisheries have averaged 100 t in the fixed gear fishery and 575 t in the mobile fishery since that time (Table 3; Figure 15). The proportion of the fall mobile fishery that is spring Herring bycatch has averaged 24.8% since 2002, whereas the proportion of bycatch in the fall fixed gear fishery has been much smaller at 2.5% (Figure 15). The fall mobile fishery tends to capture younger spring spawning Herring dominated by ages 3 to 6, while the fall fixed gear fishery captures predominately ages 6 to 8 (Figure 16). In recent years, fishing activities have decreased in the mobile gear fishery including not fishing in some years, while participation in the fixed gear fishery has remained consistent. Bycatch in the fall fixed gear fishery is greatest in the South and North regions with minimal contribution from the Middle region (Figure 17). Spring Herring bycatch in the fixed gear has predominantly occurred in the South region in recent years.

Table 3: Landings (in tonnes) of southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring in the fall Atlantic Herring fisheries by gear (fixed and mobile).

Year	Fixed gear	Mobile gear
1978	175	11,016
1979	325	7,643
1980	545	9,044
1981	293	589
1982	292	574
1983	423	1,466
1984	303	895
1985	1,287	2,154
1986	3,181	6,773
1987	2,538	9,460
1988	2,843	12,036
1989	1,691	8,778
1990	2,146	6,756
1991	178	3,319
1992	322	3,327
1993	780	3,741
1994	481	3,357
1995	2,102	7,671
1996	1,365	3,977
1997	98	3,627
1998	121	1,418
1999	176	3,770
2000	706	2,324
2001	736	2,986
2002	673	704
2003	37	449
2004	122	410
2005	14	1,084
2006	293	745
2007	10	2,414
2008	35	1,473
2009	70	519
2010	2	595
2011	18	664
2012	68	259
2013	1	547
2014	132	429
2015	3	565
2016	45	146
2017	215	42
2018	99	262
2019	44	518
2020	16	245
2021	17	-
2022	183	7

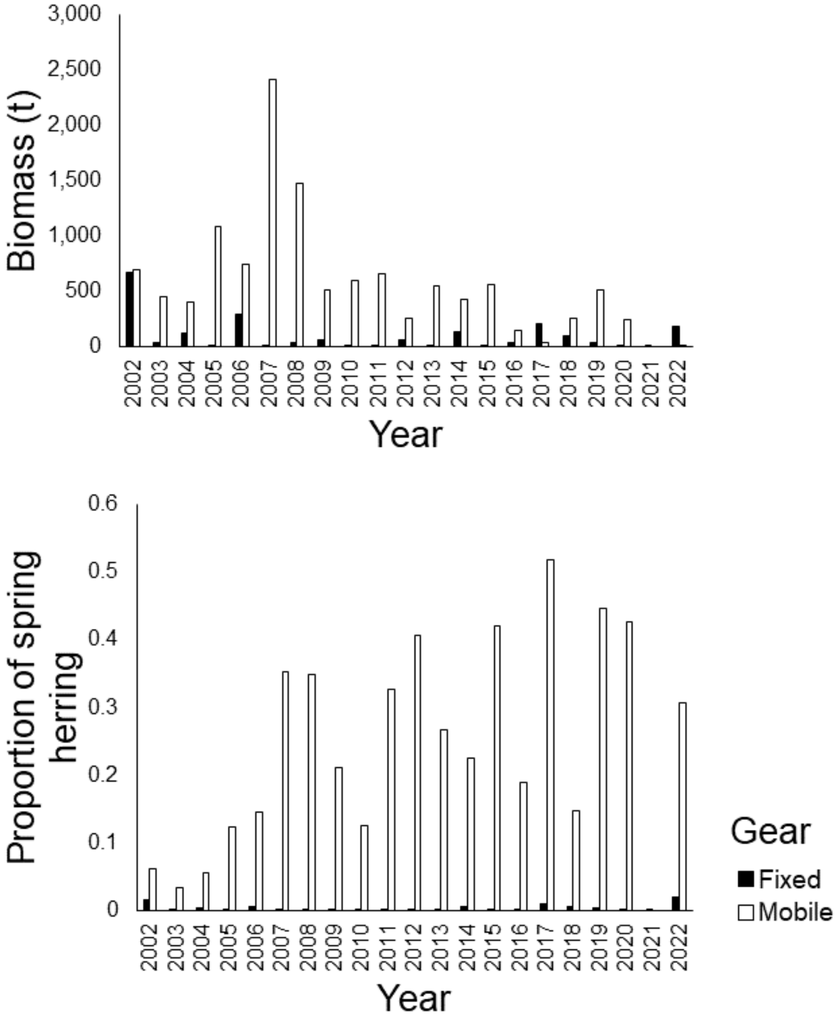

Figure 15: Biomass (tonnes) of southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring caught in the fall season fixed and mobile gear Herring fisheries (upper panel) and the proportion of bycatch that this biomass represent (lower panel) for the period of time the stock has been in the Critical Zone of the Precautionary Approach (2002 to present).

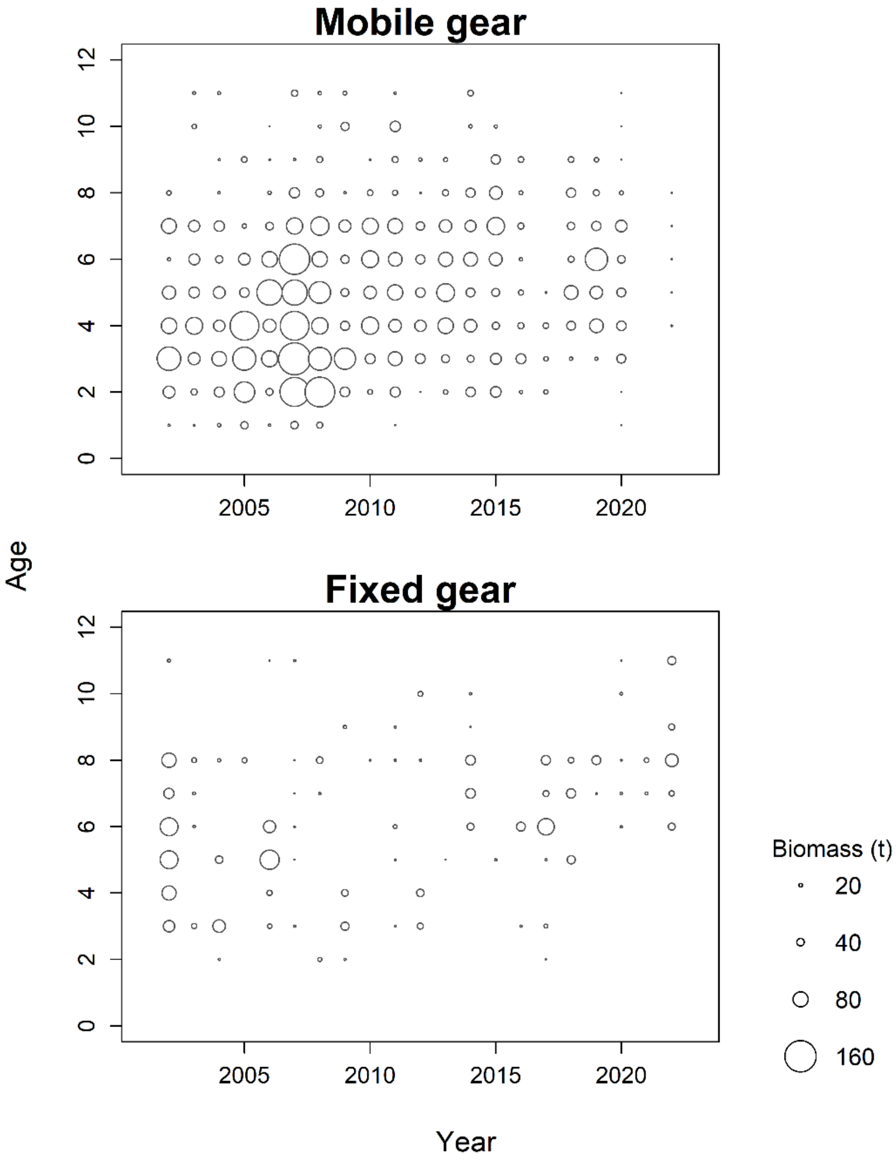

Figure 16: Bubble plots of catch-at-age (biomass in tonnes) of southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring caught as bycatch in the mobile (upper panel) and fixed (lower panel) gear fall Herring fisheries for the period of time the stock has been in the Critical Zone of the Precautionary Approach (2002 to present). The size of the bubble is proportional to the biomass of fish in the catch by age and year. The values indicated at age 11 represent catches for ages 11 years and older.

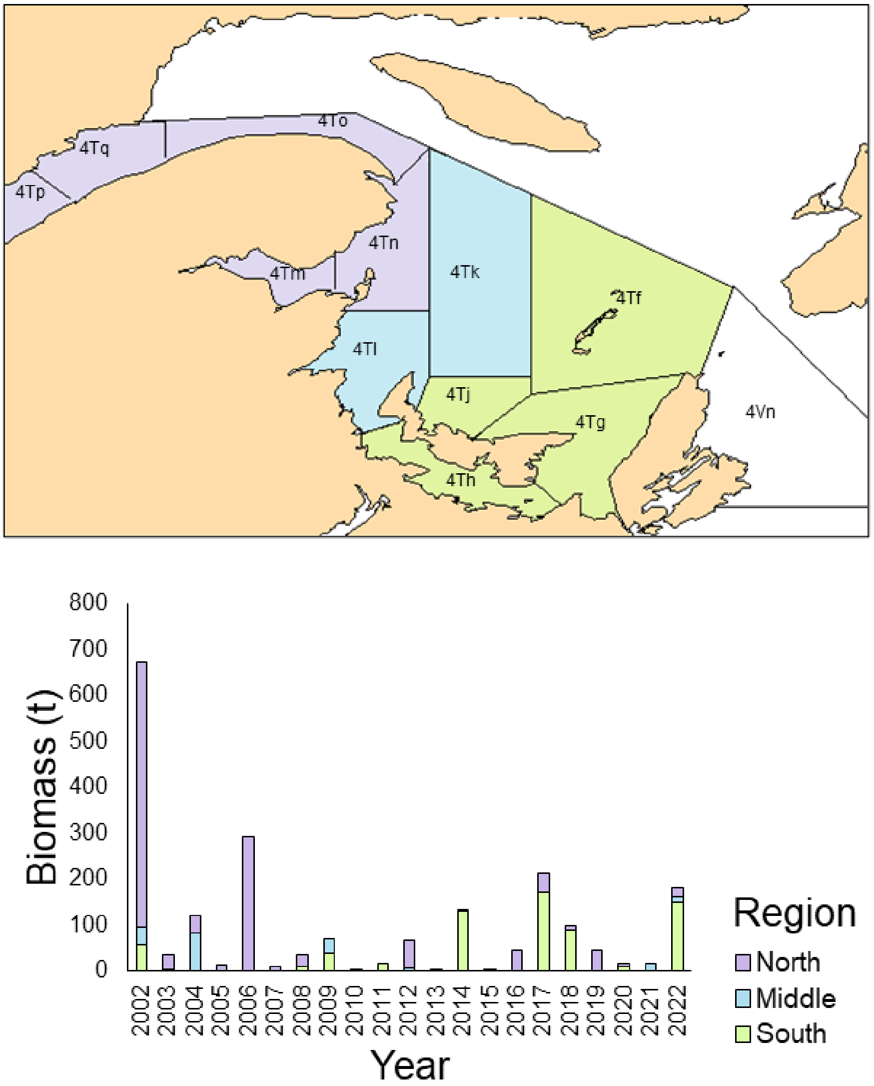

Figure 17: The three regions (North in purple, Middle in blue, South in green) of the southern Gulf of St. Lawrence where the fall fixed gear Atlantic Herring fishery occurs and the corresponding NAFO sub-divisions (upper panel). The bottom panel shows catch in biomass (tonnes; t) of spring spawning Atlantic Herring in each of region the three regions for the period of time the stock has been in the Critical Zone of the Precautionary Approach (2002 to present).

Reducing bycatch of spring Herring is unlikely to rebuild the stock, since population projections with F = 0 showed the stock would remain in the Critical Zone in the long term under prevailing environmental conditions (see Section 4.1.3; recent recruitment and recent M scenarios). To evaluate the expected impact of bycatch on the long-term population status, the spring Herring population was projected forward for 10 years given bycatch levels of 0, 50, 100 and 150 t, as routinely performed in the stock assessment. Projected SSB remained relatively stable at all catch levels, including no catch. At 50 t of bycatch, the population SSB in 10 years would be reduced by 0.3%. At 100 t of bycatch, the population SSB in 10 years would be reduced by 0.75%. At annual removals of 150 t, SSB is reduced 1% in 10 years compared to zero fishing. At 300 and 500 t SSB is reduced 2% and 4% in 10 years compared to zero fishing, respectively.

The median estimates of all bycatch scenarios are all within the 50% confidence intervals of each other.

4.2.2. Bait removals

In NAFO Division 4T, bait fishery licences are issued to all commercial fish harvesters who hold a licence for a species and fishing gear requiring bait. This includes the fisheries for: American Lobster (*Homarus americanus*), Snow Crab (*Chionoecetes opilio*), Atlantic Bluefin Tuna (*Thunnus thynnus*), and Atlantic Halibut (*Hippoglossus hippoglossus*). From 2015 to 2021, an average of 4,474 bait licences were issued for NAFO division 4T (Table 4) with 80% allocated in New Brunswick, Nova Scotia, and Prince Edward Island and the remaining 20% in Quebec. The bait fishery licence conditions allow for up to three gillnets for a maximum total length of 50 fathoms with mesh size of 2 ¼" from April 1 to June 30 (i.e., spring Herring fishing season) and 2 ⅝" (2 ½" in 4Topq) from July 1 to December 31 (i.e., fall Herring fishing season). A maximum of three hand-lines (with no mechanical device) are also allowed. In 2020, the licence conditions were updated for the Gulf Region to include mandatory self-reporting of catch estimates through hail-ins, but the level of compliance is unknown. In 2022, the spring bait fish fishery was closed.

Catches in bait fisheries were historically not accounted for in the assessments of either spring or fall spawning Herring components. A key constraint to including the bait fishery removals is that reporting is generally unreliable or absent all together. Catches in the bait fishery are reported in mandatory bait fishery logbooks in the Gulf Region and electronic logbooks in Quebec Region, but compliance with the requirement to complete and return logbooks to DFO is low in Gulf Region. By not including the bait fish removals in the assessment, this means that total reported removals are underestimated by an unknown amount. Historically, the assumption was that removals from the bait fishery were much lower than commercial landings. However, as the commercial TAC decreased and the requirement for bait increased the contribution of the bait fishery to sources of removals could have become more important. Moreover, American Lobster, Snow Crab, Atlantic Bluefin Tuna, and Atlantic Halibut stocks have all increased in the last decades. These increases in abundance can also lead an to increased need for bait and consequently, an increase in the amount of bait removals of spring Herring.

Here, we examine the bait logbook data available from 2015 to 2021 (Table 4; Figure 18). Atlantic Mackerel (*Scomber scombrus*) and Atlantic Herring are the dominant species captured in the bait fishery in NAFO Division 4T. Other species have been caught with a bait licence during this time period. In 2016, 0.045 t of Atlantic Cod was captured with a bait licences and in 2020, 0.43 t of Alewife/Gaspereau (*Alosa* spp.) were captured. Herring were predominately captured in the spring fishing season (mean 65.1%, range 44.4 to 87.5%; Figure 18), thus presumably consist of spring spawning Herring. The proportion of Mackerel caught in the same spring period was lower and varied from 5.3% in 2020 to 49.8% in 2017, with a mean of 27.4%.

Table 4: Number of bait licences issued in the southern Gulf of St. Lawrence from 2015 to 2021. The number of active licences based on bait logbook returns, showing the total weight of bait caught all species combined in tonnes and amount of Atlantic Mackerel and Atlantic Herring caught specifically.

Year	Licence	Active	Mackerel (t)	Herring (t)	Total (t)
2015	4,480	81	24.03	33.79	57.82
2016	4,456	171	86.58	88.94	175.57
2017	4,464	139	74.83	50.49	125.32
2018	4,476	134	74.48	33.50	107.98
2019	4,467	130	58.19	37.97	96.16
2020	4,477	250	54.68	248.34	303.45
2021	4,495	327	131.84	182.23	314.07

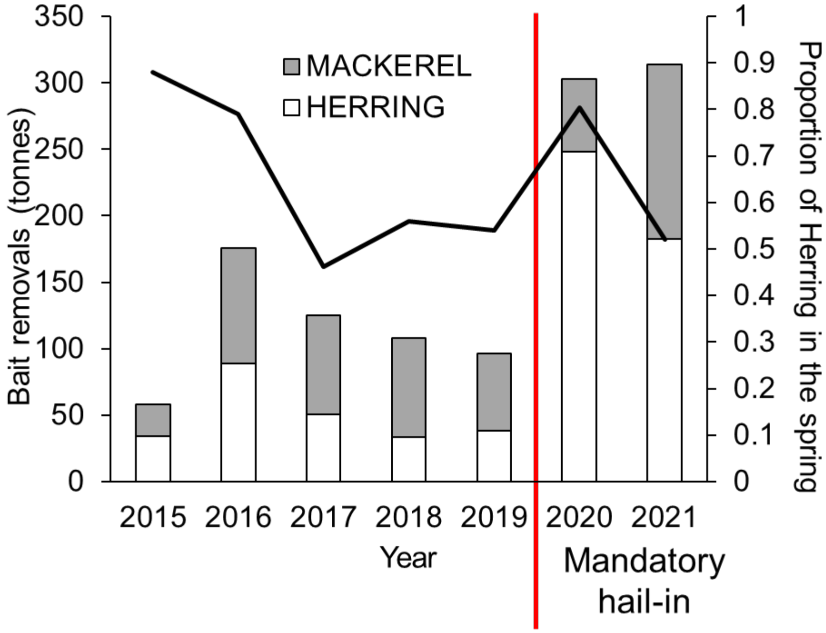

Figure 18: Removals (tonnes) of Atlantic Mackerel (grey bar) and Atlantic Herring (white bar) in the bait fishery in NAFO Division 4T along with the proportion of Herring captured in the spring season (black line). The red line denotes a change in licence conditions where in 2020 and 2021 self-reporting of catch estimates through hail-ins was made mandatory.

The 2020 licence conditions changed to mandatory reporting of bait catch estimates by hail-ins highlights potentially important issues of underreporting through logbooks. In 2020-2021, Herring bait catches averaged 215 t which was were over 4 fold higher than the 49 t average reported from the previous 5 years (Table 4; Figure 18). Typically there are discrepancies between catch estimates and direct measurements, however there was 10 instances and only in 2014 where both catch estimates and actual quantities could be compared. Differences ranged from 0 to 5 t with no consistency in the direction of the differences. Six catch estimates were less than the actual weight, however there were also three instances when the catch estimates were greater than the actual weight. On average across the 10 data points the differences were minor (0.3 t). Between 81 to 327 bait licences were active within a given year with 1.8% of licences active in 2015, up to 7.3% of licences in 2021. The percentage of active licences also nearly doubled when hail-in estimates were made mandatory. Over 50% of licences were only active in a single year during the time period examined.

By including bait removals of Herring in the spring season we were able to estimate a lower bound for how much removals of spring Herring may be underestimated in the assessment (Figure 19). The reporting bait landings represented 3% of the commercial spring Herring landings on average between 2015 and 2019. In 2020 and 2021, the spring Herring bait landings represented 28% of the total landings (Figure 19). Assuming the proportion of spring Herring landed in the bait fishery in 2020 and 2021 is representative of the actual bait removals prior to 2020, earlier years fishery removals could be under-estimated by 21 to 30%.

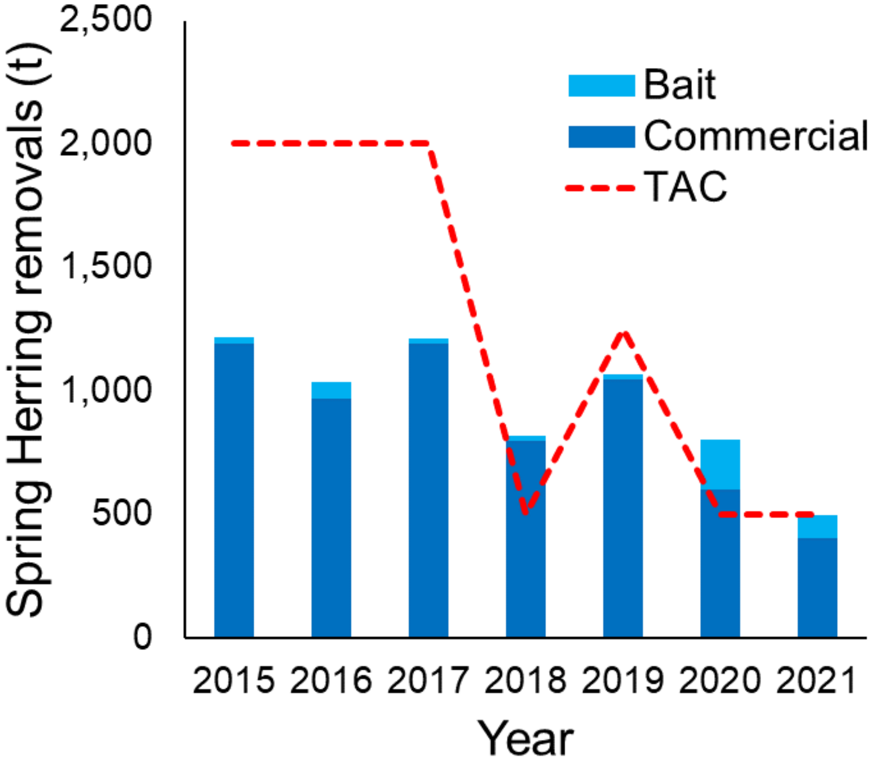

Figure 19: Removals (tonnes; t) of southern Gulf of St. Lawrence spring spawning Atlantic Herring in the commercial (dark blue) and bait (light blue) fisheries in NAFO Division 4T. The red line denotes along the total allowable catch (TAC).

There is tremendous latent potential in the bait fishery in NAFO Division 4T. To further examine the potential scale of removals from the bait fishery we also examined data from the 2016 standardized telephone survey of sGSL (Gulf Region only) lobster fishers (Boudreau and Giard 2022). American Lobster supports the most valuable commercial fishery in Atlantic Canada with landings and abundance indicators increasing in the sGSL over the past decades. All Lobster harvesters in the sGSL have a bait fishery licences, however not all actively fish for their own bait. The 2016 Lobster telephone survey successfully received responses from 592 of the 2,916 Lobster licence holders. This number represents 20% of licence holders from each Lobster Fishing Area (LFA) (Boudreau and Giard 2022). In 2016, Lobster licence holders represented 65% of all bait licences. Several questions were asked of respondents regarding their bait usage:

- Did you fish a percentage of your own bait?
  - What percentage?
  - Was bait fished during the fishing season or off season?
- If rock crab was used as bait, how many pounds approximately?
- What kind of bait were you using (please rank the top three)?
- How many pounds of bait did you use during the fishing season?

To analyze this data, we converted pounds to kilograms, and made the following corrections and assumptions to the raw data.

1. When a record contained a percentage of bait fished and/or indicated bait fishing in/off season, but either did not have an answer or stated they did not fish for their own bait we assumed that they did fish their own bait.
2. When a record indicated that they did fish their own bait but no percentage was indicated we assigned the average percentage of bait fished in that sub-LFA.
3. In LFAs 23, 24, 26 when bait fishing occurred in season, we regarded this as “spring season”, whereas in LFA 25 in season was assigned “summer/fall season” and off season was “spring season”.
4. We collapsed all bait codes to the species or species group (e.g, fresh herring, frozen herring, salted herring, and unspecified herring all became Herring).
5. When amount of bait used during the fishing season was blank we assigned the average of the sub-LFA.

On average, Lobster harvesters used 6.08 t of bait (ranging from 1.36 to 20.41 t per harvester), which when extrapolated to the all licence holders is nearly 18,000 t of bait used in the sGSL. The majority of harvesters (67.7%) did not fish for their own bait, however this differed across LFAs with those fishing for their own bait ranging from 14.9% in LFA 25 to 76.5% in LFA 26B (Table 5). The percentage of bait that they fished for ranged from 27% up to 52% depending on the LFA.

Using the survey responses of total yearly bait used and percentage of bait fished, we calculated that 398.2 t of bait was fished by the 166 Lobster harvesters that stated they fished their own bait. If we assume that all rock crab used as bait was included in the percentage of bait they reported having fished, there is still 369.9 t of other bait being fished by 161 Lobster harvesters. Despite only representing 20% of Lobster licence holders, this number is already more than double the 175.5 t of bait reported to have been fished in 2016 for all NAFO 4T including all other non-Lobster bait licences and Quebec Region harvesters (Table 4). Furthermore, the 161 respondents who fished bait other than rock crab is nearly equal to the total number of active bait fishers from the bait logbooks (171 active bait licences; Table 4). If the survey results are representative of the sGSL Lobster harvesters, then 818 Lobster licence holders would have fished their own non-rock crab bait in 2016 resulting in fishing 1,879 t of bait fish removals. This analysis further highlights a serious issue of underreporting of bait licence use and removals in NAFO 4T.

Table 5: Total number of American Lobster licences in the southern Gulf of St. Lawrence (sGSL) by Lobster Fishing Area (LFA). Number of respondents to the 2016 standardized telephone survey of sGSL (Gulf Region only) Lobster fishers, average amount of bait (tonnes; t) used and percentage of respondents that fished their own bait. Of those that fished their own bait, what percentage of their bait did they fish and what proportion of bait fishing occurred in the spring season.

LFA	Licences	Respondents	Bait (t)	Fished bait (%)	Percentage bait fished	Spring season
23A	107	23	6.91	21.7	52	0.80
23B	92	19	6.18	31.6	42	0.17
23C	298	60	5.77	26.7	27	0.94
23D	172	35	6.01	42.9	36	0.21
24	635	129	6.15	42.6	42	0.60
25	701	141	7.29	14.9	36	0.63
26A	686	138	5.10	26.8	43	0.54
26B	225	47	5.18	76.5	33	0.64
sGSL	**2,916**	**592**	**6.08**	**32.3**	**39**	**0.58**

In order to examine the potential impact of Lobster bait fishing on spring herring, we calculated how much of the non-rock crab bait fishing occurred in the spring season. Most respondents fished non-rock crab bait in the spring season (58%), though this also varied by LFA (Table 5). Not all respondents who fished a percentage of their own bait ranked the top three species used as bait. Of those that did, Herring and Mackerel were the dominant bait used with 73% of respondents using some form of Herring/Mackerel their primary bait source, 67% as their secondary source, and 47% as their third most used bait. 34% of the respondents identified Herring as their primary bait source and 39% Mackerel.

Unfortunately, information was not collected on the percentage of each species used as bait. The questionnaire does, however, allow us to estimate the proportion of bait that consists of rock crab. We used this information to conduct back-of-the-envelope calculation to estimate the amount of each species used as bait. When rock crab was listed as one of the top three most used baits, we calculated the percent of total bait that this represented and assigned the average value to a given rank. Five respondents ranked rock crab as their second most used bait. In these instances the amount of rock crab used as bait represented between 10 and 43% of the total bait with a mean of 28%. Three respondents ranked rock crab as their third most used bait ranging from 0.4 to 25% of the total bait with a mean of 15%. Using this information we assigned the third most used bait a value of 15% of the total bait, second as 28%, meaning the most frequently used bait represents 57% of total bait used.

Based on this we can roughly calculate the percentage of each species used as bait. Outside of rock crab, respondents used an average of 30% Herring and 30% Mackerel as bait. If we assume that the percentage of bait species used is also indicative of the proportion caught in their own bait, then 47 t of spring Herring was captured in 2016 by 77 Lobster harvesters. Applying the same proportions to their own bait provides a conservative estimate as we know from the bait logbooks that bait licences almost exclusively capture Herring and Mackerel. If we take this conservative estimate this would scale up to 229 t of spring Herring caught just by the sGSL Lobster fleet. This value is substantially higher than the 89 t of spring and fall herring combined as reported in bait logbooks for 2016 (Table 4) and over 3 times higher than the 70 t of Herring bait catches reported for the spring season (Figure 19).

A Lobster telephone survey has not been conducted since 2016 therefore we have no information on the recent bait fishery. However, while the average amount of bait used in 2016 was reported to be similar to previous surveys, the percentage of respondents who fished their own bait showed a decrease in 2016 compared to 2011 (Boudreau and Giard 2022; Appendix 2).

The bait logbook and Lobster telephone survey analyses highlight that removals of spring Herring by the bait fishery are greater than previously reported. The bait logbooks demonstrate that removals of spring Herring historically might have been underestimated by roughly 30%. In addition, the Lobster telephone survey results suggest that there could be conservatively a further 24% underestimate of spring Herring removals. This challenges the assumption that removals of the bait fishery were much lower than commercial landings and suggests that in recent years spring Herring removals in the bait fishery may be more comparable in scale to that of the commercial landings. Moreover, the bait removals for the other fisheries using Herring as bait (Snow crab, Atlantic Bluefin Tuna and Atlantic Halibut) are unknown.

The findings of these analyses indicate that the bait fishery is likely an important source of fishery removals for the spring spawning stock and management measures to maintain the closure of this bait fishery will help ensure that fishery removals are kept to the lowest possible level.

Nevertheless, fishery removals remain a fraction of the total mortality on this stock. In comparison to the 229 t of Herring for bait removed by the Lobster fleet, natural mortality removed 20,544 t of biomass (calculated from yearly natural mortality at age and biomass at age values; Figure 20) and the commercial fishery landed 965 t in the same year. Hence, bait removals that are not reported and hence not accounted for in the fishing mortality of the stock likely end up in the natural mortality estimates. However, when considering the scales of the estimated bait and M removals, the bait removals probably represent of small fraction of M.

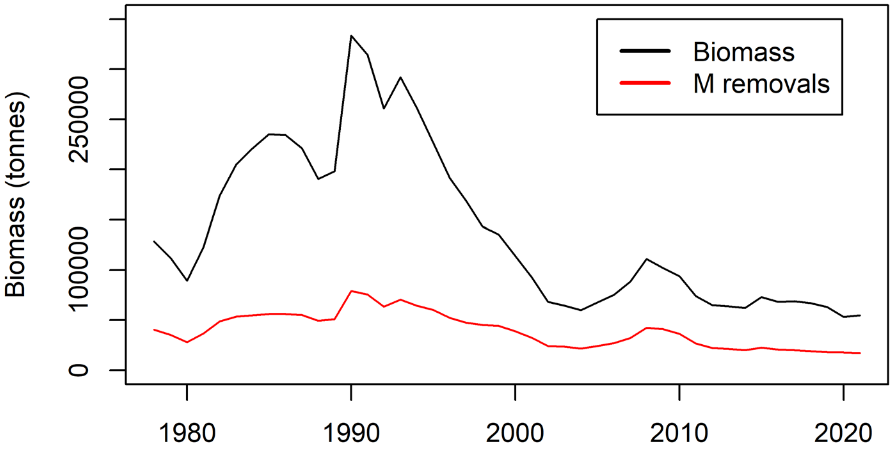

Figure 20: Southern Gulf of St. Lawrence (NAFO Division 4TVn) spring spawning Atlantic Herring Biomass (in tonnes, ages 2 to 11+; black line) and natural mortality removals (in tonnes; ages 2 to 11+; red line) between 1978 and 2021.

5. HABITAT

In section 2(1) of the Fisheries Act, fish habitat is defined 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”. With respect to this definition, habitat loss or degradation is likely to have contributed to the stock decline. Since 1992, the Gulf of St. Lawrence has experienced a trend towards warmer waters, shorter duration of ice season, and lower ice volume (Galbraith et al. 2021). Both the sea surface temperature of the sGSL and the spring Herring recruitment abruptly shifted from a cold water/high recruitment regime (1978-1991) to a warmer water/low recruitment (1992-2017) regime in the early 1990s (Turcotte 2022). These environmental changes, often linked to climate change, may have triggered seasonal fluctuations in production of phytoplankton and zooplankton, including the main food source for Herring with a decrease in abundance of cold-water copepod species and an increase of warm water copepod species abundance (Blais et al. 2021). The spring Herring stock is less likely to rebuild under prevailing environmental conditions of the current warmer water regime than it was in the former regime. This is consistent with a model suggesting that cold environmental conditions favor spring spawners, whereas warm conditions favor fall spawners in Western Atlantic Herring stocks (Melvin et al. 2009). At the distributional extremes of Atlantic Herring, stocks are restricted to a single spawning strategy, with autumn spawning in the south and spring spawning in the north (Melvin et al. 2009).

6. ADDITIONAL MEASURABLE OBJECTIVES

Rebuilding objectives may include other metrics beyond biomass-based measures (DFO 2021a). While setting measurable objectives for these metrics can be challenging, other considerations for sGSL spring Herring could include objectives of increasing the proportion of larger older fish. Setting objectives for these metrics may be challenging. In some cases, it may be possible for these metrics to be accounted for explicitly by setting specific objectives, or implicitly by setting rebuilding objectives for abundance or biomass at levels that are sufficiently high to result in a high likelihood of restoration of these other metrics of condition.

The proportion of older spring Herring (aged 9+) declined to very low levels in the mid-2000s (Rolland et al. 2022). From the period 1978 to 2004, older spring Herring aged 9+ averaged 5% of the age composition. This then dropped to less than 1% from 2006 to 2009. In the most recent period, the percentage of older spring Herring has increased to around 2% (Rolland et al. 2022).

Mean weight-at-age of spring Herring declined by 39.6% between 1978 and 2021 (Rolland et al. 2022). Weight-at-age of spring Herring captured have been declining since the mid-1980s in the spring fixed gears fishery (Rolland et al. 2022).

Older and larger herring have been found to make greater contributions to recruitment (Burbank et al. 2024).

A rebuilding plan objective could be to increase in the percentage of older spring Herring to averages observed historically. Another objective could include increasing size at age to levels observed early in the time series.

7. HOW TO TRACK REBUILDING PROGRESS

Rebuilding progress will be tracked using the spring Herring 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 stock assessment cycle. Objectives should be revised and models should be updated as estimates of stock productivity changes.

8. FREQUENCY OF PERIODIC REVIEW OF THE REBUILDING PLAN

The periodic review of the rebuilding plan should be set to every 4 years, which corresponds to every other stock assessment for spring Herring. Objectives should be revised and models should be updated if stock productivity or external factors influencing stock dynamics change.

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APPENDIX 1: PRODUCTIVITY MODULATED HARVEST CONTROL RULES

The default harvest control rules (HCR) proposed by the Precautionary Approach are stationary, whereas the capacity to sustain fishing mortality of a stock in a given state depends on the productivity components state at the time of harvest. For stocks with highly varying productivity, this can be problematic as the target harvest rate suggested by the stationary harvest control rule will almost never be accurate.

Here, the proposed harvest control rule is the same as the Precautionary Approach provisional harvest control rule when productivity is at an intermediate value, but suggests using lower fishing mortality targets when productivity is low, and higher fishing mortality targets when productivity is high. Target fishing rates are adjusted with an index of productivity, which is reflecting the environmental effects on recruitment and natural mortality, the main drivers of the stock.

The effect of natural mortality and recruitment on stock dynamics are not equal (see section 4.1.3). In order to give weights to the productivity metrics that compose the productivity index, population projections were performed with every parameter held constant except the parameter of interest. The values of the parameters for projections were selected from the scenarios in section 4.1.3 (recent recruitment and low M but low M in first projected year, recent M and high recruitment). The terminal year equilibrium SSB estimates where compared between projections and the “base” scenario (Figure 21). The ratios of SSB between projections were used calculated and used as weights for each metric in the calculations of the productivity index.

Based on these ratios, the weights were 3.2 for recruitment, and -1.4 for natural mortality. Using the 5 years with highest observed weight-at-age (1984 to 1988) in projections did not generate a perceivable effect on projected SSB when compared to the last 5 years weight-at-age of the assessment, which corresponds to a period of low weight-at-age (SSB ratio = 1.0044). Hence, growth was not included in the productivity index. The productivity index int year t (PI_{t}) was calculated as follows:

$$PI_t = 3.2r_t - 1.4\sum_{a=1}^{A} bw.m_t$$

Where r_t is the number of age 2 fish in year t, $bw.m_t$ is biomass weighted natural mortality in year t and assessment model ages were indexed as a = 1,…,A where A = 11, which corresponds to ages 2 to 11+. Time series of yearly biomass weighted natural mortality estimates for all ages, of the number of recruits (age 2 fish), and of the sum of weights at age across ages were obtained from the stock assessment outputs.

As the productivity index varied considerably between years (largely reflecting recruitment events), the index was smoothed over years using the lowess R function with a span of 0.2 (Figure 22). The smoother allows to reduce the influence of extreme points that would ultimately generate large fluctuations in target fishing mortality and TACs in the harvest control rules.

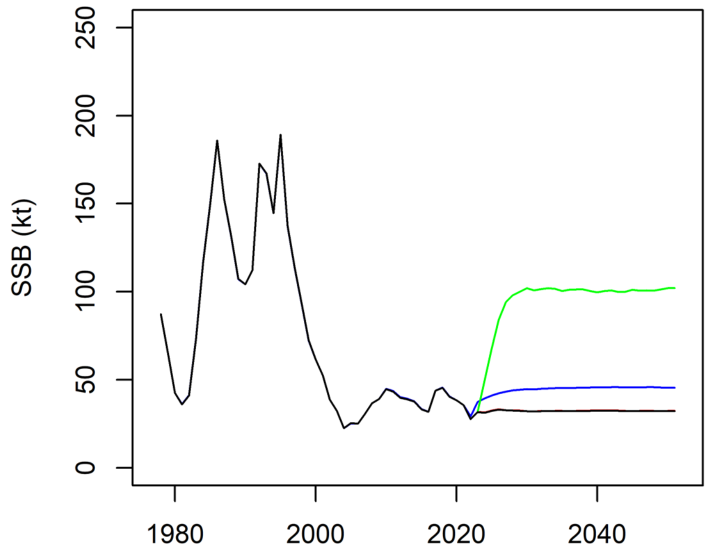

Figure 21: Historical (1978-2021) and projected spawning stock biomass (SSB; kt) with high recruitment (green line) or low natural mortality (blue line) while maintain every other parameter constant, and projections as performed in the stock assessment (black line).

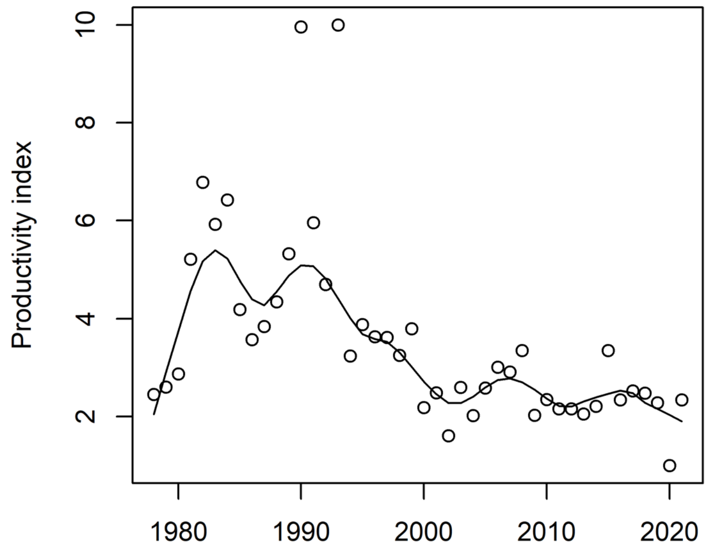

Figure 22: Productivity index (points) and smoothed productivity index (line) for NAFO Division 4TVn spring spawning Atlantic Herring, between 1978 and 2021.

The removal reference (target fishing mortality) at the USR (see section 2.5.2) was derived from the high biomass high productivity period used for the selection of the LRP, which is a period where productivity was maximal. Fishing mortality in this period ($FMSY_{proxy}$) was stable at around 0.21.

Here, the target fishing mortality at the USR to be used at the highest productivity index value was set as 1.5 $FMSY_{proxy}$. The target fishing mortality at the USR to be used at the lowest productivity index value was set as 0.5 $FMSY_{proxy}$.

The productivity index had values between 1 and 8 (9 values). The resulting range of target fishing mortality at the USR was between 0.10 and 0.31. The range of target fishing mortality at the USR was divided by 9 harvest control rules, one per productivity index value. The result is a surface of target fishing mortality, given SSB and productivity index values (Figure 23). At the intermediate productivity level, the harvest control rule is the provisional harvest control rule from the PA with $FMSY_{proxy}$ as the removal reference. As the productivity values increases or decreases, the removal reference increases or decreases accordingly and the slope of the harvest control rule is modified accordingly. Examples of harvest control rules at three selected productivity index values (maximum, intermediate and minimum) are shown in Figure 24.

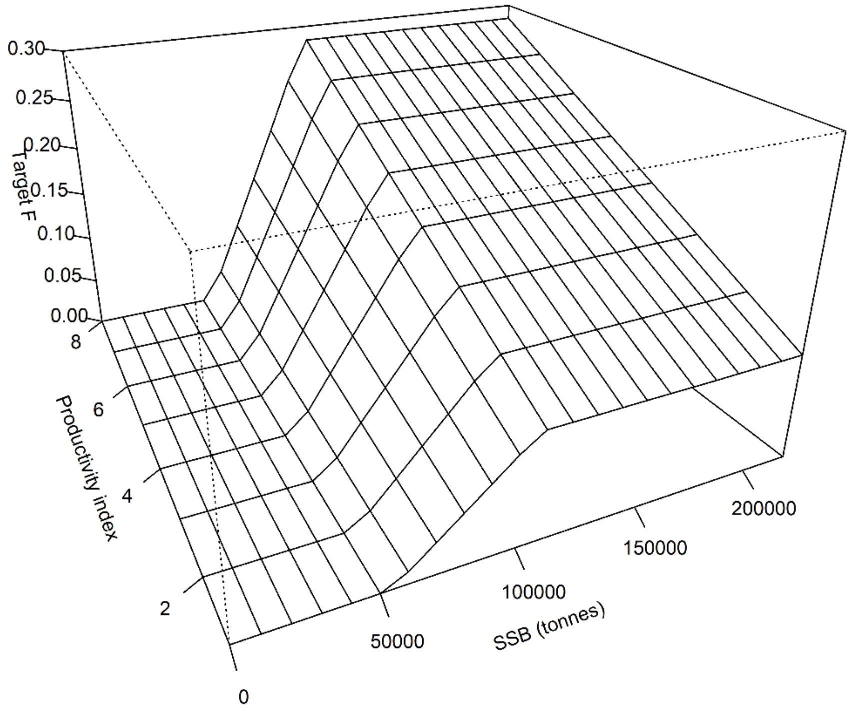

Figure 23: Productivity modulated harvest control rules for NAFO Division 4TVn spring spawning Atlantic Herring. X axis is spawning stock biomass (SSB, tonnes), y axis is productivity index (scaled) and z axis is target fishing mortality.

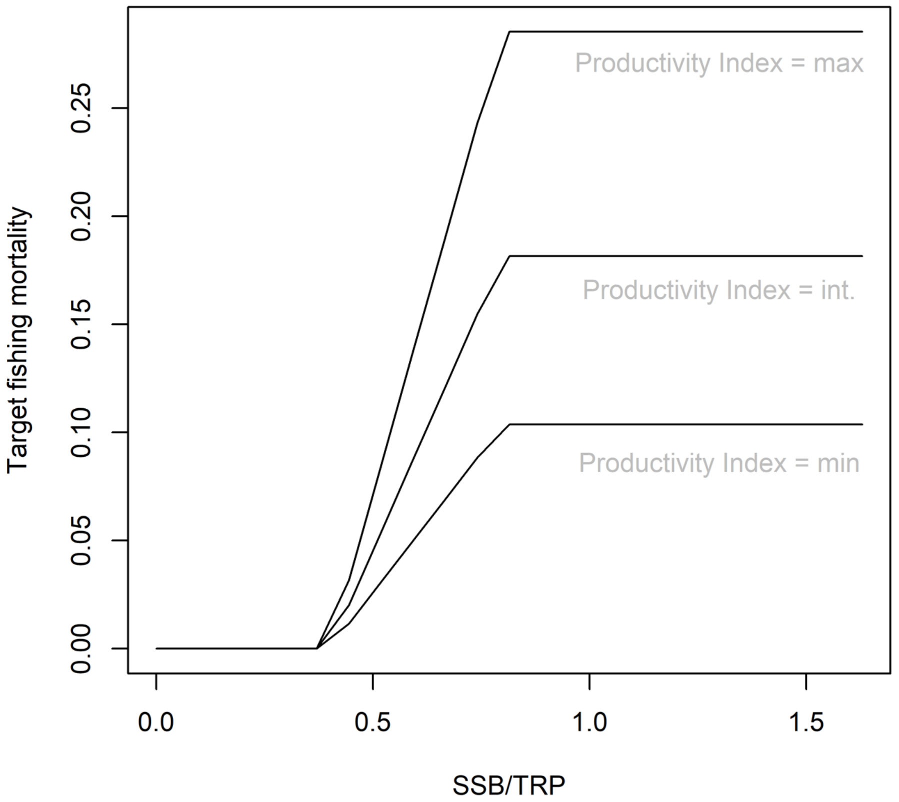

Figure 24: Selected productivity modulated harvest control rules for three values of a productivity index (maximum, intermediate and minimum) for NAFO Division 4TVn spring spawning Atlantic Herring. X axis is spawning stock biomass (SSB, tonnes), y axis is productivity index (scaled) and z axis is target fishing mortality.

Herring biomass generally declines to lower minima, recovers to higher maxima and shows larger changes in biomass than non-forage fish species, implying Herring are more prone to booms and busts dynamics (Trochta et al. 2020). Herring are generally more likely to have very large recruitment events than non-forage fish and overall to display greater variability in recruitment (Trochta et al. 2020). Natural mortality is less likely to display abrupt changes, as it is probably mostly driven by changes in predation and changes in predator abundance or behavior are slow processes. Hence, as spring Herring population size can display high variability, driven by highly variable recruitment dynamics, using harvest control rules that fluctuate with the stock productivity is likely to be more precautionary than the provisional HCRs.

Few examples of modulated harvest control rules exist in the literature. In a simulation study, Kaplan et al. 2020 found that compared to constant $F = F_{MSY}$ policies, environment driven harvest control rules led to higher stock biomass for Pacific hake in the California Current and mackerel in the Norwegian Sea. Bentley et al. 2021 found that using a zooplankton abundance indicator to adjust Herring F_{msy} reduced catches during poor ecosystem and generated higher catches when conditions where favorable. In that study, the standard F_{msy} decision rule led to lower biomasses during periods of low productivity and resulted in overly cautious harvest during periods of high productivity. In these examples, the upper and lower limits of the harvest levels were set based on group consultations in stock assessment processes.

The management of Pacific sardine is another example of modulated harvest control rule. For this stock, the decision rule accounted for changes in water temperature conditions and the resulting effect on sardine recruitment (Jacobson and MacCall 1995). The aim was to reduce the fluctuations in abundance in response to harvest and avoid rapid population collapses experienced in the past. The management of the stock was performed by allowing the harvest of available biomass above a cutoff (150 000 t) ranging from 5% during cool conditions to 15% during warm conditions (PFMC 1998).

The way to modify the HCR in response to changes in production here was to scale the removal reference (and the slope of the harvest control rule in the Cautious Zone accordingly). Determining by how much to change the removal reference as the productivity indicator changed here was somewhat arbitrary as evaluating the range of fishing mortality the stock can incur depends on many stock processes that are fluctuating in time. As done in Bentley et al. 2021, this range can be informed by consultation in stock assessment processes where the group decides what range of scaling of the HCR is acceptable. Bentley et al. 2021 used a range around F_{MSY} based on population projections where the outcome was reducing catches by 5% maximum compared to the F_{MSY} level.

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APPENDIX 2: BAIT REMOVALS BASED ON THE 2011 AMERICAN LOBSTER TELEPHONE SURVEY OF SGSL

Data from the telephone survey of sGSL (Gulf Region only) lobster fishers for the 2011 fishing season was analyzed for bait information (Boudreau and Giard 2022; hereafter 2011 Lobster telephone survey). The 2011 Lobster telephone survey received responses from 590 of the 3,127 Lobster licence holders. This number represents nearly 20% of licence holders from each Lobster Fishing Area (LFA) (Boudreau and Giard 2022). The same questions on bait usage were asked as in the 2011 Lobster telephone survey as described in the main text for the 2016 Lobster telephone survey. We made the same corrections and assumptions to the 2011 data as done in 2016.

On average, Lobster harvesters used 5.38 t of bait (ranging from 1.09 to 32.66 t per harvester), which when extrapolated to the all licence holders is nearly 17,000 t of bait used in the sGSL. The majority of harvesters (68.3%) did not fish for their own bait, however this differed across LFAs with those fishing for their own bait ranging from 15% in LFA 23B to 50% in LFA 23D (Table 6). The percentage of bait was fairly consistent across LFAs averaging 28% overall. Using the survey responses of total yearly bait used and percentage of bait fished, we calculated that 273.6 t of bait was fished by the 187 Lobster harvesters. If we assume that all rock crab used as bait was included in the percentage of bait they reported having fished, there is still 264.0 t of other bait being fished by 185 Lobster harvesters. If the survey results are representative of the sGSL Lobster harvesters, then 980 Lobster licence holders would have fished their own non-rock crab bait in 2011 resulting in fishing 1,399 t of bait fish removals.

Table 6: Total number of American Lobster licences in the southern Gulf of St. Lawrence (sGSL) by Lobster Fishing Area (LFA). Number of respondents to the 2011 telephone survey of sGSL (Gulf Region only) Lobster fishers, average amount of bait used and percentage of respondents that fished their own bait. Of those that fished their own bait, what percentage of their bait did they fish and what proportion of bait fishing occurred in the spring season.

LFA	Licences	Respondents	Bait (t)	Fished bait (%)	Percentage bait fished	Spring season
23A	124	22	5.41	36.4	30	0.50
23B	95	20	4.54	15.0	40	0.33
23C	336	60	5.11	33.3	36	0.90
23D	190	32	5.45	50.0	25	0.56
24	637	137	5.42	40.9	24	0.86
25	804	130	6.54	28.5	24	0.30
26A	714	141	4.68	19.9	30	0.78
26B	227	48	4.73	39.6	24	0.94
sGSL	**3,127**	**590**	**5.38**	**31.7**	**28**	**0.70**

In order to examine the potential impact of Lobster bait fishing on spring herring, we calculated how much of the non-rock crab bait fishing occurred in the spring season. Most respondents fished non-rock crab bait in the spring season (70%), though this also varied by LFA (Table A1). Herring and Mackerel were the dominant bait used with 76% of respondents using some form of Herring/Mackerel their primary bait source, 67% as their secondary source, and 39% as their third most used bait. 50% of the respondents identified Herring as their primary bait source and 26% Mackerel.

The same method and assumptions described for the 2016 Lobster telephone survey were employed using rock crab bait percentages to estimate the percentage of each species used as bait. Six respondents ranked rock crab as their primary source of bait with a mean of 47% of the total bait. Five respondents ranked rock crab as their third most used bait with a mean of 14%. Consequently we assigned the primary source of bait a value of 47%, the secondary as 39%, and the third most used bait 14% of the total bait used.

Based on this we can roughly calculate the percentage of each species used as bait. Outside of rock crab, respondents used an average of 37% Herring and 33% Mackerel as bait. Assuming that bait percentages are consistent in their own bait, then 78 t of spring Herring was captured in 2011 by 129 Lobster harvesters. This conservative estimate would scale up to 413 t of spring Herring caught just by the sGSL Lobster fleet in 2011. This number is much more comparable to the 682 t caught in the commercial fishery than previously believed (Table 3).

The average amount of bait used per Lobster harvester was less in 2011 compared to 2016, but the percentage of harvesters that fished their own bait was fairly consistent. When fishing their own bait, Lobster harvesters in 2016 fished for a larger portion of their bait (39%) than they did in 2011 (28%). More bait fishing occurred in the spring in 2011 compared to 2016. A larger portion of harvesters fishing for their own bait used Herring as their primary bait in 2011, whereas, Mackerel was most often used as the primary bait source in 2016.

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