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Review and Evaluation of Potential Limit Reference Points for 2J3KL Capelin (*Mallotus villosus*)

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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

Limit reference points (LRP) are an important tool for managing fisheries. In Canada, LRPs are being determined for commercial fish stocks to align with the Fish Stocks Provisions (FSP) of the revised Fisheries Act (R.S.C., 1985, c. F-14). Determining a robust LRP is especially critical for forage fish species due to their commercial value, the critical position they occupy in marine food webs linking the energy produced by plankton to higher tropic levels, and their vulnerability to overfishing. The main purpose of this Research Document is to detail the process for evaluating and determining an LRP for Northwest Atlantic Fisheries Organization (NAFO) Divisions 2J3KL Capelin (*Mallotus villosus*) (hereafter 2J3KL Capelin), a small, short-lived forage fish in the Northwest Atlantic. Specifically, we overview the relevant legislation and policies surrounding LRPs in Canada, best practices for establishing and evaluating LRPs, the considerations and challenges unique to 2J3KL Capelin and the Northwest Atlantic ecosystem, and the data sets available for this stock.

We considered a suite of potential LRPs for 2J3KL Capelin including more conventional approaches based on theoretical or historical proxies for biomass at maximum sustainable yield (B_{MSY}) and unfished biomass (B_0), recruitment, and historical trends, as well as newer methods such as multi-indicator, length-based, and ecosystem approaches. Three approaches met the criteria of being feasible, reliable and plausible, and were therefore, considered valid: $B_{recover}$ based on the 1982 survey, a historical proxy for B_0 based on the median value of the highest Capelin biomass in the survey time series (1985–90), and an ecosystem approach based on the capcod model (capcod hereafter). Briefly, capcod predicts the biomass of Northern cod (*Gadus morhua*; cod hereafter) based on the biomass index of 2J3KL Capelin in the previous year using a bioenergetic-allometric approach. Capcod effectively explained these dynamics (r^2 = 0.92) and diagnostics suggest the assumptions of the model were valid. The capcod model was used to determine an LRP for 2J3KL Capelin based on the biomass of 2J3KL Capelin required for cod to reach its own LRP. Of the three valid approaches, the LRP based on the capcod model was clearly the most robust due to the mechanistic approach, the strength of the relationship and diagnostics, and that the resulting LRP is based on an ecosystem approach tying cod to their most important prey, Capelin. The LRP for 2J3KL Capelin was determined to be 640 kilotonnes (kt) and is conceptually consistent with the other major Capelin stocks in the Barents Sea and in waters around Iceland.

INTRODUCTION

Limit reference points (LRP) are used by nations and intergovernmental bodies (e.g., NAFO, International Council for the Exploration of the Sea [ICES]) globally to help manage fisheries. LRPs are being determined for commercial fish stocks in Canada to help align with the Fish Stocks Provisions (FSP) of the revised Fisheries Act (R.S.C., 1985, c. F-14). The FSP requires a single LRP for each of these stocks and an associated determination of stock status relative to the LRP.

LRPs are usually determined for a single stock (Barrett et al. 2024; Chagaris et al. 2020) but ecosystem approaches to fisheries management can be considered (DFO 2023), especially if the stock has a critical role in the ecosystem. Forage fish can be commercially important in their own right (Alder et al. 2008; Cury et al. 2000; Pikitch et al. 2012), but they also occupy a critical position in marine food webs linking the energy produced by plankton to higher tropic levels (Bakun 2006; Cury et al. 2000; Guénette et al. 2014). In addition, forage fish abundance has been linked to long-term seabird productivity (Cury et al. 2011), and they are important prey for marine mammals (Kaschner et al. 2006; Pikitch et al. 2014) and larger-bodied fish species that comprise important commercial fisheries (Guénette et al. 2014; Pikitch et al. 2014), leading to the suggestion that forage fish are more valuable as prey than as a commercial species (Pikitch et al. 2012; Pikitch et al. 2014).

Regardless of whether a species is a forage fish or if ecosystem considerations are taken into account, developing a robust and defensible LRP can be a challenging task due to variations in the life history, stock history, and available data for a stock. Consequently, a vast array of approaches for determining LRPs have been developed (Sainsbury 2008; Smith et al. 1993). Selecting a robust LRP for forage fish from amongst the many possibilities is especially important because, in addition to their commercial value and ecosystem role, they are vulnerable to overfishing for a number of reasons. First, forage fish schooling density remains high across a range of population sizes which can result in hyperstable catch rates (Pikitch et al. 2012). Second, some forage fish species are short-lived and consequently, are less resilient to fishing induced age-truncation (Guénette et al. 2014; Pikitch et al. 2012). Finally, forage fish also tend to exhibit stochastic population dynamics which are driven largely by bottom-up processes (Chavez et al. 2003; Peck et al. 2021), i.e., recruitment may not be density-dependent, making population forecasting difficult and limiting management options (Guénette et al. 2014).

Capelin (*Mallotus villosus*) are a small, short-lived (between 3 and 6 years), shoaling forage fish species that exhibit “boom-bust” population dynamics and are characterized by facultative semelparity, i.e., a large proportion of spent adults experience post-spawning mortality (Shackell et al. 1994; Templeman 1948). The NAFO Divisions 2J3KL Capelin stock (hereafter 2J3KL Capelin) collapsed in 1991 and has not recovered (Buren et al. 2019). 2J3KL Capelin are the most abundant forage fish species on the Newfoundland and Labrador (NL) shelf (Buren et al. 2014b) and is a commercially fished species (IFMP 2022).

The main purpose of this document is to detail the process for evaluating and determining an LRP for 2J3KL Capelin. The main body of this Research Document is divided into two broad sections: Background and LRP Approaches. The Background section begins with an overview of the relevant legislation and policies. Second, in the LRP Approaches and Criteria section, we review the best practices for establishing an LRP that were developed at a National Advisory Process (NAP; (DFO 2023)) held in June 2022 in response to the FSP of the revised Fisheries Act (R.S.C., 1985, c. F-14) and the associated development of LRPs for important commercial fish stocks. Specifically, we review the best practices for evaluating LRPs using three criteria:

feasibility, reliability, and plausibility. Finally, we review the considerations and challenges unique to 2J3KL Capelin and the Northwest Atlantic ecosystem, as well as the merits and limitations of the data sets available for this stock. The LRP Approaches section presents the actual LRPs that would be produced from the various approaches following the same sequence as DFO (2023). The strengths and weaknesses of the valid LRP approaches will be discussed.

BACKGROUND – LRP

LEGAL AND POLICY

The Government of Canada has a number of polices designed to ensure healthy fish stocks and sustainable fisheries. The Sustainable Fisheries Framework (DFO 2022a) is a group of related policies intended to ensure that Canadian fisheries support conservation and use the resource sustainably, i.e., by maintaining healthy and productive fish stocks while also protecting biodiversity and fisheries habitats. A central tenant of this framework is to establish a precautionary approach (PA) to fisheries management (DFO 2009a). The PA framework acknowledges that even when adequate, information in fisheries science is inherently uncertain and that caution is warranted when implementing harvest strategies in order to avoid serious harm to a given stock. To this end, one of the main components of the PA framework are reference points and stock status zones. Stock status is divided into Healthy, Cautious, and Critical Zones with reference points defining the boundaries between the zones, where the LRP defines the boundary between the Cautious and Critical Zones. Specifically, “The limit reference point represents the stock status below which serious harm is occurring to the stock. At this stock status level, there may also be resultant impacts to the ecosystem, associated species, and a long-term loss of fishing opportunities.” (DFO 2009a).

The PA was adopted in 2009 but LRPs have not been developed for all major commercial stocks for various reasons. One reason is simply a lack of human resources and competing demands upon staff time as well as a lack of data. Another is that many data limited methods, which are required for a number of major stocks, have only recently been developed (Boudreau and Duplisea 2022) and some are analytically complex (Pons et al. 2020). An LRP for 2J3KL Capelin was proposed at the 2013 assessment meeting but it was not accepted because there was no estimate of spawning stock biomass (SSB; see Data section for more details) and it was unclear if the spring acoustic biomass index (biomass index hereafter) could be used to represent the entire stock (DFO 2015). In addition, at that time the assessment did not include a model to project stock trends (DFO 2015). In 2019, a forecast model was incorporated into the 2J3KL Capelin stock assessment which projects the spring acoustic biomass index (Lewis et al. 2019). This, along with a broadened understanding of the role of Capelin in the ecosystem, and the impact of 2J3KL Capelin stock size on the finfish community, enabled the current renewed effort to develop an LRP for this stock (Koen-Alonso et al. 2021; NAFO 2021; Regular et al. 2022).

Building on the PA, revisions to the Fisheries Act (R.S.C., 1985, c.F-14) on June 21, 2019 resulted in new considerations for ministerial decision making and the FSP. Interpreted through the lens of the Sustainable Fisheries Framework and the PA Policy, the FSPs identify objectives for sustainable use of stocks including determining a single LRP per stock and the status of the stock relative to the LRP. Stocks below their LRP require a rebuilding plan. The implementation of FSP thus led to an increased emphasis on LRP development, and resources were allocated to complete the work required to meet this objective for various major stocks (DFO 2021c).

The development of LRPs for the 180 stocks identified in the Sustainability Survey for Fisheries covered under the FSP has proceeded in batches. 2J3KL Capelin was placed in the second batch (Batch 2) of stocks where development of an LRP is to be determined (DFO 2022d) and is among 10 of the 62 stocks in Batch 2 that did not have an LRP (DFO 2022e). Inclusion in Batch 2 was based, in part, on stakeholder input indicating that forage fish were a priority. Other criteria for inclusion in Batch 2 were that the stock was on the annual Sustainable Fisheries Survey (DFO 2022b), it could be described geographically, the stock was not managed by NAFO, and it was not listed on Schedule 1 of *Species at Risk Act* (SARA) as Endangered or Threatened.

LRP APPROACHES AND CRITERIA

The vast array of approaches that have been developed for determining LRPs is due, in part, to differences in available data for a given stock, including indicators (a unit of measurement that provides information on some attribute or characteristic of the stock, e.g., spawning biomass or just biomass), length of the time-series, species-specific life history, stock trajectory, the variety of fisheries models that have been developed to deal with variation within the aforementioned factors, and how well a potential LRP fulfills various criteria (see next paragraph). Given these complexities coupled with the importance of reference points for fisheries management, especially LRPs, a number of guides/reviews have been conducted by international and national organizations (Caddy and Mahon 1995; DFO 2023; Sainsbury 2008; Smith et al. 1993). However, “There is no single correct indicator or reference point with which to evaluate objectives pertaining to serious harm for all stocks, however, nor one single way to set a LRP” (Marentette et al. in prep.[1]).

In response to the aforementioned complexities and legislative changes, DFO (2023) proposed six best practice principles (hereafter “principles” or P# if referring to a specific principle) to provide consistency in the development of LRPs. These principles suggest, in part, certain criteria that should be considered when developing an LRP, i.e., that LRPs should be feasible (P3), and that LRPs should take into account reliability, plausibility, and uncertainty (P4). The other principles are briefly discussed at the end of this section for completeness but are less relevant to the selection of an LRP for 2J3KL Capelin.

> **Feasible** simply means that the data are available and of sufficient quality that an LRP can be calculated using a given approach. For example, age-structured models can only be applied to stocks with age data and only stocks with estimates of biomass and recruitment can use LRPs based on stock recruit relationships (SRR).
>
> **Reliable** means that “estimates should be acceptably robust (considering consistency, variance and bias) to key uncertainties and assumptions in the advice framework”, i.e., just because it is feasible to calculate an LRP using a given approach does not mean it should be if the variance of an estimate is unacceptably high. The accuracy or precision of estimates can help separate reliable from unreliable approaches.
>
> **Plausible** means that estimates, assumptions or hypotheses are consistent with empirical data, ecosystem and population dynamics theory. LRP values should identify the point below which serious harm to the stock occurs. LRP values that are too low will mean that the stock is already experiencing serious harm and overfishing may be occurring. Conversely, an LRP value that is too high will mean the stock is not

[1] Marentette, J.R., Barrett, T.J., Cogliati, K.M., Ings, D.W., Ladell, J., and Thiess, M.E. In prep. Operationalizing Thresholds to Serious Harm: Existing Guidance and Contemporary Canadian Practices. DFO Can. Sci. Advis. Sec. Res. Doc.

experiencing serious harm, but could limit fishing and unnecessarily trigger a rebuilding plan under the new legislation.

Uncertainty - The PA policy explicitly states that "Both scientific uncertainty and uncertainty related to the implementation of a management approach must be explicitly considered and the management decisions taken must be tempered when necessary to give effect to the PA." When key uncertainties are identified, reliability can be evaluated. Scientific uncertainty includes observation error, imprecision or bias in model parameters, and model assumptions (Barrett et al. 2024; DFO 2023). For example, all indices have observation error, including the biomass index for 2J3KL Capelin from the spring acoustic survey (see Data section). For parameters, uncertainty could come in the form of estimates of *r* (intrinsic rate of growth) or *K* (carrying capacity) in a surplus production model or simply from the variance of a historical proxy. For model assumptions, uncertainties could be the form of the stock recruit relationship or functional response curve (see LRP approaches). Given the uncertainties inherent in all fisheries data, "The appropriate risk to consider when using this framework is the probability of and the severity of the impact from management actions on stock productivity." (DFO 2009a).

The first three of the above criteria will be used to rank different LRP approaches as valid, i.e., all criteria are fulfilled. These three criteria will be considered sequentially in the order above. If one criterion is not fulfilled, the approach will be considered invalid and subsequent criteria will not be evaluated. Valid approaches will be further assessed based on uncertainties in observations, parameter estimates, and model assumptions as appropriate.

In addition to the above criteria, some aspects of the six principles will apply to all proposed LRPs in the case of 2J3KL Capelin. The best available information, i.e., the spring acoustic survey, will be used in all cases (P1), the objective is to prevent serious harm to the stock (P2), the rationale for the choice of LRP can change over time (P5), and the rationale for the LRP will be communicated as clearly as possible (P6). Further, the spring acoustic survey is the indicator relevant to management (P3) and the observation error of the spring acoustic survey will apply to all approaches (see DFO 2023 for a full discussion of the principles).

LRP CONSIDERATIONS/CHALLENGES

Given the diversity of approaches available for developing an LRP, coupled with some of the unique aspects of the 2J3KL Capelin stock, its monitoring programs, and the NL ecosystem, the remainder of the Background section will provide an overview of the considerations and challenges unique to determining an LRP for 2J3KL Capelin including

1. population dynamics, life history, and stock history,
2. the role of Capelin in the Northwest Atlantic ecosystem,
3. the appropriate time series length to consider for the LRP given the regime shift that occurred in the early 1990s, and
4. the data sets available for this stock and their associated limitations.

Population dynamics and Life history

The population dynamics of Capelin, and pelagic species in general, are difficult to model due to their life history and a scarcity of data at critical points in their life cycle; this affects the types of LRP approaches that can be considered. Capelin are short-lived with a high intrinsic growth rate. Consequently, populations can fluctuate dramatically driven largely by bottom-up factors throughout their life cycle, e.g., the influence of water column stratification on the spring bloom and factors that affect larval survival (e.g., wind), although the primacy of these factors may change over time (Buren et al. 2014b; Leggett et al. 1984; Lewis et al. 2019; Murphy et al. 2018; Mowbray et al. 2023) and are difficult to predict. Capelin life history must also be considered because, while almost all age 4+ Capelin are mature, the proportion of maturing three-year old fish prior to the collapse and the proportion of maturing two-year old fish after the collapse vary considerably. This variation in mature spawners-at-age affects the age-structure of the spawning population which, all else being equal, affects the number and quality of eggs produced since larger females produce more eggs of larger size (Penton and Davoren 2013; Templeman 1948) and quality (Chambers and Leggett 1996). Larger eggs typically produce larger larvae with greater yolk-sac reserves which typically produces a survival advantage (Bailey and Houde 1989; Cowan Jr. et al. 1996; Dower et al. 2009), and survival of Capelin in the first few weeks of life has been related to age-2 recruitment (Murphy et al. 2018). Modelling is further complicated because, while natural mortality (*M*) can be estimated from year to year (although this is difficult in practice, see Theoretical Proxies for B_{MSY}), there are no estimates of *M* during the spawning migration. Thus, even if the spawning stock size was known (see Data section), the Capelin that actually complete the migration and spawn is unknown. Further, post-spawning mortality is generally assumed to be total for the Iceland-Greenland-Jan Mayen and Barents Sea Capelin stocks, but some females are known to survive for 2J3KL Capelin (Flynn et al. 2001). Finally, the impact of fishing mortality (*F*) on this stock is also unknown largely because the proportion of the stock that spawns is unknown. What is known is that harvesters take a small proportion of the total Capelin biomass compared to estimated consumption by finfish, seals, and whales (NAFO 2021), but the roe fishery targets not only the portion of the stock that will imminently spawn, it specifically targets the more fecund fish, i.e., individuals that are older, larger, and spawn earlier (Davoren and Montevecchi 2003).

In short, 2J3KL Capelin population dynamics are largely driven by bottom-up forces, maturity-at-age varies with population size, important phases of the life cycle are not sampled, and *F* as well as *M* are unknown. All these factors can limit the feasibility, or decrease the reliability, of model outputs, and this can limit the types of LRP approaches that meet the above criteria.

Ecosystem Role

As the dominant forage fish on the NL shelf, the ecosystem role of Capelin is an important consideration when determining an LRP (DFO 2023). Capelin biomass is a key driver of Atlantic cod (*Gadus morhua*; hereafter, 'cod' implies the Northern cod stock, i.e., NAFO divisions 2J3KL but Atlantic cod will mean the species) population dynamics (Buren et al. 2014b; Koen-Alonso et al. 2021; Regular et al. 2022). Further, Capelin biomass has been linked to changes in fecundity of NW Atlantic harp seals (*Pagophilus groenlandicus*; Stenson et al. 2016), and they are important prey for Greenland halibut (*Reinhardtius hippoglossoides*; Dwyer et al. 2010), whales (Gulka et al. 2017), and seabirds (Buren et al. 2012; Montevecchi 2007; Montevecchi et al. 2019). These factors collectively suggest Capelin are extremely important for the marine community, including commercial fish species, and it is therefore important to consider the role of Capelin in the overall functioning of the ecosystem when developing an LRP for this stock. Indeed, the proportion of a stock metric used for some LRP approaches have been increased for forage fish in recognition of their ecosystem role (Sainsbury 2008).

Time series length

Choosing the appropriate timeframe, i.e., the length of the time series, is critical to the determination of an LRP. A given LRP value is appropriate within the management framework because it relates to the productivity of the stock. However, if the productivity of the stock changes beyond the expected fluctuations around some stable long-term level, then it may be inappropriate to use the full time series to define an LRP. For example, if an ecosystem has alternate states , i.e., “two or more states at which an ecosystem can persist, within the same range of driver variables” (Ratajczak et al. 2018), then an LRP that is valid for one alternate state, may not be valid for another. LRPs derived from data corresponding to an alternate state where a stock is highly productive can unreasonably position that same stock in the critical zone if the system has moved into another alternate state where the stock is naturally less productive which could unnecessarily limit fishing. Conversely, mistakenly assuming a lower productivity alternate state can lead to inappropriate reductions in the LRP level, perhaps resulting in fishing when a stock is experiencing serious harm. It is for this reason that the PA demands a high level of evidence for the existence of an alternate state in order to prevent a continual lowering of LRPs as stocks decline (DFO 2009a).

There is a general consensus that the Northwest Atlantic experienced a regime shift, an observed large change in an ecosystem that may or may not result in the system moving into an alternate state (Ratajczak et al. 2018)[2], that began in the 1980s but saw sudden and dramatic collapses in many fish stocks in the early 1990s. The best known outcome of this regime shift is the collapse of groundfish stocks (Myers et al. 1997; Pedersen et al. 2017). Less well known is the collapse of the Capelin population a year earlier (Buren et al. 2019). The regime shift resulted in the marine community shifting from being dominated by groundfish biomass in the 1980s to shellfish (i.e., crab and shrimp) biomass in the 1990s (Koen-Alonso and Cuff 2018; NAFO 2021).

What is less clear is if the regime shift in the Northwest Atlantic resulted in a shift to an alternate state. To move between alternate states usually requires that perturbations are, at least temporarily, extreme enough to push the system from one stable configuration into another. Whether a system in an alternate state returns to its original/previous state depends on whether conditions reverse far enough to induce a change back to the original/previous state. Conversely, a given system state or system that does not possess alternate states, may also experience a severe perturbation which can change its structure dramatically but, in contrast to a shift to an alternate state, the system would be expected to recover over time. So, it is possible for a regime shift to occur and result in an alternate state or remain in the same state, albeit a highly perturbed one (Ratajczak et al. 2018).

Given that the length of the time series has a large impact on setting an LRP and the Northwest Atlantic experienced a regime shift, it is necessary to assess the evidence for whether the system is in an alternate state or remains within the same state using environmental, community, and stock level indicators (Table 1). In general, the available trends are consistent with the predictions of a single state system that is recovering, although there are indicators that are ambiguous. Briefly, some environmental trends, specifically those associated with temperature, such as sea ice coverage and sea surface temperatures, have shown distinct directional changes in the last 50 years, but these trends appear unrelated to the collapse of the Capelin stock and the groundfish community (Cyr and Galbraith 2021). Cold water events, such as those that occurred in the early 1990s when the cold intermediate layer (CIL) extended almost from the sea floor to the surface, were extreme anomalies. A perturbation like the CIL of the early 1990s could trigger a regime shift, but in themselves, would be uninformative regarding the type of configuration change they could cause. Conversely, more synoptic

[2] We note that regime shift, as used in the PA framework and other documents, is used synonymously with alternate states. We use the definitions of Ratajczak et al. (2018) as it is more aligned with the broader literature and distinguishes the transition of the system from the state of the system.

environmental indicators, such as the Newfoundland and Labrador Climate Index which combines trends in ten variables and begins in 1950, shows distinct, decadal scale fluctuations (Cyr and Galbraith 2021) that are more consistent with a single state. Similarly, the biological community was dominated by shellfish after the regime shift in the 1990s to about 2007. This trend has reversed in more recent years and, although groundfish stocks have not yet rebuilt to pre-regime shift levels (Koen-Alonso and Cuff 2018; NAFO 2021), this is also consistent with a single state. Finally, at the stock level, the Capelin population has remained at a low level (median acoustic biomass index = 156 kilotonnes (kt)) since 1991, although the stock did increase somewhat from 2013 to 2015. This trend could support either single state or alternate states. However, younger age classes have grown faster resulting in early maturation and age truncation, which is a common feature for collapsed stocks and suggests a single state situation (Gjøsæter 1998; Mowbray et al. 2023).

The PA framework requires that "there is no expectation that the conditions consistent with higher productivity will ever recur naturally or be achievable through management." Further, DFO (2013b) stated "the burden of proof should be on demonstrating a rational that there has been a regime shift (i.e., alternate state), not that conditions have remained constant". Although the Capelin stock has remained at low abundance and biomass for 30 years, the available evidence is either ambiguous or supports the hypothesis that the system has remained in a single state and is slowly recovering. Under the PA, a high degree of certainty is required to use a truncated time series for determining an LRP. Therefore, we used the whole time series for the LRP approaches below.

Data

A final consideration in the choice of LRPs are the richness of the available data or time series. Data richness is a mixture of the quality of the data, i.e., the accuracy and precision of the data, the number of time series, and their respective duration, i.e., extent. The overlap amongst time series will also determine what type of LRP approach can be taken, such as which covariates can be used in a model (e.g., the Capelin forecast model was limited by the larval abundance time series (Lewis et al. 2019)), or the overlap between these time series and the beginning of harvesting for B_0 approaches (see below).

For data-poor stocks, there are often only a few ways to establish an LRP and, therefore, options are often analytically simple (Boudreau and Duplisea 2022; NAFO 2021) but see Pons et al. (2020) for review of length-based reference points. For data-rich stocks, while there may be many possible approaches, the choice may also be straightforward assuming the required analytical expertise is available, e.g., a SRR derived from a state-space, age-structured model. For stocks in the middle of the data richness continuum, sometimes referred to as 'data-rich, information-poor', choosing an approach to determine LRPs can be a challenging process because many options may initially appear to be possible but ultimately fail to meet the criteria of feasibility, reliability, and plausibility. In short, the limitations within and among the time series will determine their usefulness for assessing the stock and determining an LRP.

The 2J3KL Capelin stock has been studied for many decades (Buren et al. 2014a; Buren et al. 2019; Carscadden et al. 2001; Davoren and Montevecchi 2003; Gulka et al. 2017; Mowbray 2014; Murphy et al. 2018; Nakashima 1996; Regular et al. 2022; Templeman 1948; Winters 1970) and consequently, there are time series for a diversity of metrics including relative capelin abundance, larval density, and capelin condition. However, while there are a number of time series, including four different acoustic surveys, the quality and consistency of these data and the applicability of these data for producing an LRP, varies.

Spring Acoustic Survey

The NL spring acoustic survey (acoustic survey hereafter) is the flagship survey of the 2J3KL Capelin stock assessments and it is the primary metric for assessing this stock (DFO 2021a). The acoustic survey has been conducted since 1982, albeit with a few years with either no survey or where the survey was incomplete. The acoustic survey is an off-shore survey conducted primarily in NAFO Division 3L with limited coverage in southern 3K. It is assumed that all maturing individuals surveyed will migrate to inshore waters to spawn in the following months.

However, the acoustic survey has several limitations. First, it is not a measurement of the biomass that actually survives to spawn but rather pre-spawning biomass. Second, as with many fishery-independent surveys, a scale mismatch exists between the survey and the stock range (Ings et al. in prep.[3]), i.e., the acoustic survey does not survey the entire population, because, historically, spring sea ice made surveying north of NAFO Div. 3L problematic. In addition, inter-annual shifts in the spatial distribution of the Capelin stock may affect the proportion of the stock that overlaps with the acoustic survey area (but see next paragraph). Third, the acoustic survey was initially a survey of the primarily non-migratory portion of the stock, consisting largely of immature age-2 fish and variable numbers of immature and maturing age-3 fish as well as some mature age-4 and age-5 fish; catchability of age-1 fish in the survey is generally poor due to gear selectivity. Further, with the population collapse in 1991, the stock age structure shifted to younger fish, i.e., the age-6 and then age-5 fish largely disappeared over time. The survey now consists largely of variable numbers of immature and maturing age-2 fish as well as mature age-3 fish and very few age-4+ fish. For these reasons, the acoustic survey is considered an index of the stock and not an estimate for the total stock biomass (Mowbray 2014).

There are, however, some indications that the acoustic survey is a useful indicator of stock status. The capelin biomass in 2J3KL, the full stock area, from the DFO Fall multi-species survey (multi-species survey hereafter) is correlated with the biomass index of the following year (Spearman's rho=0.46 p-value=0.04; period evaluated: 1995–2020). Although the multi-species survey is less than ideal for estimating pelagic fishes like Capelin, because bottom trawl surveys are known to underestimate the biomass of pelagic species, it can still track major changes in biomass over time. The general coherence in the temporal signal between these two surveys gives credence to the notion that the acoustic survey, despite its more limited spatial scope, can indeed track changes in the stock. Furthermore, the acoustic survey, under the assumption that it reasonably represents the order of magnitude of the stock, has proven to be an effective representation of Capelin as a driver of a bioenergetic-allometric model of the biomass of Northern cod (Koen-Alonso et al. 2021). Finally, in most years of the acoustic survey, there is a reasonable correlation between age-2 fish and age-3 fish the following year, suggesting that cohorts are being tracked through time and, in conjunction with the above, some aspect of 2J3KL Capelin population dynamics are captured (but see next paragraph).

Two data issues were identified in the acoustic survey values. First, the biomass estimates from the acoustic survey have been recalculated using a standard methodology. While these corrections are primarily for 2014 and 2015 (Mowbray et al. 2023), other years did have small changes in biomass estimates, but they were well within the uncertainty of the biomass index estimates. The other data issue is that in some years some cohorts do not track well, i.e., there are too many age-3 fish at t+1 given the number of age-2 fish at t. This is particularly

[3] Ings, D.W., Marentette, J.R., Thiess, M.E., and Barrett, T.J. In prep. Considerations for Stock Structure and Management Scale Under the Fish Stocks Provisions. DFO Can. Sci. Advis. Sec. Res. Doc.

problematic between 2010 and 2011 where far more age-3 fish were observed in 2011 than age-2 fish in 2010 (DFO 2013a). This, along with several other surveys that found very few capelin, suggests that the acoustic biomass estimate in 2010 was low relative to the stock size.

Other data sets and analyses

There are three other acoustic survey time series available for 2J3KL Capelin: a Canadian fall survey as well as a spring and fall survey conducted by the former Union of Soviet Socialist Republics (USSR). Similarly, other time series are available for other aspects of the Capelin life cycle such as larval density. However, none of these time series were included in the development of a Capelin LRP due to concerns over their ability to track capelin population dynamics, applicability to the stock, or redundancies with the capelin forecast model (See Appendix 1 and 2 for details on times series and explanations for why they were not included).

We performed all analyses in program R version 4.2.2 (R Core Team 2022) using RStudio (version 2022.07.2). All data and code for the analyses in this paper are available on Github except for the analyses in the Ecosystem section which were performed independently of most of the work described in this paper and had been completed before it began. Two fully interactive dashboards exploring the 2J3KL Capelin time series and the LRP approaches are available on the Github site (Regular et al. 2020).

LRP APPROACHES

LRP categories are briefly described here including whether they meet the criteria established by DFO (2023) - see Barrett et al. 2024 for definitions, methods of estimation, links to serious harm, and pros/cons of each approach. Approaches were only considered valid if they met all the criteria (Table 2). Approaches that did not meet the criteria are introduced in this section and further described in Appendix 1. Approaches that were either considered but not completed, or not explored in detail, are described in Appendix 2. All of the below approaches assume that the biomass index is a reasonable approximation for stock biomass for reasons presented in Spring Acoustic Survey section above.

PROPORTION OF B_{MSY} OR B_0

For data-rich stocks, reference points are often defined in terms of the proportion of B_{MSY}, the biomass that produces the maximum sustainable yield, or B_0 , the mean long-term equilibrium biomass of the stock in the absence of fishing which can be considered a proxy for (K). These values can be obtained from a statistical population model such as an age-structured model, delayed-difference model, or surplus production model.

Two major attempts were made to model Capelin population dynamics. First was an age-structured model that incorporated environmental covariates known to be useful in predicting Capelin biomass (i.e., the forecast model, Lewis et al. (2019)), but this was not completed in time for the 2023 assessment (see details in Appendix 2). Second, we fit the various acoustic surveys and the landings data with a Bayesian state-space surplus production model using package JABBA (Winker et al. 2018). While feasible, this approach was deemed unreliable as the process error explained most of the variation in the data (see Appendix 1 for full details).

THEORETICAL PROXIES FOR B_{MSY}

$F_{X\%SPR}$ is the fishing mortality rate that results in a spawning potential ratio (SPR) of X% (i.e., results in X% of the unfished SSB-per-recruit where X is often 40%). Although $F_{X\%SPR}$ is often used as a proxy for F_{MSY}, the equilibrium biomass at $F_{X\%SPR}$ can be used as a proxy for B_{MSY} under the assumption of equilibrium biomass at a constant F. However, estimates of M

and selectivity are required to estimate $F_{X\%SPR}$. While unknown, selectivity can be obtained from expert opinion. Further, a crude estimate of M can be obtained by estimating Z (total mortality) using well established approaches (Hilborn and Walters 1992) and subtracting a constant amount under the assumption that F is low, e.g., 0.1. However, the variability of these estimates was very high (SD = 0.64) for the younger age-classes and there are many years with no estimates for the older age-classes due to the truncation of the age-structure of this stock. Therefore, this approach was not feasible.

RECRUITMENT

An LRP can be set based on thresholds where recruitment overfishing can be determined (X% R_{max}), i.e., when biomass is low enough that recruitment is impaired, e.g. Northern and 3Ps cod (DFO 2011, 2020).

We explored SRR using the standard Beverton-Holt (BH) and Ricker curves (Figure 1). These SRR were fit to a proxy for SSB, i.e., the mature fish in the acoustic survey. However, the variance on the BH and Ricker curves was very large for all data sets and the differences in a potential LRP (50% R_{max}) using these approaches was also large (BH = 660 kt; Ricker = 387 kt). In conclusion, these approaches are feasible but not reliable.

HISTORICAL

Historical methods for determining an LRP are conceptually simple and address issues of depensation directly. There are three historical methods: B_{loss} is the lowest observed stock size in the biomass time series, $B_{recover}$ is the lowest observed biomass which produced recruitment that led to stock recovery, and B_{min} is the lowest observed biomass from which a recovery to average has been observed or other minimum biomass that produced "good" recruitment. These methods assume stationarity in productivity parameters over time.

These methods can be based on a biomass index or on model-derived values and are useful when stock dynamics are unknown. For this document, only the biomass index based values will be discussed because we do not have a model for this stock that covers its full historical range.

B_{loss} and B_{min} were not considered valid approaches due to issues of reliability (see Appendix 1). $B_{recover}$ was based on the 1982 acoustic survey which had a biomass index of 446 kt (Figure 2) and led to the highest observed biomass of the time series in 1985-1990 (maximum of 5,783 kt and a median of 3,705 kt). The 1982 biomass index value has not traditionally been used in Capelin stock assessments because this survey was conducted approximately a month earlier than the rest of the time series and the confidence intervals could not be calculated due to data availability issues. However, the 1982 survey value was reviewed and considered acceptable due to its spatial coverage, which was similar to the typical May spring acoustic survey, and because the weights of the fish in April 1982 were comparable or greater than fish sampled in subsequent May acoustic surveys. Therefore, even though the 1982 biomass value is likely an underestimate due to its timing, the survey was considered acceptable for the time series. The values for 1983 and 1984 were not accepted given the earlier survey timing (also April) and the vastly reduced spatial coverage relative to the typical May spring acoustic survey. $B_{recover}$ is feasible, reliable, and plausible.

HISTORICAL AND EMPIRICAL LRPS INCLUDING PROXIES FOR B_{MSY} OR B_0

When population dynamics are unknown, historical or empirical proxies may include some measure of central tendency of the biomass or abundance during a productive period of the time series. Depending on the situation, this productive time period can be considered B_{MSY} or

B_0. For 2J3KL Capelin, the period from 1985–90 may be a reasonable proxy for B_0 for two reasons. First, historically there was an inshore Capelin fishery for food, bait, and fertilizer but this would have had little impact on stock size because so few fish were landed. Second, there has been a commercial fishery since 1972 (Mowbray et al. 2023), but the stock was at a high biomass index in the late 1980s after relatively high levels of fishing in the 1970s. Considering the variability of the stock from 1985–90, it is possible that this stock reached or exceeded its carrying capacity and, therefore, a median of these values could represent a reasonable estimate of B_0. This seems more probable than this period being a proxy for B_{MSY} which would suggest an even higher carrying capacity and that the relatively low levels of fishing during this period had a significant impact on this stock (DFO 2021a). Therefore, using the median biomass of 1985–90 as a proxy for B_0, a common method to determine an LRP is 0.2* B_0 = 741 kt while 0.3* B_0 = 1,110 kt is sometimes used for forage fish or stocks where a more precautionary approach is warranted (DFO 2017, Sainsbury 2008; Figure 2). This approach is feasible and reasonably reliable (mean = 3,913 +/- 1,072 kt). The use of B_0 as a proxy was considered plausible given our assumptions about the state of the stock and will be further explored in the Discussion as will the multiplier, i.e., 0.2 or 0.3.

ECOSYSTEM

The ecosystem approach to fisheries management is increasingly being used and promoted as a path towards sustainable fisheries (Koen-Alonso et al. 2019). Koen-Alonso et al. (2021) showed that fisheries catches, and Capelin availability were good predictors of Atlantic cod biomass using a bioenergetic-allometric approach (the capcod model, 'capcod' hereafter). Briefly, capcod predicts the next year's Atlantic cod biomass based on the current year's biomass, the estimation of biomass losses due to respiration, landings and density dependent mortality, and biomass gains due to food intake, which is modeled using a Type III functional response and driven by Capelin biomass as well as an alternative food source (see Koen-Alonso et al. (2021) for full details). This model has effectively explained the dynamics of both Northern cod and Barents Sea cod (r^2 = 0.92 for both stocks) despite the different population dynamics of these stocks, highlighting the robustness and generality of the basic principles and processes captured in the model architecture. In addition to a high r^2, the evaluation of the standardized residuals (fairly homogeneous and largely within ±2 standard deviations) and the lack of retrospective patterns (Mohn's rho = 0.013) indicate that capcod fits the data well and is not unduly influenced by the changes in the length of the time series values.

Using capcod, it is possible to calculate the net production per capita of cod for any combination of cod and Capelin biomasses (Figure 3) which can be used to determine the Capelin biomass required to maintain cod biomass at a given level. Using this approach, and under the assumption of no fishing for cod, the biomass index in the spring acoustic survey required to rebuild cod to its LRP, i.e., the mean cod SSB from 1983–89 based on capcod model output, is 640 kt (see Appendix 3 for further details). Cod biomass is currently 52% of its LRP (DFO 2022c). However, if the cod LRP changes due to a future review, the Capelin LRP will have to be recalculated.

An additional advantage of the capcod approach is that cod biomass correlates positively and significantly with the biomass of various finfish functional groups in the multi-species survey suggesting that cod can serve as an indicator of ecosystem status (Figure 4; Spearman correlations between cod and functional groups: Plank-piscivores, rho = 0.72; Large Benthivores, rho = 0.96; Medium Benthivores, rho = 0.48; non-cod Piscivores, rho = 0.58). This suggest that a biomass index of 640 kt would allow for the cod stock to rebuild which, in turn, suggests that ecosystem processes and overall productivity could return to a pre-collapse state. Therefore, the capcod approach is feasible, reliable, plausible, and serves the larger purpose of moving beyond a single-stock assessment towards an ecosystem approach to fisheries management which is a departmental objective.

DISCUSSION

We considered a large suite of potential LRPs for 2J3KL Capelin including more conventional approaches based on theoretical or historical proxies for B_{MSY} and B_0, recruitment, and historical trends, as well as newer methods such as multi-indicator, length-based, and ecosystem approaches. Three approaches met the criteria of being feasible, reliable and plausible, and were considered valid: $B_{recover}$, a historical proxy for B_0, and the capcod approach (Table 2).

A COMPARISON OF VALID LRP APPROACHES

Although any of the three approaches might have been considered valid in the absence of the others, they were not considered to be equal when the strengths and weaknesses (i.e., uncertainties) of each approach were assessed (Table 3). Briefly, the $B_{recover}$ approach was rejected due to considerable concerns over the point estimate, i.e., there was no replication during this early 1980s time period (no values pre-1982 and 1983–84 are not considered valid), the 1982 biomass index was likely underestimated due to the timing of the survey, and that possible future stock recovery depends on prevailing conditions relative to 1982. The B_0 proxy was not fully rejected but there were concerns over justifying 1985–90 as a proxy for B_0 and that choosing the multiplier was somewhat arbitrary (Table 3). Further, a multiplier of 0.3 is often used for forage fish and would give an LRP of 1,110 kt which is far above the peak biomass during the post-collapse period (780 kt in 2014). An LRP of this magnitude is problematic because there are currently no stock level traits available to determine if serious harm to the stock occurs between 780 and 1,110 kt. The strength of these approaches is that they are empirically based and make fewer assumptions than model- based approaches.

The strengths of the capcod model were that it promotes an ecosystem-based approach to fisheries management and that it has a solid theoretical and analytical foundation. Capelin are the dominant forage fish in the Northwest Atlantic. Cod biomass is largely driven by Capelin biomass (Buren et al. 2014a; Koen-Alonso et al. 2021), while cod biomass in turn is a good indicator of finfish biomass from the multi-species survey (Figure 4). Supporting the capcod approach, Regular et al. (2022) found a relationship between cod condition and natural morality, and that cod condition is related, in part, to Capelin availability. These studies suggest that when there are more Capelin, cod tend to be in better condition, their mortality decreases, and cod biomass subsequently increases as does the biomass of other finfish (Koen-Alonso and Cuff 2018; NAFO 2021).

Two weaknesses of the capcod approach were identified. First, the model parameter representing the amount of alternative prey (the capelin prey replacement parameter) is assumed constant over the whole time period; this has been identified as a research recommendation but is not expected to result in large-scale changes in model outputs (Koen-Alonso et al. 2021). Second, the capcod model does not directly demonstrate serious harm to Capelin. However, since the collapse of the Capelin stock, multiple stock indicators have shown trends consistent with other Capelin stocks when they are in a “bust” state (Gjøsæter 1998) including faster immature growth resulting in early maturation; age truncation (DFO 2021b; Engelhard and Heino 2004; Wheeler et al. 2009); smaller fish spawning later in the year which generally produces weaker year classes (Murphy et al. 2021); and generally weak Capelin recruitment (Mowbray et al. 2023). The 95th percentile of the biomass index estimates for all years from 1991 to the present, with the exception of 2013 and 2014, were below the LRP value of 640 kt obtained from the capcod approach which suggests the stock has been in a “bust” state almost continually since 1991, i.e., a state of serious harm. An additional line of evidence that supports the capcod LRP is that changes to Capelin stock traits, such as length-at-age and maturity-at-age, vary with stock size in a manner consistent with density-dependence. In 2013–15, the post-collapse years with the greatest biomass index, these traits were more similar to the pre-collapse period than any others in the post-collapse period (Mowbray et al. 2023) i.e., only when the stock is above the capcod LRP do stock traits resemble those from before the collapse. Collectively, these lines of evidence indicate that the stock is likely in a state of serious harm when the biomass index is below 640 kt although this value will have to be recalculated if the cod LRP is reviewed in the future.

In summary, the strengths of the capcod approach were considerable when compared to the other valid approaches considered for a Capelin LRP. The capcod approach produced an LRP that is consistent with other biological evidence indicating a state of serious harm for the Capelin stock. The capcod model is an important step towards an Ecosystem Approach to Fisheries Management (EAFM) as it explicitly links the Capelin and cod LRPs, and, by proxy, begins to consider the role of Capelin as forage species at the fish community level. For these reasons, the capcod approach was accepted as the basis for a Capelin LRP (Figure 5).

COMPARISONS WITH OTHER JURISDICTIONS

There is no one correct way to determine an LRP and the choice of approach is often heavily influenced by the available data, species life history, and the stock history. However, the capcod approach to an LRP is conceptually similar to other Capelin and forage fish stocks’ LRPs. The two largest Capelin stocks, Barents Sea and Iceland-east Greenland – Jan Mayen (IEGJM), are managed using an escapement strategy, i.e., the biomass of fish allowed to escape the fishery and spawn, that allows for catches when the stock is healthy while protecting the stocks when it is not. For both stocks, the escapement strategy is based on $B_{recover}$ (or B_{lim}) derived from an estimated SSB from acoustic surveys that cover the entire stock areas but that also incorporates losses to groundfish predation. The main difference between the reference points for the Barents Sea and IEGJM Capelin stocks and 2J3KL Capelin is, the LRPs for the ICES-assessed stocks are estimated using conventional approaches (i.e., B_{lim}) but do not integrate the ecosystem role of Capelin into the LRP value. Rather, ecosystem needs are incorporated as a precautionary harvest control rule i.e., the escapement strategy. Since SSB is not available for 2J3KL Capelin, the ecosystem role of Capelin is integrated directly into the LRP value through the use of the capcod model, where it is captured in terms of a long-term average outcome.

The use of an EAFM is not unique to Capelin stocks. The largest fishery in the eastern United States, menhaden (*Brevoortia tyrannus*), also uses an ecosystem approach based on a model of intermediate complexity that takes the role of this forage fish into account (Drew et al. 2021). Indeed, management objectives for this stock include sustaining menhaden for directed fisheries, the consumptive needs of predators, providing stability across fisheries, and accounting for a changing environment (Chagaris et al. 2020).

However, most LRPs for forage fish, and fish stocks in general, do not explicitly take ecosystem considerations into account even though the call for a move from the conventional, single-species approach to EAFM began over two decades ago (see Guénette et al. 2014 and references therein) and this has subsequently been advanced for forage fish (Pikitch et al. 2012). Indeed, conventional approaches for setting LRPs, such as $B_{recover}$, B_{min}, surplus production models, and $F_{X\%SPR}$, are generally employed for forage fish (see Guénette et al. 2014 for a review). We explored these approaches and they were either not valid, or were considered weaker approaches compared to the capcod approach (Table 2,3). Although EAFM is not typically used for setting LRPs, the revised Fisheries Act includes an “ecosystem approach” in its Considerations for decision making in addition to the environmental conditions affecting the stock which the Minister must already take into account. EAFM is also consistent with DFOs Policy on New Fisheries for Forage Species (DFO 2009b) which considers the threshold of serious harm to apply to both target and ecologically dependent species. The EAFM approach has also been advanced by national (NOAA Fisheries. 2016) and international bodies (Möllmann et al. 2014). Therefore, the capcod approach, in addition be being consistent with the approach used for management of the Barents Sea and IEGJM Capelin stocks as well as other major forage fish stocks, is consistent with policies and recommended approaches that acknowledge the importance of forage fish in the ecosystem and as the main prey for stocks of larger commercial fisheries.

SUMMARY

A suite of LRP approaches were considered for 2J3KL Capelin but most approaches did not meet the criteria of being feasible, reliable, and plausible and, therefore, were not considered valid. The three LRP approaches that did meet these three criteria (i.e., were valid) were further assessed based on their strengths and weaknesses. Of these, the LRP based on the capcod model was clearly the most robust approach and was accepted by consensus during the CSAS Regional Assessment Process (DFO 2024). The LRP for 2J3KL Capelin is 640 kt and is conceptually consistent with LRPs for other major Capelin stocks. The 2J3KL Capelin stock was estimated to be 262 kt and is therefore currently in the Critical Zone (Figure 5).

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TABLES

Table 1. Predictions of trends in environmental, community, and stock level variables if the hypotheses of a single but perturbed system returning to its original state (single state) or a new, alternate state (alternate state) are true.

State	Environmental	Community	Stock Level
Single	The indicator will vary without trend before and after the pre-regime shift.	The indicator returns to patterns consistent with the previous state in terms of variability and community composition.	The population may remain in a prolonged low phase, but stock traits would be expected to be consistent with a perturbed/stressed population (e.g., truncated age structure, increased length-at -age for young fish followed by early maturation).
Alternate	If in a new environmental state, the environmental indicator will be different than pre-regime shift. If a new community state, the environmental indicator will be similar to the previous state in the medium to long term (hysteretic – see next column).	A new pattern in community composition will emerge for a given indicator.	A lower population level associated with a stable alternate state (e.g., reduced carrying capacity) would be expected to show stock traits more consistent with pre-regime shift (no or little truncation in age structure, no change in length- or maturation-at-age).

Table 2. Summary of LRP approaches considered for 2J3KL Capelin with general method of estimation and specific method of calculation, whether the criteria (feasible, reliable, plausible, and associated uncertainties) are met, and the proposed LRP (kt = kilotonnes) if applicable. Uncertainties in data, parameters (params), and model structure (str) are used to evaluate reliability. See text for acronyms and citations. If one criterion is not met, subsequent criteria are not evaluated (NA).

LRP approach	Estimation	Method	Feasible	Reliable	Plausible	Uncertainties (parameters, structure)[1]	LRP (kt)
Proportion B_{MSY}/ B_0	Age- or size-structured, DD	IPM	Yes, but incomplete	NA	NA	NA	-
	SPM	JABBA	Yes	No	NA	Params - Value of the *r* prior affects model (see Appendix 2) Str - process error explains most of the total variation	-
	Catch only; CLS	CMSY	Yes	No	NA	See SPM	-
B_{MSY} proxy – $F_{X\%SPR}$	Estimate *F* and *SPR*	Calculate	No	NA	NA	NA	-
X% R_{max}	SRR	Beverton-holt, Ricker	Yes	No	NA	Params – NA Str – large differences between SR curves	-
Historical - Time series[2]	B_{loss},	Lowest value	Yes	Yes	No	NA	-
	$B_{recover}$	Expert judgement	Yes	Yes	Yes	Data – concerns over 1982 value Params & Str – NA	446
	B_{min}	Percentiles	Yes	No	NA	LRP values varies widely based on percentiles values	-

LRP approach	Estimation	Method	Feasible	Reliable	Plausible	Uncertainties (parameters, structure)[1]	LRP (kt)
B_{MSY} / B_0 – historical proxies	Estimate of high or pre-exploitation stock size	mean or median multiplied by a fraction	Yes	Yes	Yes	Params - Uncertainty in years used for when indicator is high Str - NA	741
Ecosystem Approach	Bioenergetic-allometric	capcod	Yes	Yes	Yes	Params - acceptable Str - acceptable	640

[1] All approaches depend on the spring acoustic survey and its associated observation error, i.e., this uncertainty underlies all LRP approaches for this stock. Therefore, only parameters and structural uncertainties are discussed with the exception of $B_{recover}$.

[2] Historical values can be based on the observed values or model-based values but the latter were not available due to lack of a model.

Table 3. A summary of the strength and weaknesses of the three valid LRP approaches with the associated decision and LRP value (kt = kilotonnes).

VALID LRP APPROACH	STRENGTHS	WEAKNESSES	DECISION	LRP VALUE (KT)
$B_{RECOVER}$	Value not influenced by model assumptions (empirically based) Recommended for stocks with occasional large year classes, i.e., stocks with spasmodic recruitment 1982 survey point is consistent with data from predator stomachs from early 80s	Based on one point – 1982 (risk associated – no replication, no measure of variation) Concerns over 1982 survey (timing in particular) Uncertainty in catch levels during that time Assumption of possible recovery in future depends on prevailing conditions relative to 1982 Diet data do not provide stock index Weak approach relative to other options	Rejected	446 kt
Proxy B_0	LRPs derived from empirical indicators are based on (multiple) observable quantities that do not rely on assessment model assumptions Clear indication that the time period chosen is a productive one	Multiplier is somewhat arbitrary Wide variation in practice for selecting historical time periods, and thus may be variation in suitability for approximating B_{MSY} or B_0	Rejected	741 kt (0.2 multiplier) 1,100 kt (0.3 multiplier)

VALID LRP APPROACH	STRENGTHS	WEAKNESSES	DECISION	LRP VALUE (KT)
		Difficult to justify what we are choosing as the proxy, i.e., B_{MSY} or B_0		
capcod	Solid theoretical and analytical foundation Applied in another system and parameter values are virtually identical (replication) Consistency in LRP settings between Capelin and cod Ecosystem approach based on a solid foundation of analytical work	Approach does not explicitly consider demographic impairment in the Capelin stock itself Model assumptions (e.g., capelin prey replacement parameter is constant)	Accepted	640 kt (1983–89)

FIGURES

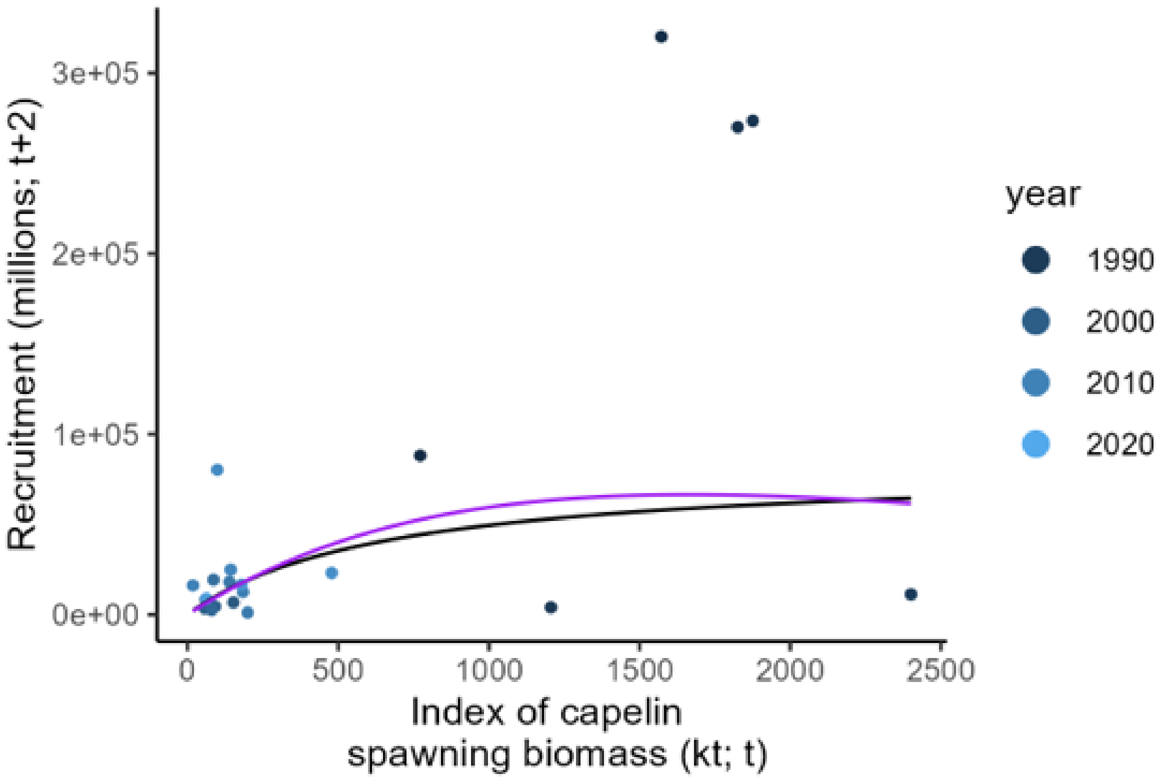

Figure 1. The stock recruit relationships for NAFO division 2J3KL Capelin (1985–2022) using Beverton-Holt (black) and Ricker (purple) approaches. Kt = kilotonnes; t = time (year).

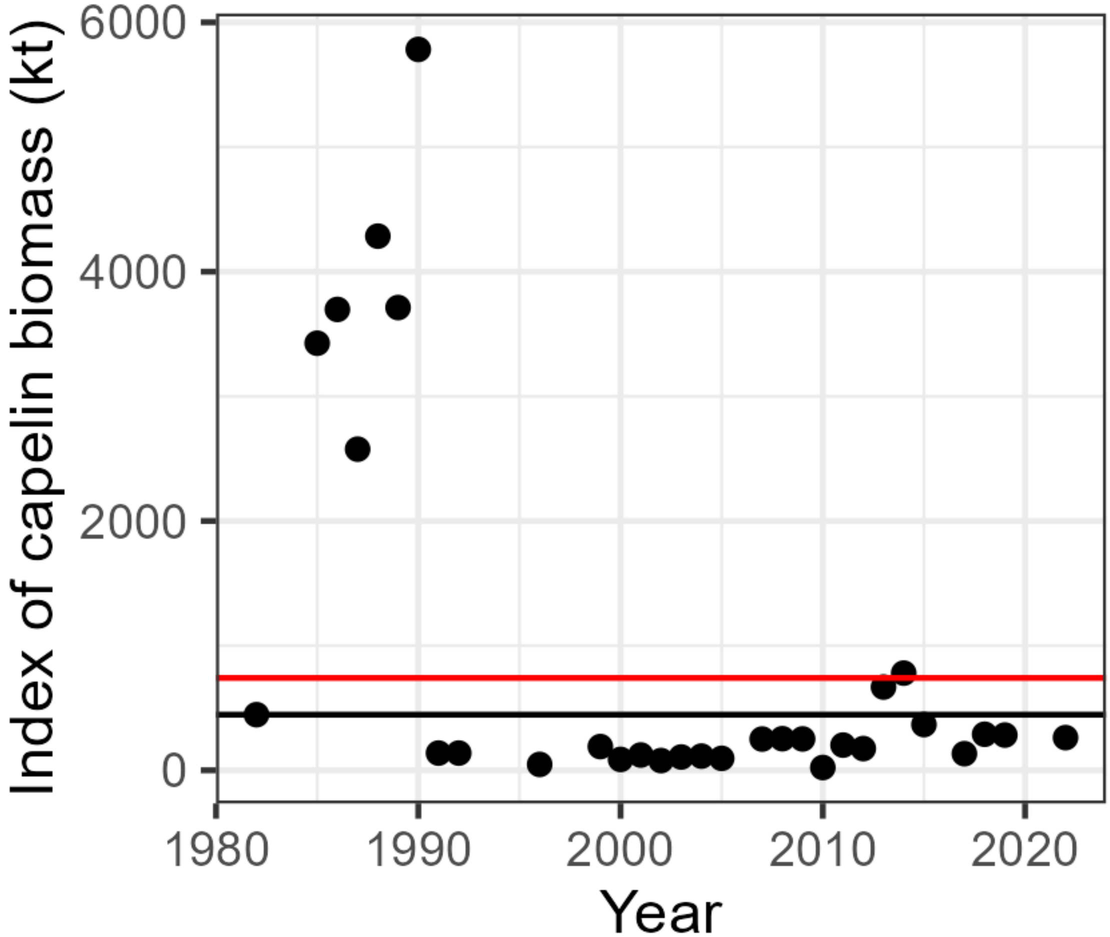

Figure 2. The biomass index for NAFO division 2J3KL Capelin in kilotonnes (kt) from the spring acoustic survey. The value in 1982 (solid, black line) is the lowest value that produced recruitment that lead to stock recovery, i.e., $B_{recover}$ (446 kt). The B_0 proxy is 741 kt (solid red line).

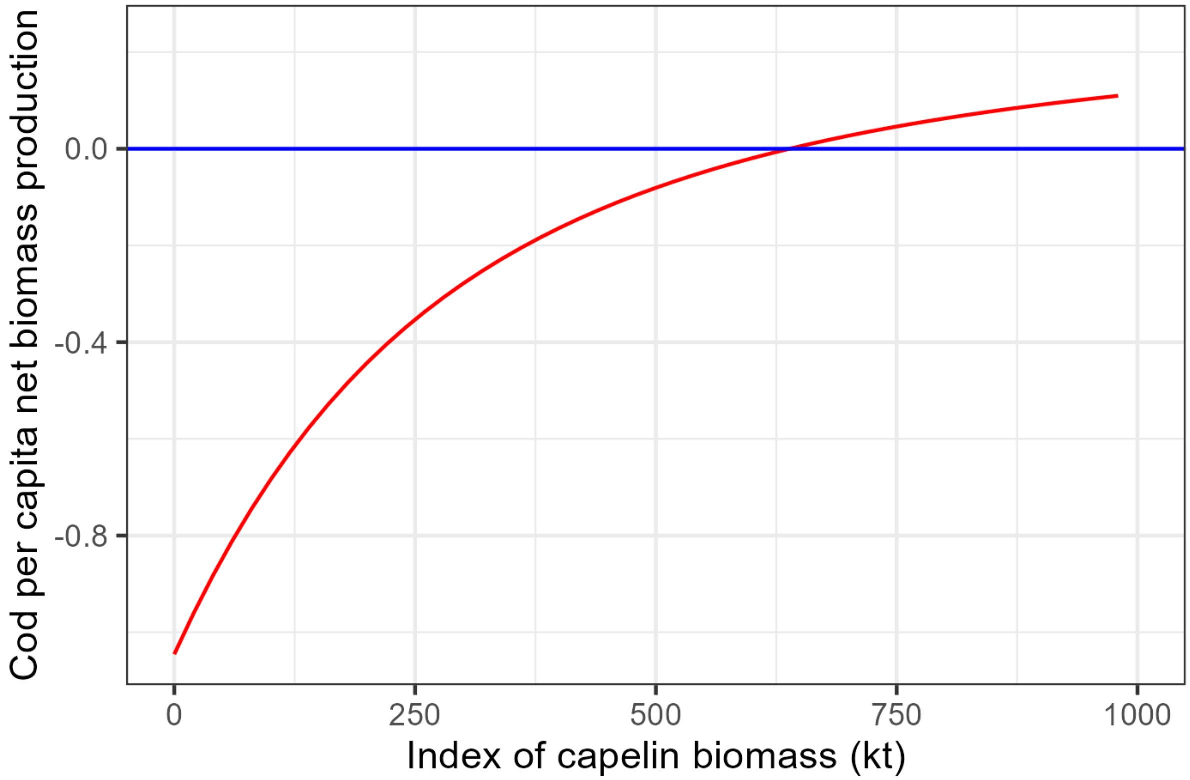

Figure 3. Cod net per capita production (red line) for a cod biomass level (1,500 kt = kilotonnes) consistent with cod Limit Reference point (average SSB from 1983–89) as a function of Capelin biomass as measured in the spring acoustic capelin survey (biomass index) as estimated by the capcod model (Koen-Alonso et al. 2021). A value of zero (blue line) corresponds to no expected change in cod biomass, indicating a stable cod population. The average biomass index required for the cod stock to reach and stabilize at its LRP is 640 kt (red line intersects blue).

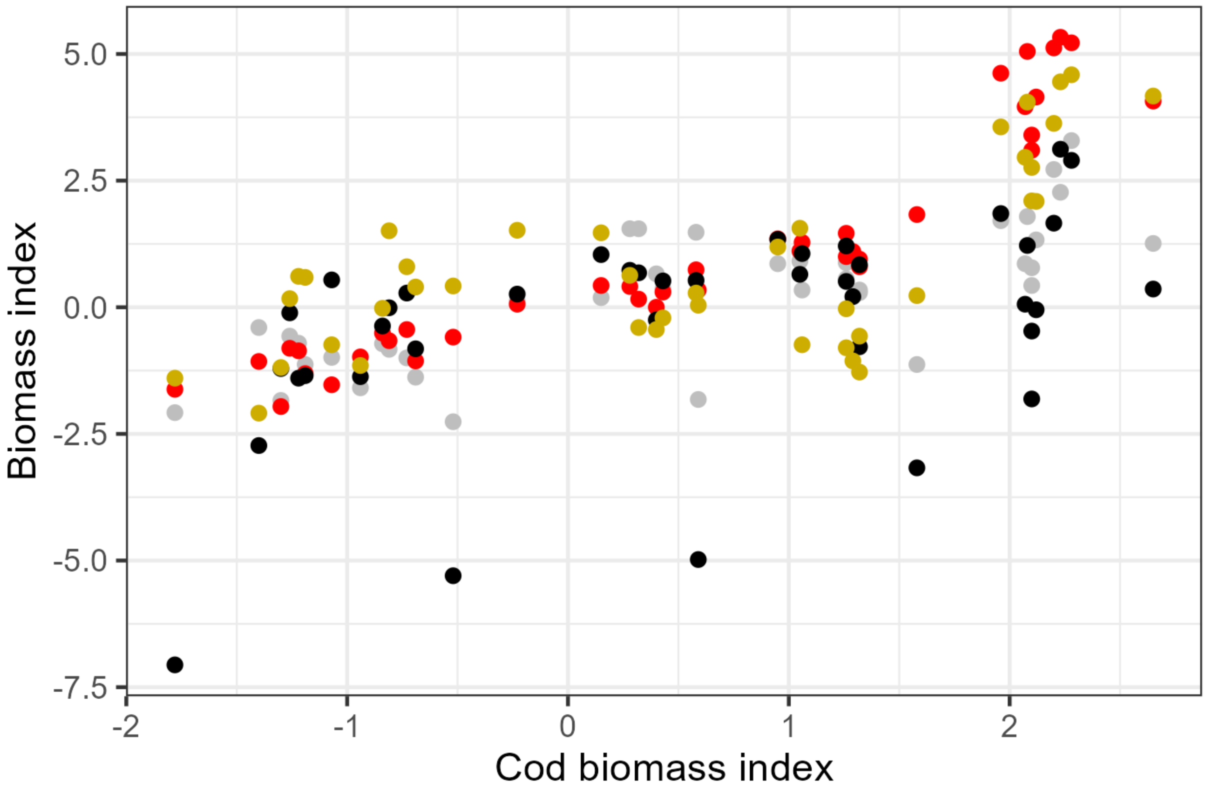

Figure 4. The relationship between the biomass of cod and several finfish functional groups (Koen-Alonso and Cuff 2018, NAFO 2021) from the DFO annual fall multi-species survey in North Atlantic Fisheries Organization Divisions 2J3KL. Values have been transformed (natural log) to facilitate displaying relationships with large differences in range and magnitude (normalization), but these transformations do not affect the rank correlations. Red = Plank-piscivores; yellow = Large Benthivores; black = Medium Benthivores; grey = non-cod Piscivores.

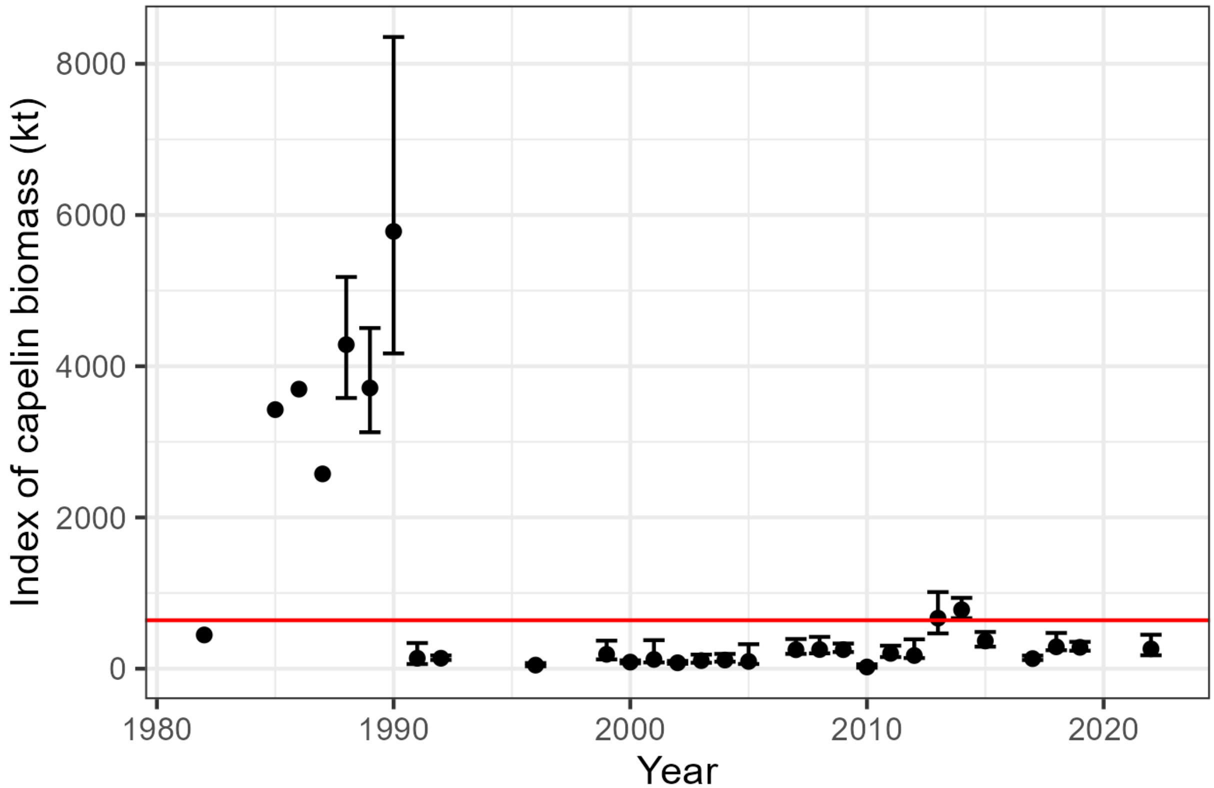

Figure 5. The index of capelin biomass with 95% confidence intervals from 1982–2022 with the Limit Reference Point (horizontal red line; 640 kt).

APPENDIX 1: INVALID APPROACHES

PROPORTION OF B_{MSY} OR B_0

Surplus Production Models

Surplus Production Models (SPM, also known as biomass dynamic models) have been used extensively for stock assessments despite their well-known limitations (Hilborn and Walters 1992). In earlier SPM formulations, the models did not account for depensation, i.e., reductions in the rate of recruitment at low biomass, and this resulted in an assumption of an increase in the biomass growth rate as biomass approaches zero (Froese et al. 2017; Schnute and Richards 2002). These problems have been somewhat ameliorated by a simple hockey stick model that assumes constant stock recruitment above a threshold and a linear decline below it (Froese et al. 2016). However, SPMs do not account for stock age structure which can be problematic when modelling stocks with variable recruitment, short life-spans, post-spawning mortality, or that are bottom-up driven. Finally, all SPMs assume that the parameter *r* captures growth, natural mortality, maturity, and recruitment.

Despite these limitations, we used package JABBA (Winker et al. 2018) which was developed to make Bayesian state-space SPMs relatively easy to perform using a R (R Core Team 2022) to JAGS (Plummer 2003) interface. Package JABBA is relatively easy to run, can perform Schaefer, Fox, and Pella-Tomlinson versions of SPMs, and generates a number of standardized and useful outputs (e.g., Kobe plots and B_{MSY} estimates).

Package JABBA can utilize multiple indices. Thus, in addition to the spring acoustic survey, we also included acoustic surveys conducted by the former USSR in the spring and fall in 2J3KL. The USSR fall surveys were conducted from 1982–92, generally in November and mostly in 2J3K. The USSR spring acoustic survey was conducted in 3LNO from 1975 to 1994 although coverage varied substantially (Buren et al. 2019). A Canadian fall acoustic survey was conducted from 1981 to 1991 but cohorts do not track well across years and therefore, this survey will not be considered in this analysis. Note that the Soviet spring and fall acoustic surveys have not been quantitatively compared to the NL index and their relationship to each other is unknown. Further, the Soviet surveys conflate the 2J3KL and 3NO Capelin populations (DFO 2021a). Utilization of the Soviet surveys in future analyses requires further investigation. We also used Capelin landings which have been reported since 1972. The fishery was dominated by an offshore fishery that captured both mature and immature fish in the 1970s. In 1978, an inshore fishery for roe-bearing female Capelin began. After the collapse of the 2J3KL Capelin stock in 1991, the offshore fishery ended. The inshore fishery has averaged 25 kt with decreases in total allowable catches in recent years (DFO 2021a). Fisheries landings do not necessarily reflect the total fishery-induced mortality in the inshore fishery as catches may be discarded due to red feed content, inadequate roe percentage, and small Capelin size. These issues were most predominant prior to the early 1990s, when a test fishery was put in place to ensure marketability of the catches prior to opening of the fishery and consequently, discarding was reduced.

Models were run with the catch data and the acoustic survey alone, and also with the USSR surveys. For *K*, we used both the maximum (5,783 kt) observed biomass and the median (3,704 kt) biomass from 1985–90 as a starting point for the priors. Given that JABBA has an option for inputting *K* as a range, we then tested diffuse and more informative priors around these values. For the point estimate of *r*, we used the values from Fishbase (Froese and Pauly 2022) and the max observed *r* in the time series not counting the change from 2010 to 2011 (see Data – Spring Acoustic Survey section). For the variability of *r*, we used the observed SD from the time series as well as more diffuse values. Rather than using the JABBA defaults for the variable psi, which is used to estimate the ratio of spawning biomass in the first year to *K*, i.e., an initial biomass depletion ratio, we used a lognormal mean of 0.5 and a CV of the same value for two reasons. First, this stock had been fished since the 1970s and the acoustic survey began in 1985 so it is unlikely the stock is at K. Second, we thought it prudent to create a more uninformative prior given our poor understanding of what value K might take for this species. For the process error (sigma), we used an uninformative prior and employed an inverse gamma distribution (shape = 0.01, rate = 0.01). In JABBA, catchability (q) is normally allowed to vary. However, we were consistently getting values > 1 which is difficult to explain for an acoustic survey. We therefore modified the JABBA code so that q was uniformly distributed between ~0 and 1.

However, in all the formulations of the model and despite using a variety of priors, the process error explained much of the variability in the data while the underlying process model explained relatively little of the population dynamics over time. Further, all of the models estimated *r* near zero. Finally, even when we used an informative prior for *r*, *K* declined and F/F_{MSY} increased suggesting that the value of the prior has an undue affect upon the model.

Therefore, this approach is feasible but not reliable.

HISTORICAL

B_{loss} is the biomass corresponding to the lowest observed stock size. The lowest observed value from the acoustic survey was in 2010 so using this approach, the LRP = 23 kt. However, 2010 was likely a very poor year for Capelin and the spring acoustic survey clearly missed a portion of the stock (see Data – Spring Acoustic Survey section). If the 2010 biomass index value is eliminated, the lowest value is 1996 and the LRP = 47 kt. This LRP is feasible and, within the context of observation error, is reliable. But given that 4 kt is ~ 1% of the median of the most productive period and ~6% of the highest value of the post-collapse period, and that the stock is considered to be in a collapsed state since 1991, this value was considered to be an unplausible boundary for a stock experiencing serious harm.

B_{min} is the lowest observed biomass from which a recovery to average has been observed or other minimum biomass that produced “good” recruitment. This approach is similar to the Barents Sea approach and a recognized ICES approach (see Discussion). While feasible, B_{min} is not reliable in this case because the 80^{th} and 90^{th} percentile for recruitment are produced by 174 kt (2012) and 3.7 Mt (1987) respectively, i.e., small changes in the percentiles produce wildly different biomasses and LRPs. Further, there are no values between the high and low productivity phases which also suggests that B_{min} is not a reliable approach.

APPRENDIX 2: APPROACHES THAT WERE NOT PURSUED

CATCH-ONLY

Froese et al. (2017) introduced the CMSY method which addressed some of the shortcomings of its forerunner, Catch-MSY. CMSY is similar to package JABBA in many respects. CMSY is a Bayesian state-space implementation of the Schaefer surplus production model. Like package JABBA, CMSY is fitted to catch and biomass or catch-per-unit-effort data. Where they differ is that CMSY uses catch and productivity to estimate biomass and uses a Monte Carlo approach to detect *r-K* pairs. These pairs are considered viable if the calculated biomass is compatible with the observed catches.

Catch-only approaches have been developed primarily to assess the global status of unassessed stocks (e.g., Costello et al. 2012; Kleisner and Pauly 2011; Palomares et al. 2020). These models assume that catch is proportional to abundance which is not the case with 2J3KL Capelin for much of the time series, as fishing effort is driven by market forces, not abundance, and prior to the early 1990s, there was likely a high amount of unreported discards. Further, recent reviews have evaluated the performance of catch-only methods to estimate stock status (Free et al. 2020; Ovando et al. 2022; Sharma et al. 2021) and found that they produced biased and imprecise estimates of stock status. For a brief review of these methods, see Appendix A in Barrett et al. 2024.

Finally, an effort to produce an LRP using this approach yielded results that are similar to package JABBA which is not surprising given the similarity in the methodology (Jubinville et al. 2022). The same issues and limitations should apply to this method as to package JABBA and diagnostics are not provided. Therefore, while this approach is feasible, it is not reliable.

AGE-STRUCTURED MODEL

Considerable efforts were devoted to developing a Bayesian state-space, age-structured model that incorporated the environmental aspects of the capelin forecast model (Lewis et al. 2019). Significant progress was made but a functioning model with all the associated diagnostics was still at least 1–2 months away at the time of the Capelin assessment. Progress was hindered by structural issues within the data including a number of years where the abundance of immature, age-2 fish at time t was approximately equal to or less than the number of age-3 fish at time t+1, Soviet data was not directly comparable to Canadian data, and concern over the amount of post-spawning survival (Flynn 2001). The structural issues with the data and post-spawning survival are being resolved, but the comparability of the Soviet acoustic data to the Canadian acoustic data will require substantial effort and may not be feasible. It is hoped that it is feasible to produce a useful age-structured model and it is a Research Recommendation, but as it was not completed, it will not be considered further in this document.

MULTI-INDICATOR

The "traffic light" or multi-indicator approach can be used where a threshold for serious harm is known for multiple indices. An example of the multi-indicator approach is the NL snow crab (*Chionoecetes opilio*) LRP (Mullowney et al. 2018; Mullowney and Baker 2023), where three metrics of stock health aim for both biological protection and fishing efficiency.

The advantage of the multi-indicator approach is that reliance on a single indicator for an LRP can be misleading. For example, it is well known that the reproductive potential of a SSB composed of small fish is far less than one composed of large fish, i.e., the relationship is allometric, and therefore, an LRP based on SSB may be deceptive if size-structure is truncated. The multi-indicator approach could also be useful if some of the indices are relevant for predicting future stock size. For example, larval density of Capelin at time *t* has been shown to be a reasonable predictor of recruitment at time *t*+2 (Murphy et al. 2018). This could give advanced warning as to the state of the stock.

However, the multi-indicator approach was not deemed to be appropriate for Capelin. Although multiple indices (i.e., ice, condition, and larvae) are used for projecting the index from the acoustic survey, these values are already incorporated into the forecast of this index (Lewis et al. 2019) rendering this approach redundant as a candidate LRP. Further, some of the relationships in the forecast model are not as robust as in previous years making them less reliable as the basis for an LRP (DFO 2023).

LENGTH-BASED APPROACHES

Given that many stocks are data-poor and that fish length is commonly measured, a number of length-based approaches to stock assessment have been developed, and these can be used to estimate *F*-based LRPs (Barrett et al. 2024). These approaches include length-based spawning potential ratio (LBSPR), length-based integrated mixed effects (LIME), and length-based Bayesian approach (LBB). These approaches were reviewed and compared to catch-based methods by Pons et al. (2020). The assumptions underlying many of these methods is that the stock is under equilibrium conditions, and that average length in the catch declines due to either high fishing mortality or size-selective fishing mortality where the larger fish are removed from the population.

However, these assumptions are not valid for 2J3KL Capelin for at least three reasons. First, truncation of the age-distribution in the post-collapse period has eliminated the older, larger fish but there is no indication that these older age classes were lost due to fishing. Second, 2J3KL Capelin display a negative relationship between length of age-2 fish and strength of the age cohort suggesting a density-dependent response independent of fishing. Finally, it is generally believed that fishing takes a relatively small proportion of this stock in most years because the landings are a fraction of the acoustic survey index, which itself is an unknown fraction of the total stock. Given that the fishery is targeted towards spawning fish that would likely die in the weeks following spawning, size-selective fishing is unlikely to occur (Murphy et al. 2023). This assertion is supported because the length of age-3 and age-4 fish have remained largely the same since the population collapse in 1991 and age-3 lengths remain similar to the pre-collapse period.

We also chose not to employ length-based approaches because these methods have been developed for data-poor stocks that lack age-structure data. While there are certainly limitations with the data associated with the 2J3KL Capelin stock (see Data section), the stock is not data-poor or data-limited.

APPENDIX 3: TIME PERIODS AND MODELS USED FOR COD AND CAPELIN LRPS

The cod LRP is based on the mean SSB of the 1980s which was the last period to produce medium levels of recruitment (DFO 2011). However, with the development of the Northern Cod Assessment Model (NCAM, Cadigan 2015), the mean SSB from 1983 to 1989 has been used as the basis of the cod LRP because the multi-species survey began covering all of NAFO divisions 2J3KL in 1983 and NCAM was not designed to utilize catch and tagging data collected prior to this time.

Unlike NCAM, capcod does not calculate SSB. Capcod was intended to model the whole cod stock and therefore, predicts cod biomass. However, biomass can be considered a proxy for SSB and the two indicators show similar trends in the NCAM outputs. Therefore, for the Capelin LRP, the cod LRP was the average cod biomass from 1983 to 1989 as calculated by capcod (1,500 kt), not as calculated in NCAM.

Note that the cod LRP is scheduled to be reviewed in the fall of 2023 and a change will require the Capelin LRP to be recalculated.

Also note that some consideration was also given to a capcod-based average cod biomass from 1987 to 1990 in order to characterize the immediate, “pre-collapse” state for both stocks. The resulting Capelin LRP was 480 kt but this option was not considered further because it did not correspond to the time period used for the current cod LRP.