Fisheries and Oceans Canada
Pêches et Océans Canada

Ecosystems and Oceans Science
Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2024/042

Gulf Region

Gaspereau Assessment for the Gulf Region to 2019: Population Dynamics, Reference Points and Status

A. Jamie F. Gibson[1] and Cindy Breau[2]

[1]Fisheries and Oceans Canada
Maritimes Region Science Branch
One Challenger Drive
Dartmouth (NS) B2Y 4A2

[2]Fisheries and Oceans Canada
Gulf Region, Science Branch
343 University Avenue
Moncton (NB) E1C 9B6

June 2024

Canada

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.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-72174-3 Cat. No. Fs70-5/2024-042E-PDF

Correct citation for this publication:

Gibson, A.J.F. and Breau, C. 2024. Gaspereau Assessment for the Gulf Region to 2019: Population Dynamics, Reference Points and Status. DFO Can. Sci. Advis. Sec. Res. Doc. 2024/042. iv + 53 p.

Aussi disponible en français :

Gibson, A.J.F. et Breau, C. 2024. Évaluation du gaspareau dans la région du Golfe jusqu'en 2019 : dynamique des populations, points de référence et état de la situation. Secr. can. des avis sci. du MPO. Doc. de rech. 2024/042. iv + 56 p.

TABLE OF CONTENTS

ABSTRACT

This working paper was prepared in support of the “Assessment of the status of gaspereau stocks of the southern Gulf of St. Lawrence (sGSL)” Regional Advisory Process, April 20-21, 2021. Reference points and assessment approaches for gaspereau (Alewife and Blueback Herring) fisheries; and the status of the Margaree River Alewife population, are provided in this paper. Fisheries and Oceans’s (DFO) precautionary approach to fisheries management allows for assessment relative to biomass or abundance reference points and relative to removal reference levels. The spawner biomass that produces maximum sustainable yield (MSY) is proposed as the upper stock reference level, and the biomass at which the recruitment is reduced to one half the maximum recruitment as the limit reference point. Because of the inherent variability in gaspereau population size and fisheries, the removal reference level when the population is in the healthy zone is defined as a fully-exploited zone ranging from the exploitation rate that produces 90% of MSY up to the exploitation rate that produces MSY. Data availability is a limiting factor for assessing gaspereau populations and fisheries throughout the Maritime Provinces. Age-structured assessment models are appropriate for populations with sufficient data; currently the Margaree River Alewife population is the only gaspereau population in DFO’s Gulf Region where this approach can be applied. For populations without data, collection of age and previous spawning information provides a mechanism to assess fisheries relative to removal reference rates. This approach has been demonstrated to bring exploitation rates into the appropriate range when coupled with management actions. Five variants of age-structured models were fit to data for the Margaree River Alewife population. Although status determinations vary among models, all models place the spawner biomass near the critical cautious boundary or in the cautious zone, and the exploitation rate in the over-exploited zone for the majority of years from 1983 to 2019.

1. INTRODUCTION

This working paper was prepared in support of the “Assessment of the status of gaspereau stocks of the southern Gulf of St. Lawrence (sGSL)” Regional Advisory Process, April 20-21, 2021. “Gaspereau” is a colloquial name for two anadromous species of fish, Alewife (*Alosa pseudoharengus*) and Blueback Herring *(Alosa aestivalis*). Where both species co-exist, they are harvested and marketed together as “gaspereau”. Fisheries are geographically widespread, with fishing practices and gear types that differ among rivers, and are managed primarily through effort controls (Breau and Gibson 2024, Gibson et al. 2016). There is strong evidence that anadromous *Alosa* home to natal rivers, including tagging studies that show homing to rivers of previous spawning in both American shad (a closely related species) and gaspereau, as well as genetic studies that show substantial differentiation among samples collected from different rivers (McBride et al. 2014, Palkovacs et al. 2014). As such, fisheries located in rivers and estuaries primarily target individual populations, and these individual populations of each species can be considered the appropriate level for assessing the status of these stocks (*sensu* DFO 2001; ASMFC 2012a,b; Gibson et al. 2016). Within the DFO Gulf Region, commercial gaspereau fisheries in the Margaree and Miramichi rivers have historically been the major fisheries in Gulf Nova Scotia and Gulf New Brunswick, respectively, and therefore, were chosen for monitoring in their specific areas. The status of gaspereau stocks in this region has not been regularly assessed. The last published assessment of the status of gaspereau stocks in the Gulf Region was published in 2001 (DFO 2001).

This working paper is one of two that were prepared for this advisory process. It addresses the Terms of Reference pertaining to:

1. Estimates of total biomass as derived from population models for the Margaree River;
2. Estimates of absolute fishing mortality rates for the stocks;
3. Develop reference points by species against which to assess stock status; and
4. Develop indicators of stock status which can be used to inform fisheries management in the intervening years of the multi-year assessment and management cycle.

These Terms of Reference are addressed via:

1. An adaptation of a life cycle based population model used to estimate fishery reference points for Alewife consistent with DFO’s precautionary framework for fisheries management (2006) – Section 2;
2. Adaptations of life-cycle-specific stock assessment models used to estimate abundance and fishing mortality rates for the Margaree River Alewife population – Section 3.1;
3. For stocks that are not currently assessed, a proposal for their assessment via the collection of biological characteristics data based on a management strategy evaluation – Section 3.2.

The other working paper (Breau and Gibson 2024), addresses the terms of reference pertaining to:

1. Description of present and recent management measures and catches to the end of 2019, including best estimates of total removals by all fisheries;
2. Overview of species biology and characteristics (for ex. size at age, age at maturity);
3. Indicators of stock status and trends (commercial catch rates, fishery independent indices) by size and age group (if available);

4. Description of the impacts of fishing activities for gaspereau on other species and fish habitat;
5. Description of the impacts of fishing activities for other species on gaspereau stocks; and
6. Description of ecosystem components which are modifying the species abundance and population dynamics (for ex. temperature, predators, prey).

2. POPULATION DYNAMICS, PRODUCTION AND BIOLOGICAL REFERENCE POINTS

This section applies the work of Gibson and Myers (2001, 2003a, 2004) for the development of reference points for gaspereau in the Gulf Region. In these papers, a model based on the life cycle of anadromous *Alosa* was developed to analyze the population dynamics of Alewife and to estimate reference points for stock assessment. Their work is an adaptation of an approach for estimating reference points described by Sissenwine and Shepherd (1987) that is now standard in many marine fishery stock assessments where MSY reference points or their proxies are derived when the population is at equilibrium (Quinn and Deriso 1999). The difference between the *Alosa*-specific models and the models used for marine fish stock assessments is that the spawner-biomass-per-recruit (SPR) and yield-per-recruit (YPR) relationships are changed to match the life cycle of anadromous *Alosa* and their in-river fisheries (Gibson 2004) and specifically address the issues that arise when fisheries almost exclusively harvest mature fish. This model (and/or components of it) has previously been used for an Alewife fishery in Canada (Gibson and Myers 2001), for gaspereau in the USA (ASMFC 2012a,b), and was used to develop reference points for Alewife fisheries in DFO’s Maritimes Region (Gibson et al. 2016). The notation used in the model description below differs from the work published by Gibson and Myers and better matches modern conventions.

Reference points discussed in this document are defined in Table 1. Following Gibson and Myers (2003a), we modeled the population dynamics and fishery yield of alewives using three equations: a spawner-recruit (SR) relationship that expresses recruitment as a density dependent function of spawner biomass, a spawner biomass per recruit (SPR) relationship and a yield-per-recruit (YPR) relationship. The model formulations are configured to match the life cycle and in-river fisheries for anadromous *Alosa* (Gibson 2004). We choose age-2 as the age of recruitment (the oldest age that could be chosen prior to fish entering the fishery). Inputs to the model are: a spawner-recruit time series, estimates of weight-at-age, maturity schedules, and estimates of the immature and adult instantaneous natural mortality rates. The number of recruits was calculated from the assessment models used to estimate abundance as described in Section 3.1.1.

2.1. THE SR MODEL

We used the Beverton-Holt spawner-recruit function to model the SR relationship. This model and Ricker model are the most commonly used two parameter spawner-recruit models (Hilborn and Walters 1992). Gibson and Myers (2003c) found that the Beverton-Holt model provided a consistently better fit to Alewife spawner-recruit data than did the Ricker model. The Beverton-Holt spawner-recruit model gives R_t as a function of the spawning biomass in year t, SSB_t:

$$R_t = \frac{\alpha SSB_t}{1 + \left(\frac{SSB_t}{K}\right)}$$

Here, α is the slope at the origin, and in the deterministic model is the maximum rate at which spawners can produce recruits at low population sizes (Myers et al. 1999) and K is the half-saturation constant (the value of SSB that produces half the maximum recruitment). Parameter estimates for the SR model were obtained by using maximum likelihood assuming a lognormal error structure for recruitment (Myers et al. 1995). Denoting the Beverton-Holt spawner-recruit function as $g(s_i)$, the log-likelihood is given by:

$$\ell(\alpha, R_0, \boldsymbol{\sigma}) = -\boldsymbol{n} \log \boldsymbol{\sigma} \sqrt{2\pi} - \sum \log r_i - \frac{1}{2\sigma^2} \sum \log\left(\frac{r_i}{g(s_i)}\right)^2$$

where s_i and r_i are the observed spawner biomass and recruitment data, σ is the shape parameter and n is the number of paired SR observations.

2.2. THE SPR MODEL

We modelled the rate at which recruits produce spawners by calculating the spawner biomass per recruit (*SPR*) as a function of the instantaneous fishing mortality rate, *F*.

$$SPR_F = \sum_{a_{rec}}^{a_{max}} SS_a w_a e^{-F}$$

where SS_a is given by:

$$SS_2 = m_2$$

$$SS_3 = SS_2 e^{-(M^{adult+F})} + (1 - m_2) e^{-M^{juv}} m_3$$

$$SS_4 = SS_3 e^{-(M^{adult+F})} + (1 - m_2)(1 - m_3) e^{-2M^{juv}} m_4$$

$$SS_5 = SS_4 e^{-(M^{adult+F})} + (1 - m_2)(1 - m_3)(1 - m_4) e^{-3M^{juv}} m_5$$

$$SS_6 = SS_5 e^{-(M^{adult+F})} + (1 - m_2)(1 - m_3)(1 - m_4)(1 - m_5) e^{-4M^{juv}} m_6$$

$$SS_7 = SS_6 e^{-(M^{adult+F})}$$

$$SS_{a_{max}} = SS_{a_{max}-1} e^{-(M^{adult+F})}$$

Here, *a* is the age of the fish and m_a is the probability that a fish that is alive at age *a* will mature at that age, and M^{adult} and M^{juv} are the instantaneous natural mortality rates of mature and immature fish, respectively. The value for M^{adult} is either obtained from the model used to estimate the abundance (Section 3), or an assumed value is used.

2.3. THE YPR MODEL

The yield per recruit for a given *F* (YPR_F) is found analogously to the spawning biomass per recruit for a given *F* above:

$$YPR_F = \sum_{a_{rec}}^{a_{max}} SS_a w_a (1 - e^{-F})$$

2.4. THE PRODUCTION MODEL

Equilibrium values occur where the rate at which spawners produce recruits (the SR model) equals the inverse of the rate that recruits produce spawners throughout their lives (Quinn and Deriso 1999). This is found using the standard method for finding the intersection of two lines (set them equal to each other, solve for one variable and substitute the result into one of the equations to obtain the other variable). For a given value of *F*, the spawning biomass produced by the number of recruits in year t is $SSB = SPR_F \cdot R_t$. Equilibrium spawning biomasses and recruitment levels (denoted with asterisks) were found by solving this equation for R_t, and substituting the result in the SR model (Quinn and Deriso 1999):

$$\frac{SSB^*}{SPR_F} = \frac{\alpha SSB^*}{1 + \frac{SSB^*}{K}}$$

The equilibrium spawning biomass (SSB^*) is then:

$$SSB^* = (\alpha SPR_F - 1)K,$$

and the equilibrium number of recruits (R^*) is found by substituting the SSB^* in the spawner-recruit model:

$$R^* = \frac{\alpha SSB^*}{1 + \left(\frac{SSB^*}{K}\right)}$$

The equilibrium catch (C^*) is R^* multiplied by the yield per recruit for the given value of F:

$$C^* = R^* \cdot YPR_F$$

2.5. REFERENCE POINT CALCULATIONS

Reference points from the spawning biomass per recruit and yield per recruit analyses were found using a grid search across a set of F's {0,0.02,0.04,0.06,......4.0}. We calculated YPR_F and SPR_F for each value of F, and reference points were then estimated by selecting the fishing mortality rate corresponding to the appropriate reference point criterion. The yield per recruit reference point, F_{max} was found by selecting the fishing mortality rate where YPR_F takes its largest value, and $F_{1.0}$ was found by selecting the fishing mortality rate where the marginal gain in yield was 10% that at F=0. The $SPR_{x\%}$ reference points were found by selecting the fishing mortality rate where the SPR_F was x% that of $SPR_{F=0}$.

We estimated five reference points from the production model. The equilibrium spawning biomass in the absence of fishing, SSB_{eq}, was estimated directly from the production model. A spawning biomass of 20% SSB_{eq} is often used as a minimum threshold population size (Beddington and Cooke 1983, Goodyear 1993). $SSB_{20\%}$ was calculated as 20% the equilibrium spawner abundance in the absence of fishing:

$$SSB_{20\%} = 0.2(\alpha SPR_{F=0} - 1)K$$

Grid searches were used to find the fishing mortality rate that produces maximum sustainable yield (F_{msy}), the corresponding spawner biomass that produces maximum sustainable yield (SSB_{msy}) and the fishing mortality rate that drives the population to extinction (F_{col}). We estimated F_{msy} by calculating C^* for each value of F, and selecting the value where C^* was maximized. SSB_{msy} was the value of SSB^* corresponding to this fishing mortality rate. The equilibrium fishing mortality rate at which the population goes extinct, F_{col}, is determined by the slope of the SR relationship at the origin α , and is the value of F where $1/SPR_{F=0} = \alpha$.

We calculated a decision-theoretic reference point, $F_{max.E(C)}$, which is the fishing mortality that maximizes the expectation of the catch (Gibson and Myers 2004), where the expectation of the catch, $E(C^*(F))$ is given by:

$$E\left(C^*(F)\right) = \iint C^*(F, \alpha, K) p(\alpha, K) dK d\alpha.$$

Gibson and Myers (2004) showed, via simulation, that this reference point produces higher yields than fishing at the maximum likelihood estimate of F_{msy} (the standard method of estimating it) while reducing the probability of over-exploiting the stock. They explored four methods of deriving $p(\alpha, K)$. Here, we only used the joint likelihood for α and *K* for its derivation. Further details are in Gibson and Myers (2004).

2.6. REFERENCE POINTS CONSISTENT WITH THE PRECAUTIONARY APPROACH

In 2006, Fisheries and Oceans Canada published a framework that includes policies to support conservation and the sustainable use of fisheries resources (DFO 2006). The precautionary approach (PA) framework applies to fish stocks for which Total Allowable Catch have to be determined based on harvest strategies or harvest rates. The PA framework has three main parts:

1. References points and stock status zones,
2. Harvest strategies and harvest decision rules, and
3. The requirement to incorporate uncertainty and risk in the development of reference points and the implementation of decision rules.

The three stock status zones in the PA framework (Figure 1) are separated by biological reference points (RPs). The Limit Reference Point (LRP) defines the boundary between the critical and cautious zones and represents the biomass below which the population faces serious harm. The LRP should be set to avoid risk of stock extinction, and detrimental effects to the ecosystem and long-term fishing opportunities. The Upper Stock Reference (USR) defines the boundary between the cautious and healthy zone below which removal must be reduced to avoid reaching LRP. The USR must be set at a level far enough from LRP to allow Fisheries Management to act upon the change in status and stocks to respond to management changes.

When a stock is in the healthy zone, a Removal Reference Level (RRL) is set as the maximum acceptable removal rate and includes all anthropogenic mortality. The removal rate should be lower in cautious zone and near zero in the critical zone. Serious harm in the PA framework includes both human-caused mortality and ecosystem changes not related to human activities. Although RPs are in place to protect stocks, social and economic perspectives are also considered in the establishment of the USR.

The selection of RPs within the framework depends in part on the data available for the fish populations and fisheries. When developing RPs consistent with the precautionary approach for DFO's Maritimes Region Alewife fisheries, for populations with sufficient data to estimate the reference points, Gibson et al. (2016) proposed to use population-specific reference values, using SSB_{msy} as the USR, and 10% of the unfished equilibrium spawner biomass ($SSB_{10\%}$) as the LRP. $SSB_{10\%}$ has the disadvantage that it is partially dependent on the adult natural mortality rate: as the natural mortality rate increases, $SSB_{10\%}$ decreases. An alternative for the LRP is to use the Beverton-Holt half-saturation constant, *K*. This reference point has the advantage that it depends only on the stock recruitment relationship and does not scale with the adult natural mortality rate. This approach is consistent with the idea that when avoiding serious harm, the PA framework should include both human-caused mortality and ecosystem changes not related to human activities.

Gaspereau fisheries are inherently variable and both abundance and fishing mortality rates can vary markedly from year-to-year. Rather than providing a single removal reference level for an Alewife fishery in the healthy zone, a similar approach to Gibson et al. (2016) was used where by a population was considered fully-exploited if the exploitation rate, *u*, was between the exploitation rate that produces MSY (U_{MSY}) and the exploitation rate that produces 90% of MSY

($U_{90\%MSY}$) and over-exploited if u was above U_{MSY}. The population would be considered under-exploited if it is in the healthy zone and u is below $U_{90\%MSY}$. Adoption of this approach is proposed here with the addition of a target exploitation rate in the fully-exploited zone. The reference point $U_{max.E(c)}$, is the rate that maximizes the expected yield, and can be the appropriate place to target the exploitation rate in the healthy zone[1].

The overall reference point framework is outlined in Table 2. The Margaree River Alewife population and fishery is the only one in the Gulf Region with sufficient data to estimate and apply these reference points using population-specific data.

For populations with only a few years of age-previous spawning composition data, catch curves provide a method to estimate the total mortality rate, and if a natural mortality rate is assumed (the estimated rate from the Margaree River is proposed as the most appropriate rate), the exploitation rate can be estimated. Catch curves are not without issue, but have recently been evaluated for Alewife for both accuracy and precision, and in a management strategy evaluation. This is discussed in Section 3.2.

Abundance or biomass reference levels are more problematic for populations with little data. For the Miramichi River, the trapnet CPUE from each branch can be used as an abundance or preferably biomass index. The issue is how to scale the trapnet CPUE to be able to derive MSY and K proxies (CPUE values) to be able to apply the framework. There are a few years with age-previous spawning composition data. These can be used to estimate the total mortality rate, and based on the assumption that the population dynamics in this river are similar to the Margaree population, these can potentially be used to map status relative to these reference levels.

Most, if not all fisheries in the smaller rivers do not have sufficient data for an assessment. Collection of species and age-ps composition data, possibly on a rotating basis, would provide a mechanism to assess these stocks using catch curves, but assessment relative to abundance or biomass levels would not be possible using this approach. This approach has been tested using a management strategy evaluation (Section 3.2). Sampling issues are discussed generally in Section 4.

Currently, there are very few data to derive reference points for Blueback Herring. This species is a very close relative to Alewife. Here, it is proposed that an assumption is made that their population dynamics are similar enough that the approach above, using the same reference levels, be adopted for Blueback Herring. A similar approach was used for Blueback Herring in ASMFC (2017).

3. ESTIMATION OF ABUNDANCE, FISHING MORTALITY RATES AND NATURAL MORTALITY RATES

3.1. MARGAREE RIVER ALEWIFE

3.1.1. Methods

Population models used to estimate abundance, fishing mortality rates and natural mortality rates for Margaree River Alewife are described in this section. Two age-structured models are

[1] The peer review meeting (DFO 2022) decided that, when in the healthy zone, having a single removal reference point (as opposed to a range) and using $U_{90\%MSY}$ as the target removal reference point was more appropriate. The text here differs from DFO (2022) for this reason.

used: a virtual population analysis (VPA) originally described by Chaput et al. (2001) and a statistical catch-at-age model (SCA), originally described by Gibson and Myers (2003b). Data available for fitting these models include:

1. The commercial landings (1983-2019);
2. Age-composition data representative of the number of fish caught in the commercial fishery by year, age and number of previous spawnings (1983-2019);
3. A larval abundance index considered an index of the spawner biomass (1983-2000 with missing years);
4. A catch-per-unit-effort (CPUE) index considered an index of the total abundance of fish returning to the river to spawn before fishery removals (1983-2019); and
5. Life history parameter estimates, including weight-at-age and natural mortality rates.

The commercial landings, age composition data, CPUE time series and life history parameter estimates are described in Breau and Gibson (2024). The larval CPUE abundance index is described in Chaput et al. (2001). Gaspereau in the Margaree River are predominantly Alewife, and abundance and mortality estimates are therefore produced for this species only.

Both models differ from traditional age-structured fishery models used for marine fish populations. The primary difference is that rather than tracking the abundance of individual year classes (cohorts) through time, sub-cohorts are defined based on year classes and the age-at-maturity. As such, rather than tracking abundance by year and age using a two dimensional matrix (year and age), the core of these models is a three dimensional array that tracks abundance by year, age and number-of-previous-spawnings. This approach is necessary because immature fish that do not return to the river to spawn are not available to the fishery. For this reason, the equations used to calculate at least the age-specific fishing mortality rates, spawner biomass, SPR and YPR in marine fishery models do not match the life cycle of *Alosa* species and the characteristics of their in-river fisheries (Gibson and Myers 2003b). The primary difference in the VPA and SCA model is that, in the VPA model, the catch-at-age-and-previous-spawning (CAAPS) history is assumed known without error; whereas in the SCA model, the model is fit to the CAAPS data allowing for errors in the reconstruction of this data input (Gibson et al. 2003b).

3.1.1.1. Statistical Catch-at-Age Models

Gibson and Myers (2001) and Gibson and Myers (2003a,b) provide descriptions of variations of a statistical catch-at-age model designed to estimate the abundance, fishing mortality rates and the natural mortality rate (sometimes) for anadromous *Alosa* species with in-river fisheries. The core of the model is a 3-dimensional array used to estimate the abundance through time by year, age and number of previous spawnings (ps). The model is fit to the available data by minimizing the value of an objective function which is the sum of the (sometimes weighted) likelihoods associated with each data set. Here, the available data are the CAAPS array, the larval index, the commercial CPUE index and the commercial landings (Breau and Gibson 2024). Several variants of the model were explored, including: adding or dropping the larval and/or CPUE time series, whether or not the natural mortality rate is estimated, and using different error structures when fitting to the CAAPS array. The model is as follows:

$$N_{t+1,a+1,p+1} = N_{t,a,p}(1-u_t)e^{M^{adult}}$$

Of interest is the number of fish returning to the river in year *t*, of age *a*, that have spawned *p* times previously, denoted $N_{t,a,p}$. Alewife in the Margaree River mature between 2 and 6 years of age, with the majority maturing at ages 3 and 4. We set up the model to estimate the number of first time spawners in each age class (ages 2 to 6) in each year ($N_{t,a,0}$), and the exploitation rate in each year (u_t), assuming a non-selective fishery. We attempted to estimate the instantaneous rate of natural mortality for mature fish (M^{adult}), assuming M^{adult} constant across age and year classes, which could only be estimated via specific model configurations. Abundance-at-age-ps was projected forward through time as:

The number of fish caught in year *t* is calculated as:

$$C_t = \sum_a \sum_p \left(N_{t,a,p} u_t \right)$$

and the number of spawners in year *t*, S_t, as:

$$S_t = \sum_a \sum_p N_{t,a,p} (1 - u_t),$$

The spawner biomass in year *t*, SSB_t, is calculated as:

$$SSB_t = \sum_a \sum_p N_{t,a,p} (1 - u_t) w_a,$$

where w_a is the weight-at-age.

The age of recruitment is defined as age-2. The number of recruits in year *t*, R_t, is given by:

$$R_t = \sum_{a=2}^{6} \left(N_{t+a,a} / e^{-M^{juv}(a-2)} \right).$$

We do not have the data to estimate M^{juv} within the models and assumed a constant value of 0.4 based on the empirical relationship between longevity (maximum age of 11 years) and natural mortality developed by Hoenig (1983). This value does not have a role in the estimation of the exploitation rates or $N_{t,a,ps}$, it is only used in calculating the number of recruits.

For fitting the model to the larval abundance index, the index value for year *t* , I_t^{larval} is calculated as:

$$I_t^{pred} = qSSB_t,$$

where, *q* is the catchability coefficient.

In order to allow for hyperstability in the CPUE index (Harley et al. 2001), a power function is used for fitting to this time series:

$$CPUE_t^{pred} = g \left(\sum_a \sum_p N_{t,a,p} \, w_a \right)^h,$$

where *g* and *h* are the parameters for the power function and $CPUE_t$ is the CPUE index value in year *t*. A value of *h*=1 indicates that the CPUE is proportional to abundance, whereas a value of *h* <1 is indicative of hyperstability (the index declines more slowly than the abundance) and *h* >1 is indicative of hyperdepletion (the index declines more rapidly than the abundance).

Model initial abundance-at-age-and-previous-spawning

Filling in the numbers-at-age-previous-spawning array in the first year was accomplished by adding four estimated parameters to the model: three initial abundances corresponding to the numbers of first time spawners in age-at-maturity classes 3 to 5 ($N_{t,a,0}$), and an initial *Z*, Z_{init}, used to estimate the abundance for repeat spawners. The first year of the array was filled in using:

$$N_{t,a+1,p+1} = N_{t,a,p}e^{Z_{init}}$$

Model fitting

The model is fit to the data by minimizing the sum of an objective function value which is the weighted sum of the non-constant portions of the likelihood for each model component. When fitting to the commercial catch, the larval index and the CPUE index, a lognormal likelihood is used:

$$\ell_{catch} = -\sum_{t}\left(\ln C_t^{obs} - \ln C_t^{pred}\right)^2,$$

$$\ell_{CPUE} = -\sum_{t}\left(\ln CPUE_t^{obs} - \ln CPUE_t^{pred}\right)^2,$$

$$\ell_{larval} = -\sum_{t}\left(\ln I_t^{obs} - \ln I_t^{pred}\right)^2$$

where “obs” and “pred” indicate the observed and predicted value for each component.

There are a few options for fitting to the age and previous spawning composition data. In theory, an appropriate distribution would be based on both the process and observation error. While the process error (resulting from variation in survival) would lead to a lognormal distribution, given the way that the numbers-at-age-ps are calculated (Breau and Gibson 2024), the appropriate distribution is unclear (this does not mean that the method of calculation is inappropriate). Use of a lognormal distribution for fitting to these data has a couple of disadvantages. First, the dataset contains many zeros, necessitating the addition of a small constant to fit to these data, the effect of which is unclear. Additionally, the abundance in some age and ps categories is based on the observation of very few fish relative to the more abundant age and ps categories, and age determinations of older fish is not always as certain as for younger fish. The lognormal likelihood weights these values equally, although there is likely less certainty in the abundance of the lower abundance age-ps categories. This approach was explored in this assessment, but the results were not carried forward due to issues related to the reasons above.

When combined with the catch likelihood above, an alternative is to fit to the age-ps composition data using the non-constant portion of a multinomial likelihood to fit to the proportions-at-age-ps:

$$\ell_{composition} = -\sum_{t}\sum_{a}\sum_{p}\left(n_{t,a,p}^{obs}\ln p_{t,a,p}\right),$$

where $n_{t,a,p}^{obs}$is the observed number of fish of age *a* that have spawned *p* times previously within a sample collected in year *t*, and $p_{t,a,p}$ is the predicted proportion of fish in each age and previous spawning catagory in that year. This approach has the advantage that the contribution to the objective function of the lower abundance age-ps classes are down-weighted relative to the higher abundance age-ps classes. However, age-ps classes with observed abundances equal to zero do not directly contribute to the likelihood.

An alternative approach is to fit to the age-ps composition data using a normal error structure. While on a theoretical basis this additive structure is inconsistent with the multiplicative nature of survival, it has the advantages that age-ps classes with observed abundances of zero still contribute to the likelihood, and the contribution to the likelihood of the lower abundance age-ps classes are still down-weighted relative to the higher abundance age-ps classes. Here, the non-constant portion of the likelihood is given by:

$$\ell_{composition} = -\sum_{t}\sum_{a}\sum_{p}\left(n_{t,a,p}^{obs} - n_{t,a,p}^{pred}\right)^2$$

This approach can be sensitive to the sample size: when the sample size is small, lower abundance age-ps classes are less likely to appear in the sample.

The relative contribution of each likelihood to the objective function was controlled using a set of weighting values, λ_i, selected to keep any one part of the objective function from dominating the fit and for exploring the effect of the different data sources on the model output.

$$O.B.V. = -\left(\lambda_1 \ell_{composition} + \lambda_2 \ell_{catch} + \lambda_3 \ell_{CPUE} + \lambda_4 \ell_{larval}\right)$$

Because the age-ps composition data are input as the total numbers of fish by age-ps caught in the fishery, ℓ_{catch} is dropped from the objective function equation when the normal likelihood (or lognormal) is used to avoid incorporating the total catch data twice.

We fit these models using AD Model Builder (Fournier 1996). AD Model builder uses the C++ auto-differentiation library for rapid fitting of complex non-linear models, has Bayesian and profile likelihood capabilities (not used here), and is designed specifically for fitting these types of models.

3.1.1.2. Virtual Population Analysis

The last published assessment of the status of Margaree River Alewife (Chaput et al. 2001) used a VPA to estimate abundance and fishing mortality rates. To provide continuity with the last assessment, the VPA has been updated with recent CAAPS data, but fitted with a different tuning index. Chaput et al. (2001) used a larval abundance index to tune the VPA. This data series has been discontinued in 2001. In the assessment presented here, the VPA is tuned using the catch-per-unit-effort (CPUE) time series for the fishery.

A VPA uses fishery-dependent data to reconstruct past stock size from mortality rates (Jennings et al. 2001). The number of fish alive in each cohort is estimated by a backward calculation adding the number of fish landed and an estimated natural mortality to the last age class in each age-at-maturity sub-cohort as:

$$N_{t,a,p} = \frac{N_{t+1,a+1,p+1}}{exp^{(-M)}} + C_{t,a,p}$$

A larval index was available to tune the VPA in Chaput et al. (2001) however, this index has been discontinued in 2001. In this assessment, CPUE from the fisher's logbooks were used to tune the final year and oldest age *F*'s by minimizing the log of the total biomass and the CPUE index for each sub-cohort. A value of *M*=0.4, was used in the model, in part to facilitate comparison with the previous assessment, and in part to provide a scenario with a lower value for *M* than estimated with the SCA. The value may be low given the estimates from theoretical approaches (Breau and Gibson 2024), as well as the estimates obtained with the SCA obtained here.

The annual exploitation rate, u_t, is calculated as:

$$u_t = \frac{\sum_a \sum_p C_{t,a,p}}{\sum_a \sum_p N_{t,a,p}}$$

The annual spawner biomass, SSB_t, is calculated as:

$$SSB_t = \left(\sum_{a,p} N_{t,a,p} - \sum_{a,p} C_{t,a,p} \right) w_t$$

The model is fit in EXCEL.

3.1.1.3. Selection of a preferred model

Merritt and Quinn (2000) suggest that conservatism and the biological plausibility of parameter estimates are two criteria that can be used to select between alternative models and to assess auxiliary data. To these criteria, we added: whether there are potential convergence issues (does the model produce a Hessian matrix), whether the model may have retrospective issues (confidence intervals on the *SSB* and *F* estimates during the final few years), whether the model can estimate the natural mortality rate, a low value of σ for the SR model. Application of these criteria was done qualitatively.

3.1.2. Results

Several variants of statistical catch-at-age (SCA) models were explored during this assessment. The five main variants carried forward are the VPA, and 4 variants of the SCA. Three of these were fit to the CAAPS data using a multinomial likelihood; one of these included both the CPUE and larval indices, one included just the CPUE index, and one was fit without indices. The fourth variant was fit only to the CAAPS data using a normal likelihood. When the indices were included in the model, the natural mortality rate could be estimated. The qualitative application of the model selection criteria is summarized in Table 3. SCA 3 was chosen as the preferred model, primarily because the natural mortality rate could be estimated with this model, and because it had the lowest σ for the SR model. The status evaluation from the VPA was also carried forward.

The correlation plot for the CPUE tuning index for the VPA is shown in Figure 2 and for SCA 1 and 3, the fits to the commercial landings and to the indices are shown in Figure 3. The SCA models were weighted to fit the commercial landings closely, reflecting greater certainty in this value than in the CAAPS or the indices. Both SCA models capture the basic pattern in the index time series, although there is high variability in the early part of the CPUE time series that is not well captured. Moderate hyperstability was evident in the CPUE index (SCA 3 estimate of *h* = 0.652; s.e. = 0.025).

SCA 3 model fits to the CAAPS data are shown in Figure 4. The fits are generally close, although the residuals (Figure 5) indicate some issues fitting the abundance peak in the mid-1980’s and a pattern of overestimating the age-3 first time spawners (possibly due to selectivity in the fishery or a different natural mortality rate for this sub-cohort after spawning for the first time). While a pattern exists, the deviations are small. This can be seen by comparing the large residual for age-3 first time spawners in 1988 with the observed and fitted values for the 1985 cohort maturing at age-3 (Figure 4b, second row, second panel from the left).

Both exploitation rate and *SSB* estimates varied among the five models (Figure 6). When estimated with the VPA, SCA 2 and SCA 4, exploitation rates were higher and SSB estimates lower, most likely due to the difference in the natural mortality rates between the models. Exploitation rate estimates from the VPA, SCA 1 and SCA 3 drop during the final few years, a pattern not evident in the SCA models without the indices (2 and 4). Confidence intervals are large for the last few years for the models without the indices, weakening the support for these estimates (but see the retrospective plot for SCA 2).

The retrospective pattern for the VPA is shown in Figure 7, and in Figure 8 for SCA 2 and SCA 3. SCA 2 shows a variation in the final year estimates, but without a pattern (this is reflective of noise in the data). The retrospective pattern for SCA 3 is negligibly better than the VPA.

Maturity schedules varied slightly among the five models (Table 4).

Exploitation rate, SSB and recruitment estimates from SCA 3 are provided in Table 5 for reference.

The YPR, SPR and SR relationships resulting from SCA 3 are shown in Figure 9. The majority of the SR data is at low abundance and, like Alewife generally, exhibit high variability. SR residuals (Figure 10) fluctuate through time and exhibit a pattern of declining magnitude and a tendency for positive or negative residuals to cluster together, although autocorrelation at 1 to 4 years is not significant. The larger residuals in the early part of the time series likely result from the rapid increase and decrease in abundance during the mid-1980's.

The joint likelihood surface for the SR parameters (Figure 11) shows the "banana shape" typical of SR likelihood surfaces due to correlation in the model parameters. The 95% confidence region for the model parameters spans a region with both a more productive, but smaller population, and a less productive, but larger population. The reference point $U_{\text{max.E(C)}}$ formally incorporates these scenarios.

Stock recruitment parameter, natural mortality rate and reference point estimates from the five models, are provided in Table 6. The value of α is highest from SCA 3, and lowest from the VPA. The $SPR_{F=0}$ is highest from the VPA, and lowest for the model with the highest estimated natural mortality rate (SCA 1). Reference fishing mortality rates follow a similar pattern, U_{MSY} and $U_{\text{Max.E(C)}}$ are lowest from the VPA. Similarly, biomass reference points are highest from the VPA.

The yield curve associated with SCA 3 exhibits a "flat-topped" shape (Figure 12). A reduction in yield of 10% from MSY (without over-exploiting the population) corresponds to a decrease in the exploitation rate from 56% to 35% (Table 6). Associated with this is near doubling of the spawner biomass (Figure 12). Recruitment does not change as significantly due to density dependent effects.

Uncertainty in the SR parameters and associated reference points was evaluated using the SCA 3 model output. The Markov Chain Monte Carlo capability within ADMB was used to produce Markov chains of the SR parameters. These results were mapped to the reference points using the SR, YPR and SPR functions described above. Other than bounds placed on the range or plausible values for alpha (0 to 10,000 age-2 recruits per kilogram of spawner biomass) and K (0 to 10,000,000 kilograms), no priors were specified. Markov chains used in the analysis were generated using 8.8 million iterations saving every 8,000$^{\text{th}}$ iteration after a burn-in of 1,200,000 steps. The results of these analyses (Table 7) generally support the use of the M.L.E's for assessment purposes, although a significant portion of the probability density for both the biomass and removal rate reference points is below the M.L.E for the reference point.

3.1.3. Status

Although the output from all models explored here differ slightly, all models indicate that the Margaree River Alewife population has been over-exploited in the majority of years, and that the SSB has been below the USR in most years since the 1980's. When status is determined using SCA 3, the population is over-exploited in the majority of years (Figure 13), and abundance is mostly in cautious zone. When status is determined using the VPA, biomass reference points are shifted to higher values and annual exploitation rate estimates are higher (Figure 14), most likely because a greater portion of the total mortality is attributed to the fishery. Abundance is mostly in the critical zone, or near the critical-cautious boundary when estimated with this model.

3.2. MIRAMICHI RIVER ALEWIFE AND BLUEBACK HERRING

3.2.1. Methods

Commercial landings data are not available for the Miramichi River Alewife and Blueback Herring fisheries. Data available for assessing the status (mortality rates and/or biomass) for each species are trap net data collected on each branch upstream of the fisheries. These include the number of fish of each species that were caught from 2001 to 2019, and age and previous spawning (age-ps) data, currently available from 2006 to 2013, excluding 2011 (Breau and Gibson 2024). The Miramichi gaspereau fishery was last assessed using data from 1983 to 2000 (Chaput and Atkinson 2001; DFO 2001). No sampling of the fishery occurred after 2000 and the data after 2000 come exclusively from catches and sampling at DFO estuary index trap nets in the Miramichi.

When assessing status relative to exploitation rates, the use of the three status zones (under-exploited, fully-exploited and over-exploited) is proposed, using U_{msy} and $U_{90\%.msy}$ values for the Margaree River to delineate among the zones. Removal reference points are only appropriate when the population is in the healthy zone.

The number of years with age data is low for fitting a cohort-based model to estimate the total mortality rates and exploitation rates, and number of fish caught in the trap nets are variable from year-to-year. For these reasons, catch curves are used in this analysis. The catch in the trap nets provides a time series of abundance, however without information about the number of fish remaining after the fishery, scaling to the biomass reference points is problematic. The assumptions of the analyses undertaken here are:

1. That the dynamics of the Margaree River Alewife population can be used as a proxy for both the Miramichi River Blueback Herring and Alewife populations.
2. That, because there have been no significant recent (since 2001) changes in fishery, the abundance is near a stochastic equilibrium (abundance is variable, perhaps highly variable, around a stable mean).
3. That, by scaling the dynamics (the relationship between total mortality rates and biomass) of the Margaree River Alewife population to its biomass in the absence of fishing, the total mortality rate estimates from the catch curves can be informative about biomass and stock status (whether the populations would be expected to be in the in the critical, cautious or healthy zones).

Rescaling the trap net index as a proxy was considered, but was not explored further due to uncertainty about how to address its variability.

Instantaneous total mortality rates and exploitation rates were estimated using catch curves. The total instantaneous mortality rate, Z, can be estimated two ways, both using a generalized linear model assuming a Poisson distribution and a log link function. The first model:

$$E(N_a) = \exp\left(\log(N_0) - Za\right),$$

is a “typical” catch curve analysis where the expected number of fish of age *a* (N_a), is modeled as a function of the number of fish of age-0, N_0, and *Z*.

The second model is the extension to incorporate previous spawning history:

$$E(N_{\tau,ps}) = \exp(\log(N_{\tau,0}) - Zps),$$

where $N_{\tau,ps}$ is the number of fish that matured at age τ, and ps is the number of previous spawnings (zero for a first-time spawner). Here, there is a separate intercept term $N_{\tau,0}$, for each possible age-at-maturity. Issues with age determinations aside, this second approach has been shown to perform better for iteroparous, anadromous Alewife (Gibson et al. 2016, Billard 2020) and is used here. Age-at-maturity and number-of-previous-spawnings categories with zero abundance were removed from the data prior to fitting the model. The exploitation rates are calculated from *Z* using the natural mortality rate from the VPA and SCA 3.

To determine whether populations were in the fully-exploited or over-exploited removal reference zones, the threshold values (U_{msy} and $U_{90\%msy}$) from the Margaree River from SCA 3 and the VPA are used.

To determine the stock status (whether the populations are in the healthy, cautious or critical zones), the equilibrium biomass corresponding to the estimated total mortality rates for each species in each branch are calculated. Status is approximated using the range of estimated values.

3.2.2. Results

The annual catches at the trap nets on the NW and SW branches are show in Figure 14. Catches are primarily Blueback Herring and on the scale of the data, appear variable. The years with age-ps composition data span almost the entire abundance range for each species on each branch.

Based on the trap net catches, abundance of Blueback Herring populations in both branches have trended downward since the years with age-ps composition data. Abundance of Alewife in the SW branch has also trended downwards; the trend for the Alewife population in the NW branch is less clear.

The relative abundance by age-at-maturity and number of previous spawnings for Blueback Herring and Alewife in the two branches is shown in Figures 15 to 18. For both species, most fish spawn for the first time at ages 3 and 4, with high variability in the number of first time spawners. For Blueback Herring in both branches, there are few fish that are spawning for a third time, and, for Alewife, there are few fish spawning for a second time.

Instantaneous total mortality rates and exploitation rates differ between the branches and the species, and in some cases are sensitive to the model being used (Table 8). For Alewife in the northwest branch, the results indicate that the population was over-exploited in all years for which there are data, regardless of the model being used (Table 8).

For Alewife in the SW branch, the results indicate that the population was over-exploited in 6 of the 7 years, and under-exploited one year (Table 8).

The results for Blueback Herring in the NW branch are more variable, ranging from under-exploited (one year) to over-exploited (3 years), and was fully-exploited in 3 years (Table 8).

Instantaneous total mortality rates are lower for the SW Blueback Herring. This population was under-exploited in 6 years and over-exploited in one year (Table 8).

At equilibrium, the relationship between the instantaneous total mortality rate and the percent of the unfished equilibrium biomass from both the VPA and SCA 3 are shown in Figure 19. The instantaneous total mortality rates corresponding to SSB_{msy} from the VPA and SCA 3 are 1.13 and 1.52 respectively. The rates from the two models corresponding to *K* are 1.55 and 2.32, respectively (Table 9).

Results from extrapolating the total mortality rates to the stock status, based on the assumption the population would be near an equilibrium, varied among populations. Based on the SCA 3 results (Figure 20), if near an equilibrium based on these mortality rates, the NW branch Alewife population would be expected to be near the critical-cautious boundary. In contrast, Alewife in the SW branch, would be spanning the cautious-healthy boundary (two points in the heathy zone and five in the cautious zone). Blueback Herring in the NW branch have a wider range of values, ranging from near the critical-cautious boundary to well into the healthy zone (Figure 20). The analysis is perhaps least informative about the status of blueback Herring in the SW branch, for which the status determinations ranged from near the unfished equilibrium biomass, to well into the critical zone (Figure 20).

The status determinations using the Margaree River Alewife VPA output as a proxy for the population dynamics are more pessimistic (Figure 21). For Alewife, the evidence is that the populations are in the cautious zone or lower. For Blueback Herring in the NW branch, only one point is above the critical-cautious boundary. For Blueback Herring in the SW branch, the maximum value is just over 50% of the unfished equilibrium biomass, in comparison with the maximum near 100% from SCA 3.

3.2.3. Status

For Alewife in the Northwest branch, the results indicate that the population was over-exploited in all years for which there are data, regardless of the model being used (Table 8). For Alewife in the Southwest branch, the results indicate that the population was over-exploited in 6 of the 7 years, and under-exploited one year. The results for Blueback Herring in the Northwest branch are more variable, being over-exploited in 3 years, fully-exploited in 3 years and under-exploited one year. Instantaneous total mortality rates are lower for the Southwest Blueback Herring. This population was under-exploited in six years and over exploited in one year. When last assessed in 2000, the exploitation rate in the Miramichi River were high. The catch curve analysis of catches from research trapnets indicates that the estimated exploitation rates are very high for both Alewife and Blueback Herring and have remained high since previous assessments (DFO 2001; Chaput and Atkinson 2001). Particularly for Northwest Alewife, where the population is over-exploited in all years, the analyses indicate that the abundance status is not in the healthy zone.

3.3. A PROPOSAL FOR ASSESSING GASPEREAU IN RIVERS WHERE THEY ARE UNASSESSED

In a framework for building an assessment program for gaspereau in the Maritimes Region, Gibson et al (2016) proposed that collection of data for fitting catch curves (proportions by age and previous spawning history) could be used as a method to assess whether exploitation rates (or total mortality) are in the appropriate range. Catch curves have inherent issues (bias and variability) that have been well described (Smith et al. 2012, Millar 2014). For relatively short-lived species such as gaspereau, where only a few age classes are available for fitting the curves, traditional methods using age as the independent variable perform poorly (Gibson et al. 2016, Billard 2020). A recommendation to evaluate other methods of fitting catch curves came out of the Maritimes Region framework. This work was undertaken in Billard (2020). Billard (2020) tested two model structures fit to data simulated with a life cycle model using four statistical models. The use of the age at maturity and previous spawning information as independent variables improved the accuracy and precision of the estimates over the use of age as the independent variable, but did not completely alleviate the issues, particularly when the simulated exploitation rate was high (Figure 22).

There has been a shift in fisheries science away from evaluating the precision and accuracy of models and estimators to testing management systems, known as management strategy evaluation (MSE). Billard (2020) also undertook an MSE that showed, despite their inherent issues, the use of catch curves as an assessment method, coupled with reasonably frequent management changes to increase or decrease the exploitation rate, can bring the exploitation rate into the appropriate range (Figure 23). Gibson et al. (2016) proposed this method as something that could be applied in the short term, recognising that it does not assess all factors that can effect fishery productivity (e.g., recruitment failure could drive a population to extinction while the exploitation rate is in the appropriate range). Additionally, it is not fully compliant with the precautionary approach because the LRP and USR are not defined. Finally, if the approach is implemented, a key consideration is how to collect a random sample of the age and previous spawning distribution that is representative of the complete spawning run.

4. DISCUSSION

Gaspereau fisheries in the Maritimes Provinces are typically managed using effort controls rather that quotas. This approach makes sense given the high variability in spawning run size relative to what would be expected given a longer longevity, as well as population growth rate typical of some marine species (Myers et al. 1999). In this assessment, rather than choosing a single upper removal reference level for the precautionary approach, the approach here was to use a range of values that span the exploitation rate range that produces MSY at the upper end, to 90% of MSY at the lower end. This approach avoids increases in the fishing effort (to increase the exploitation rate) when the actual increase in the yield would be low; and also avoids the situation where, if the exploitation rate is near that which produces MSY, the status of the fishery changes annually in response to annual variability in the fishery. Removal reference points are only appropriate when the population is in the healthy zone.

Annual variability in the exploitation rates for in-river gaspereau fisheries can arise from several sources, including environmental factors such as flow, which can affect gear efficiency; and when there are weekly closed days, the timing of the run relative to those days. These sources have implications for management changes to keep exploitation rates in the appropriate range. Although not explored here, reducing the efficiency of the gear (for example by reducing the amount of the river that is blocked at individual fishing stands) would be expected to reduce the exploitation rate, but at the same time would increase the amount of effort required to catch an appropriate proportion of the fish. Reducing the amount of time that the fishery is open each week would also be expected to reduce the exploitation rate, but at the same time might increase the variability in the proportion harvested, depending whether the fishery is open on days when the run is “strong”, or whether more fish run on days when the fishery is closed. This trade-off between effort to obtain the catch and variability in the catch is a consideration when deciding how to keep exploitation rates within the appropriate range.

With respect to status of the Margaree River Alewife population and fishery, while there are differences in their results, all model runs indicate that in the majority of years, the population is over-exploited and the population is in the critical or cautious zone. A key source of the differences is the value of the natural mortality rate. When the natural mortality rate is input as a constant value of 0.4 (e.g. the VPA), biomass reference points are shifted to higher values and annual exploitation rate estimates are higher, most likely because a greater portion of the total mortality is attributed to the fishery. Abundance is mostly in the critical zone, or near the critical-cautious boundary when estimated with this model. When the natural mortality is a higher value, as is the case when it is estimated in SCA 3, the population is still over-exploited in the majority of years, but the abundance is in the cautious zone in a greater portion of the years.

The natural mortality rate is a key parameter in stock assessment models. In this process, values were proposed based on theoretical relationships and it was also estimated with the model for Margaree River Alewife. The low standard error on the SCA 3 model estimate, coupled with the similarity to the estimate based on Tmax (Breau and Gibson 2024), lends support for the value used in this assessment. However, when a very similar SCA was run using data only to 1999 (Gibson and Myers 2003a), a lower value for the natural mortality rate with a small standard error was obtained. Additionally, there are species that do not conform to the theoretical relationships for estimating the natural mortality rate (Atlantic salmon is an example). Uncertainty remains in its value. In this assessment, while the values for the reference levels, spawner biomass and the exploitation rate varied among the model runs with different natural mortality rates, the overall status determination of the Margaree River Alewife population and fishery remains similar.

While the use of catch curves as a basis for managing gaspereau fisheries has been shown (via simulation) to be effective for controlling exploitation rates, methods sampling the population to obtain age and previous spawning composition data warrant further consideration, particularly the extent to which they produce a random sample. The intended use of the data is also a consideration. The method used for the Margaree River is intended to be used to reconstruct the catch-at-age-and-previous-spawnings. While these data could be used in a catch curve, the statistical error would be under-estimated because the sample size is not really known. In the Maritimes Region, where sampling typically occurs in fish ladders with daily counts, the approach has been to collect a large number of scale samples (1000 to 2000). At the end of the season, a set of roughly 500 scale samples are randomly drawn from the collection using a weighted sampling scheme, where the ratio of the count to the number of samples collected each day is used as the weight. Location may also play a role. If either the fishery or the fish ladder (say) are selective, the sample is still not random.

The question of age and previous spawning determinations from scales for *Alosa* is currently topical (e.g. ASMFC 2020). The use of the data and the source of the error also plays a role here. For example, if the age determinations are systematically biased by confusion between the freshwater mark and the first annulus, the use of catch curves and SCA models without a stock recruitment model would still provide estimates of the total mortality rate, although errors would be introduced into the subsequent estimation of MSY reference points. If the ages and number of previous spawnings are biased low due to erosion of the edge of the scale, the age-at-first maturity would still be appropriately calculated, but survival would be underestimated. This issue may be partially alleviated (or not) by fitting catch curve or SCA models that use likelihoods that down-weight the contributions from lower abundance age classes, or the use of plus groups. In summary, both sampling methods and age-ps determinations warrant further consideration, but perhaps with less emphasis on the accuracy and precision of the method and greater emphasis on their effect on the assessment results and the extent that they can be addressed via different modelling approaches. Given the end goal is to effectively manage gaspereau populations, this would ultimately be carried through a management strategy evaluation.

5. REFERENCES CITED

ASMFC 2012a. Stock Assessment Report No. 12-02 of the Atlantic States Marine Fisheries Commission Gaspereau Benchmark Stock Assessment Vol. I.

ASMFC 2012b. Stock Assessment Report No. 12-02 of the Atlantic States Marine Fisheries Commission Gaspereau Benchmark Stock Assessment Vol. II.

ASMFC 2017. River herring stock assessment update, Vol. 1. Atlantic States Marine Fisheries Commission, Arlington, Va.

ASMFC 2020. 2020 American Shad Benchmark Stock Assessment and Peer Review Report.

Beddington, J. R. and J. G. Cooke. 1983. The potential yield of fish stocks. U.N. FAO Fisheries Tech. Paper 242. Rome, Italy.

Billard, M. 2020. Two simulation approaches for evaluating catch curve models as an assessment method for gaspereau. Master of Science Dissertation. Department of Biology, Acadia University, Wolfville, Nova Scotia, Canada.

Breau, C., and Gibson, A.J.F. 2024. Gaspereau Assessment for the DFO Gulf Region to 2019: Fisheries, Biological Characteristics and Indicators of Status. DFO Can. Sci. Advis. Sec. Res. Doc. 2024/041. v + 87 p.

Chaput, G., and Atkinson, G. 2001. The gaspereau fisheries (*Alosa pseudoharengus* and *A. aestivalis*) of the Miramichi River with updates on the fishery of the Richibucto River of Gulf New Brunswick. CSAS Res. Doc. 2001/047. 39p.

Chaput, G., P. LeBlanc, and R. Crawford. 2001. Assessment of the Margaree River gaspereau fishery, 1997 to 2000. DFO CSAS Res. Doc. 2001/046.

DFO 2001. Gaspereau Maritime Provinces Overview. DFO Science Stock Status Report D3-17 (2001).

DFO. 2006. A Harvest Strategy Compliant with the Precautionary Approach. DFO Canadian Science Advisory Secretariat Advisory Report 2006/023.

DFO. 2022. Stock status of Alewife and Blueback Herring (Gaspereau) in the DFO Gulf Region. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2022/014.

Fournier, D. 1996. An introduction to AD Model Builder for use in nonlinear modelling and statistics. Otter Research Ltd., Nanaimo, BC, Canada.

Gibson A.J.F. 2004. Dynamics and management of anadromous alewife (Alosa pseudoharengus) populations. PhD. Thesis. Department of Biology, Dalhousie University, Halifax, NS. 198p.

Gibson, A.J.F., H.D. Bowlby, and F.M. Keyser. 2016. A Framework for the Assessment of the Status of Gaspereau Populations and Fisheries in DFO's Maritimes Region. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/105.

Gibson, A.J.F., and R.A. Myers. 2001. Gaspereau River alewife stock status report. DFO Canadian Science Advisory Secretariat Research Document 2001/061.

Gibson, A.J.F. and R.A. Myers. 2003a. Biological Reference Points for Anadromous Alewife (Alosa pseudoharengus) Fisheries in Atlantic Canada. Canadian Technical Report of Fisheries and Aquatic Sciences 2468. 50p.

Gibson, A.J.F. and R.A. Myers. 2003b. A statistical, age-structured, life history based, stock assessment model for anadromous Alosa. p. 275-283. In K. E. Limburg, and J.R. Waldman [ed.] Biodiversity and Conservation of Shads Worldwide. American Fisheries Society Symposium Series. American Fisheries Society, Bethesda, MD.

Gibson, A.J.F. and R.A. Myers. 2003c. A meta-analysis of the habitat carrying capacity and the maximum lifetime reproductive rate of anadromous alewife in eastern North America. p. 211-221. In K. E. Limburg, and J.R. Waldman [ed.] Biodiversity and Conservation of Shads Worldwide. American Fisheries Society Symposium Series. American Fisheries Society, Bethesda, MD.

Gibson, A.J.F. and R.A. Myers. 2004. Estimating reference fishing mortality rates from noisy spawner-recruit data. Canadian Journal of Fisheries and Aquatic Sciences 61: 1771-1783.

Goodyear, C. P. 1993. Spawning stock biomass per recruit in fisheries management: foundation and current use. p. 67-82. *In* S. J. Smith, J. J. Hunt and D. Rivard [ed.] Risk evaluation and biological reference points for fisheries management. Can. Spec. Publ. Fish. Aquat. Sci. 120.

Harley, S.J., R.A. Myers, and A. Dunn. 2001. Is catch-per-unit-effort proportional to abundance? Can. J. Fish. Aquat. Sci. 58: 1760–1772.

Hilborn, R. and C. J. Walters 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman and Hall, New York.

Hoenig, J. M. 1983. Empirical use of longevity data to estimate mortality rates. Fish. Bull. U.S. 81: 898-902.

Jennings, S., Kaiser, M.J., Reynolds, J.D., 2001. Marine Fisheries Ecology, Blackwell Science Ltd, Oxford, UK

McBride, M.C., T.V. Willis, R.G. Bradford and P.Bentzen. 2014. Genetic diversity and structure of two hybridizing anadromous fishes (Alosa pseudoharengus, Alosa aestivalis) across the northern portion of their ranges. Conservation Genetics 15: 1281-1298.

Merritt, M.F., and T.J. Quinn II. 2000. Using perceptions of data accuracy and empirical weighting of information: assessment of a recreational fish population. Can. J. Fish. and Aquat. Sci. 57: 1459-1469.

Millar, R. B. 2014. A better estimator of mortality rate from age-frequency data. Canadian Journal of Fisheries and Aquatic Sciences 72:364-375.

Myers, R. A., Bowen, K. G., and Barrowman, N. J. 1999. The maximum reproductive rate of fish at low population sizes. Can. J. Fish. Aquat. Sci. 56: 2404-2419.

Myers, R. A., Bridson, J., and Barrowman, N. J. 1995. Summary of worldwide stock and recruitment data. Can. Tech. Rep. Fish. Aquat. Sci. 2024: iv + 327p.

Quinn, T.J. II and R.B. Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press. New York.

Palkovacs, E.P., D.J. Hasselman, E.E. Argo, S.R. Gephard, K.E. Limburg, D.M. Post, T.F. Schultz, and T.T. Willis. 2014. Combining genetic and demographic information to prioritize conservation efforts for anadromous alewife and blueback herring. Evolutionary Applications 7: 212-226.

Sissenwine, M.P. and J.G. Shepherd. 1987. An alternative perspective on recruitment overfishing and biological reference points. Canadian Journal of Fisheries and Aquatic Sciences 44: 913-918.

Smith, M. W., A. Y. Then, C. Wor, G. Ralph, K. H. Pollock and J. M. Hoenig. 2012. Recommendations for catch-curve analysis. North American Journal of Fisheries Management 32(5): 956-967.

6. TABLES

Table 1. Definitions of the reference points discussed in this document.

Theoretical basis	Reference point	Definition
Yield per Recruit	$F_{0.1}$	The fishing mortality rate where the marginal gain in yield is 10% that at *F*=0
Spawner per Recruit	$SPR_{F=0}$	The spawner biomass produced by a recruit throughout its life in the absence of fishing
Spawner per Recruit	$F_{35\%}$	The fishing mortality rate where the *SPR* is reduced to 35% that of $SPR_{F=0}$
Spawner per Recruit	$F_{25\%}$	The fishing mortality rate where the *SPR* is reduced to 25% that of $SPR_{F=0}$
SR relationship	K	The Beverton-Holt half saturation constant (the spawner biomass that produces ½ the maximum recruitment)
Life Cycle Model	U_{col}	The exploitation rate that would drive the population to extinction (the exploitation rate that produces a replacement line equal to the inverse of the estimate of the slope at the origin of the stock-recruitment relationship).
Life Cycle Model	U_{msy}	The exploitation rate that produces the maximum sustainable yield (based on the maximum likelihood estimates of the stock recruitment parameters).
Life Cycle Model	$U_{90\%.msy}$	The exploitation rate that produces 90% of the maximum sustainable yield (based on the maximum likelihood estimates of the stock recruitment parameters).
Life Cycle Model	SSB_{msy}	The spawner biomass that produces the maximum sustainable yield (based on the maximum likelihood estimates of the stock recruitment parameters).
Life Cycle Model	$SSB_{F=0}$	The equilibrium spawner biomass expected in the absence of fishing.
Life Cycle Model	$SSB_{20\%}$	The spawner biomass corresponding to 20% of the unfished equilibrium spawner biomass.
Decision Theoretic	$F_{max.E[C]}$	The fishing mortality rate that maximizes the expectation of the catch using both the joint posterior probability density for the SR parameters and the expected yield conditional on the parameters and assumed *F*'s.

Table 2. Reference points for the management of gaspereau populations for status determination. Removal reference points are exploitation rates (the proportion of the spawning run being removed) and are only appropriate when the population is in the healthy zone[2].

Population	Reference level	Acronym	Value	Assessment Method
Margaree River Alewife	Upper stock reference level	USR	SSB_{MSY}	Statistical catch at age-ps model
	Limit reference point	LRP	K	-
	Removal reference level	RRL	U_{MSY}	-
	Lower removal reference level	LRRL	$U_{90\%.MSY}$	-
	Target exploitation rate	-	$U_{\mathrm{max.E(C)}}$	-
Miramichi River Alewife	Abundance Reference points: Not available			
	Removal reference level	RRL	U_{MSY}	Catch curves assuming M from the Margaree River
	Lower removal reference level	LRRL	$U_{90\%.MSY}$	-
	Target exploitation rate	-	$U_{\mathrm{max.E(C)}}$	-
Miramichi River Blueback Herring	As above, assuming Blueback Herring have similar dynamics to Alewife			
Other populations	Removal reference levels: As above using catch curves (new data collection required)			
	Abundance Reference points: Not available			

[2] The peer review meeting (DFO 2022) decided that, when in the healthy zone, having a single removal reference point (as opposed to a range) and using $U_{90\%MSY}$ as the target removal reference point was more appropriate. This table differs from Table 2 in DFO (2022) for this reason.

Table 3. Summary of model selection criteria for the five age structured model runs carried forward in this assessment.

Parameter / Reference Point	VPA	SCA 1	SCA 2	**SCA 3**	SCA 4
Indices Included	CPUE	CPUE, larval	none	**CPUE**	none
CAA likelihood	correlation	multinomial	multinomial	**multinomial**	normal
Retrospective pattern or ability to estimate *SSB* and *U* in the most recent years	poor	poor	best	**Poor**	better
Conservatism (low U_{msy})	best	good	better	**Better**	worst
Biological plausibility	good	good	good	**Good**	worse
Ability to estimate the adult natural mortality rate	no	yes	no	**yes**	no
Stock recruitment σ	1.05	0.99	0.98	**0.94**	1.01

Table 4. Maturity schedules for Margaree River Alewife from the 5 model runs carried forward in this assessment. Values are the probability that a fish that is alive at a given age spawns for the first time at that age. Values are conditional on the assumed natural mortality rate for immature Alewife (M_{juv}=0.4). The same value is used in all model runs.

Maturity probability	VPA	SCA 1	SCA 2	**SCA 3**	SCA 4
Indices Included	CPUE	CPUE, larval	None	**CPUE**	None
CAA likelihood	n/a	multinomial	multinomial	**multinomial**	normal
m_2	0.02	0.01	0.01	**0.01**	<0.01
m_3	0.69	0.62	0.62	**0.62**	0.60
m_4	0.98	0.89	0.89	**0.89**	0.89
m_6	0.91	0.98	0.98	**0.98**	0.99
m_6	1.0	1.0	1.0	**1.0**	1.0

Table 5. SCA 3 Exploitation rate and Spawner Biomass estimates (M.L.E.) and standard errors (S.E.) from 1983 to 2019 for the Margaree River Alewife population and fishery. Estimates after 2016 are suspect due to the retrospective pattern. Age-2 recruits are indexed by the year class. "na"=not available.

Year	Exploitation rate		Spawner biomass (kg)		Age-2 recruits (number of fish)	
	M.L.E.	S.E.	M.L.E	S.E.	M.L.E	S.E.
1983	0.587	0.028	307,850	29,665	6,196,300	214,880
1984	0.504	0.027	655,190	54,993	19,424,000	194,120
1985	0.678	0.024	534,340	45,752	15,617,000	563,140
1986	0.464	0.023	513,060	30,994	1,198,500	73,861
1987	0.438	0.030	1,367,400	73,589	7,650,500	340,180
1988	0.600	0.029	926,000	64,692	1,518,500	85,613
1989	0.683	0.025	483,220	39,104	5,084,100	241,190
1990	0.889	0.012	105,200	10,960	8,703,200	388,690
1991	0.744	0.022	137,000	13,449	400,270	34,938
1992	0.795	0.020	119,600	12,105	1,353,900	75,228
1993	0.766	0.020	192,450	17,799	234,260	26,402
1994	0.719	0.023	161,480	15,140	4,972,800	301,090
1995	0.738	0.026	59,443	6,961	3,329,600	175,360
1996	0.802	0.034	25,575	5,192	339,430	30,757
1997	0.394	0.028	323,520	30,910	414,200	35,724
1998	0.483	0.029	287,000	25,588	1,292,600	82,935
1999	0.607	0.029	142,840	13,741	4,381,000	248,770
2000	0.814	0.031	26,704	5,005	1,528,400	106,090
2001	0.529	0.036	71,228	8,640	3,333,400	234,490
2002	0.738	0.027	160,320	18,708	1,779,600	124,710
2003	0.562	0.038	125,670	16,788	2,758,900	180,490
2004	0.377	0.032	288,340	31,952	2,817,100	161,030
2005	0.478	0.034	226,670	25,944	3,949,800	222,220
2006	0.364	0.028	300,660	29,141	3,813,400	208,370
2007	0.577	0.032	219,030	23,095	2,941,600	158,710
2008	0.529	0.031	292,990	29,139	1,704,300	100,980
2009	0.528	0.030	311,350	29,043	793,360	51,980
2010	0.670	0.027	190,240	19,004	1,124,500	70,318
2011	0.697	0.028	117,460	12,856	1,107,800	68,740
2012	0.613	0.033	66,000	8,096	2,633,800	147,300
2013	0.521	0.032	74,966	8,221	2,404,400	164,970
2014	0.709	0.030	57,438	7,295	na	na
2015	0.710	0.030	90,494	11,290	na	na
2016	0.577	0.037	129,860	17,069	na	na
2017	0.482	0.042	289,710	41,229	na	na
2018	0.286	0.035	337,810	51,063	na	na
2019	0.389	0.059	334,020	75,319	na	na

Table 6. Stock recruitment parameters, natural mortality rate estimates and biological reference points for Margaree River Alewife from 5 model runs used in this assessment. The preferred model is shown in bold. Definitions of the reference points are provided in Table 1 and explained in the text.

Parameter / Reference Point	VPA	SCA 1	SCA 2	**SCA 3**	SCA 4
Indices Included	CPUE	CPUE, larval	None	**CPUE**	None
CAA likelihood	n/a	multinomial	multinomial	**multinomial**	normal
Adult *M* (s.e)	fixed at 0.4	0.66 (0.04)	fixed at 0.4	**0.61 (0.05)**	fixed (0.4)
α	65.0	71.2	84.2	**82.6**	99.4
K (kg)	113,920	79,169	58,697	**64,272**	48,395
R_{asy}	7,403,399	5,637,667	4,943,892	**5,308,999**	4,810,740
σ	1.05	0.99	0.98	**1.00**	1.01
Max. lifetime reproductive rate	30.7	20.9	38.6	**25.98**	45.7
$SPR_{F=0}$ (kg)	0.473	0.294	0.459	**0.314**	0.460
F_{msy}	0.72	0.88	0.80	**0.91**	0.98
U_{msy}	0.51	0.58	0.55	**0.60**	0.62
F_{col}	2.15	2,19	2.36	**2.34**	2.85
U_{col}	0.88	0.89	0.91	**0.90**	0.95
$F_{90\%msy}$	-	-	-	**-**	-
$U_{90\%msy}$	0.33	0.40	0.35	**0.41**	0.39
$F_{max.E(C)}$	0.42	0.53	0.50	**0.56**	0.65
$U_{max.E(C)}$	0.34	0.41	0.39	**0.43**	0.48
$SSB_{F=0}$ (kg)	3,389,115	1,577,946	2,209,855	**1,606,020**	3,067,987
SSB_{msy} (kg)	590,828	292,797	348,721	**276,016**	381,446
$SSB_{20\%}$(kg)	677,822	315,589	441,971	**321,204**	613,587
$F_{35\%}$	0.42	0.57	0.42	**0.54**	0.42
$F_{25\%}$	0.60	0.80	0.60	**0.76**	0.60
$F_{0.1}$	0.60	0.95	0.59	**0.88**	0.59

Table 7. A comparison of the spawner-recruit parameter and reference point maximum likelihood estimates with the means and percentiles for these parameters calculated from the Markov chains from the analysis of uncertainty in the spawner-recruit analyses using model output from SCA 3.

Parameter	M.L.E.	mean	10%	25%	50%	75%	90%
α	82.6	133.28	20.55	28.71	49.22	125.89	359.68
K (t)	64.3	155.80	6.14	21.06	68.48	181.13	469.58
R_{asy} (millions of recruits)	5.31	4.77	2.15	2.54	3.41	5.26	9.87
Max. lifetime reproductive rate	25.98	41.93	6.47	9.03	15.48	39.61	113.16
U_{msy}	0.60	0.54	0.37	0.43	0.52	0.66	0.77
U_{col}	0.90	0.83	0.67	0.75	0.84	0.94	0.98
$U_{90\%msy}$	0.41	0.37	0.25	0.29	0.35	0.45	0.54
$SSB_{F=0}$ (t)	1,606.02	1343.53	657.71	776.20	1012.17	1474.90	2603.54
$SSB_{20\%}$(t)	321.20	268.71	131.54	155.24	202.43	294.98	520.71
SSB_{msy} (t)	276.02	311.40	63.24	112.83	211.56	379.97	758.93

Table 8. Status relative to exploitation rate reference points by year for Alewife and Blueback Herring (BB) fisheries in the Miramichi River, as estimated using catch curves. Z est. and Z s.e. are the estimates of the of the instantaneous total mortality rate for each species in each branch. U is the calculated exploitation rate based on the value of the instantaneous natural mortality rate from either SCA 3 (M=0.61) or the VPA (M=0.4). Status is relative the removal rate reference zone from each model (over=above U_{MSY}, fully=above $U_{90\%.MSY}$ but below U_{MSY}, under= below $U_{90\%.MSY}$).*

Branch	Species	Year	Z est.	Z s.e.	Exploitation Rate		Status	
					SCA 3	VPA	SCA 3	VPA
Northwest	Alewife	2006	2.58	0.61	0.86	0.89	over	over
Northwest	Alewife	2007	2.13	0.31	0.78	0.82	over	over
Northwest	Alewife	2008	2.53	0.27	0.85	0.88	over	over
Northwest	Alewife	2009	1.78	0.34	0.69	0.75	over	over
Northwest	Alewife	2010	2.07	0.32	0.77	0.81	over	over
Northwest	Alewife	2012	2.03	0.45	0.76	0.80	over	over
Northwest	Alewife	2013	2.22	0.37	0.80	0.84	over	over
Northwest	BB	2006	2.11	0.45	0.78	0.82	over	over
Northwest	BB	2007	1.24	0.16	0.47	0.57	fully	over
Northwest	BB	2008	1.86	0.15	0.72	0.77	fully	over
Northwest	BB	2009	1.16	0.09	0.43	0.53	fully	over
Northwest	BB	2010	1.78	0.15	0.69	0.75	over	over
Northwest	BB	2012	0.91	0.27	0.27	0.40	under	under
Northwest	BB	2013	2.18	0.22	0.79	0.83	over	over
Southwest	Alewife	2006	1.62	0.26	0.64	0.71	over	over
Southwest	Alewife	2007	1.17	0.27	0.43	0.54	over	over
Southwest	Alewife	2008	1.78	0.20	0.69	0.75	over	over
Southwest	Alewife	2009	1.28	0.33	0.49	0.58	under	fully
Southwest	Alewife	2010	1.99	0.31	0.75	0.80	over	over
Southwest	Alewife	2012	1.92	0.36	0.73	0.78	over	over
Southwest	Alewife	2013	3.58	1.06	0.95	0.96	over	over
Southwest	BB	2006	1.05	0.16	0.36	0.48	under	under
Southwest	BB	2007	1.01	0.12	0.34	0.46	under	fully

Branch	Species	Year	Z est.	Z s.e.	Exploitation Rate		Status	
					SCA 3	VPA	SCA 3	VPA
Southwest	BB	2008	1.07	0.09	0.38	0.49	under	under
Southwest	BB	2009	0.80	0.08	0.18	0.33	under	under
Southwest	BB	2010	1.17	0.10	0.44	0.54	under	fully
Southwest	BB	2012	0.63	0.16	0.02	0.20	under	under
Southwest	BB	2013	2.75	0.31	0.88	0.90	over	over

Table 9. Relationship between the biomass reference points SSBmsy and K as a percentage of the unfished equilibrium biomass (SSB_0), and the corresponding total instantaneous mortality rate Z from the Margaree River Alewife models SCA 3 and the VPA.

Model	Biomass RP	% SSB_0	Z
SCA 3	SSB_{msy}	17.2	1.52
	K	4.0	2.32
VPA	SSB_{msy}	17.4	1.13
	K	3.33	1.55

7. FIGURES

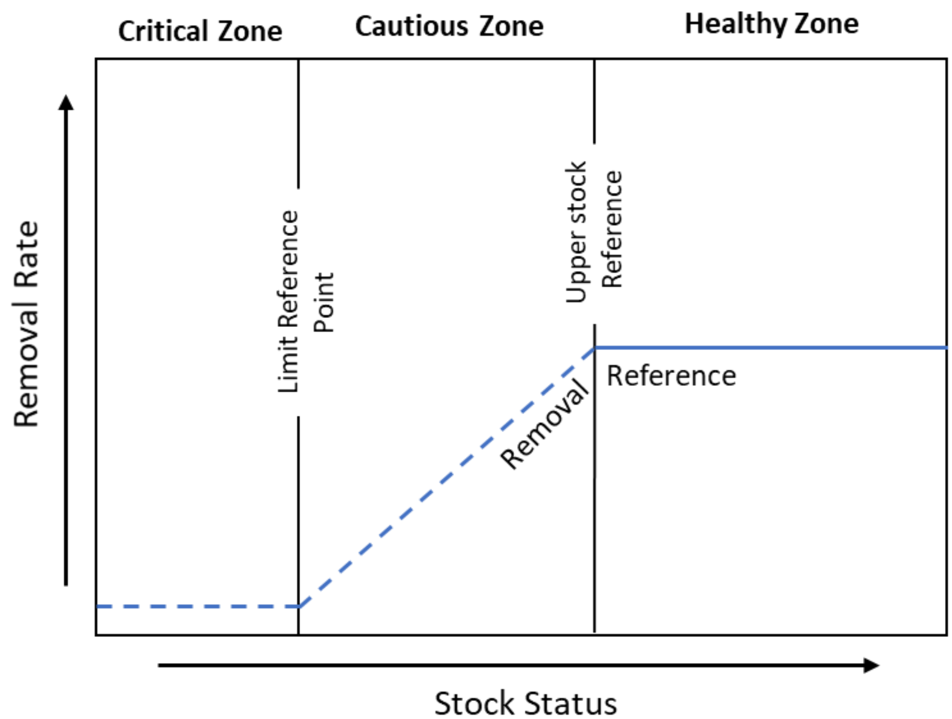

Figure 1. Fisheries management framework consistent with the Precautionary Approach (redrawn from DFO 2006a).

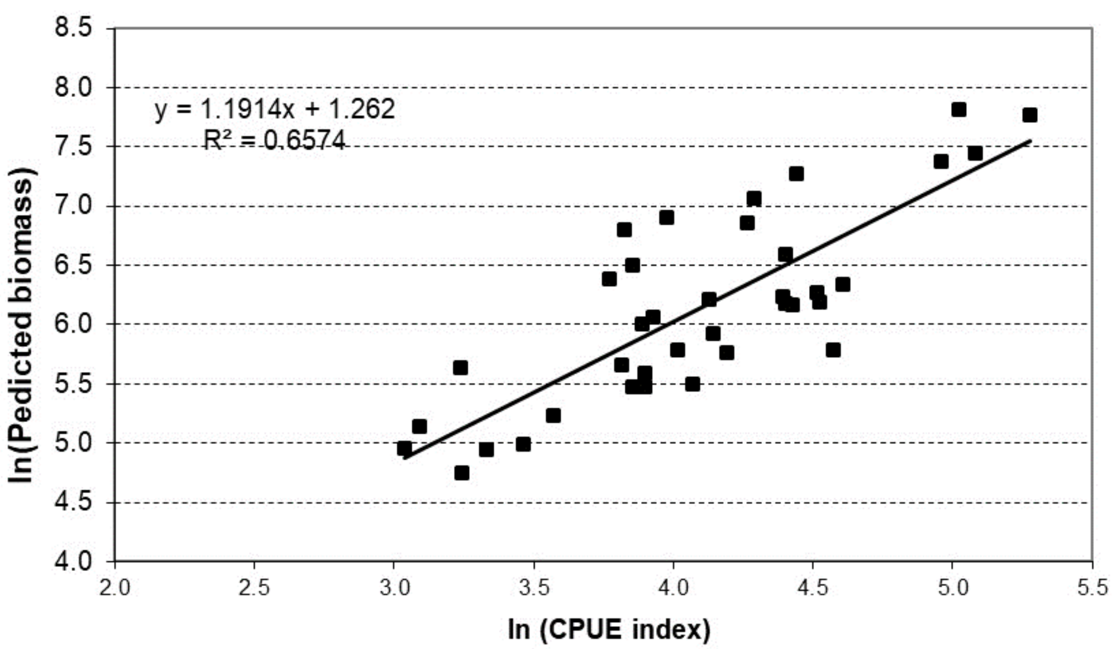

Figure 2. Relationship between the logbook CPUE and the total biomass from the Virtual Population Analysis in relation to the logbooks CPUE from the commercial gaspereau fishery on the Margaree River for years 1983 to 2019.

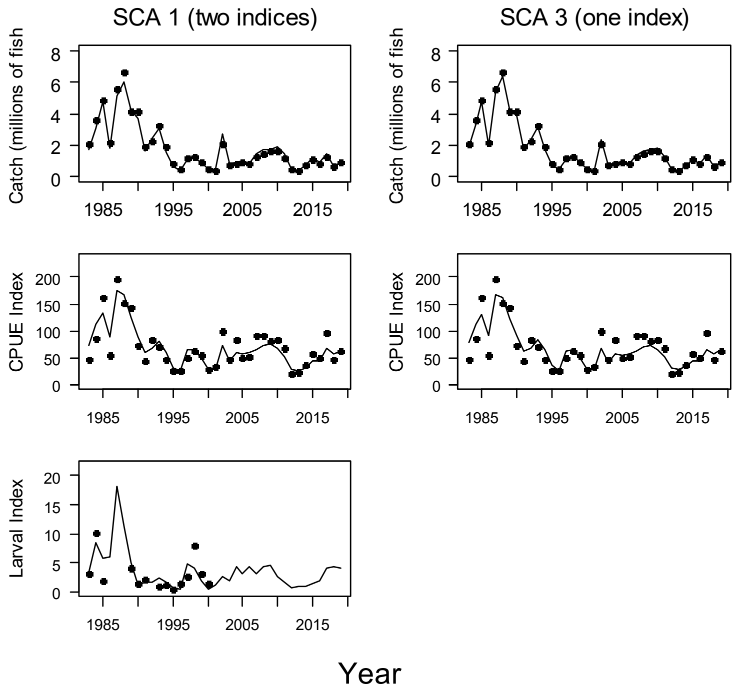

Figure 3. Fits to the commercial catch, the CPUE index and the Larval index for SCA models 1 and 3 (SCA 3 does not include the larval index).

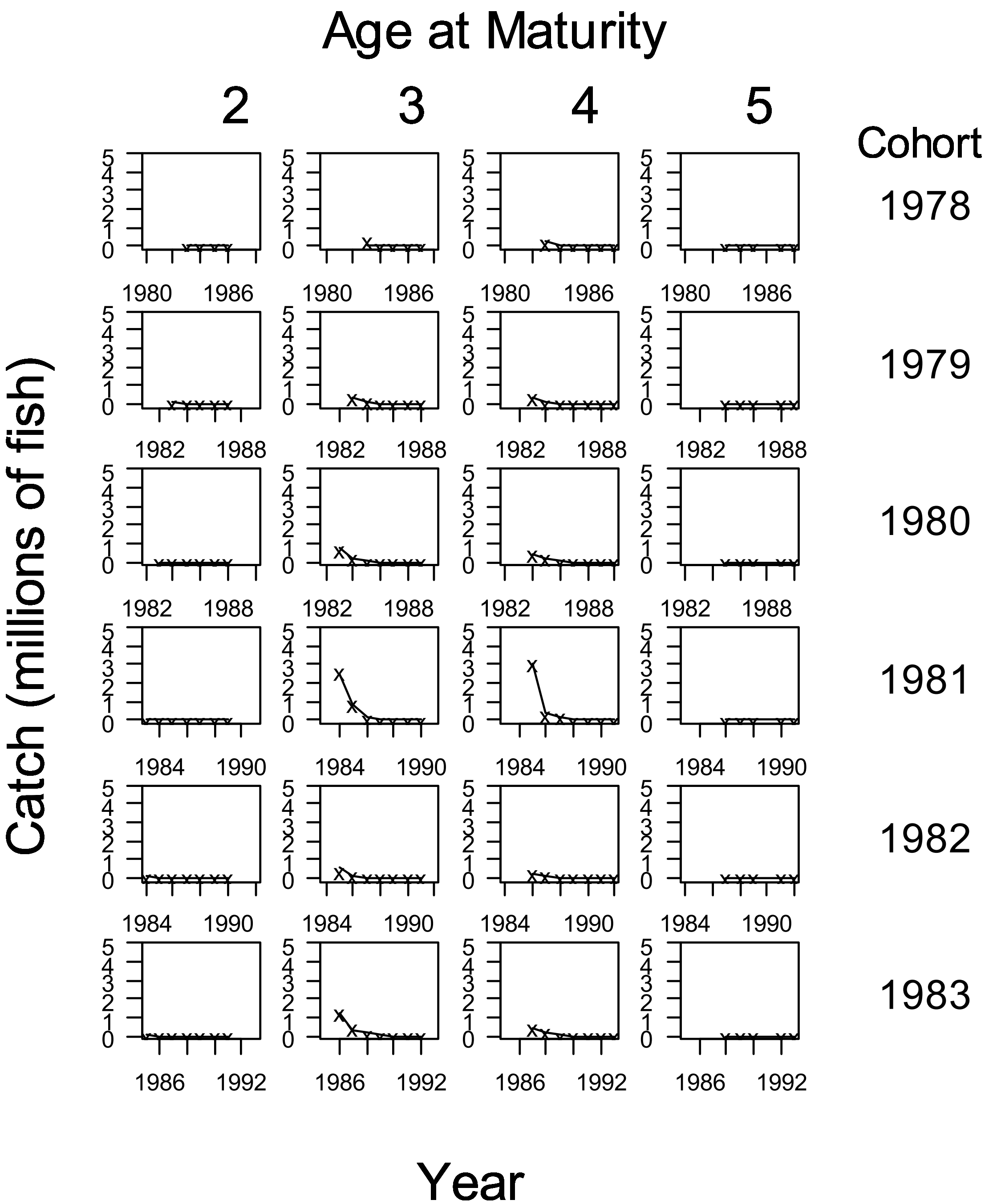

Figure 4a. The observed (x's) and predicted (lines) catch-at-age-previous-spawning arrays for the Margaree River alewife population. Catches are partitioned by cohort year (right column) and age at maturity (labels at the top). The year (bottom labels) is the year of capture.

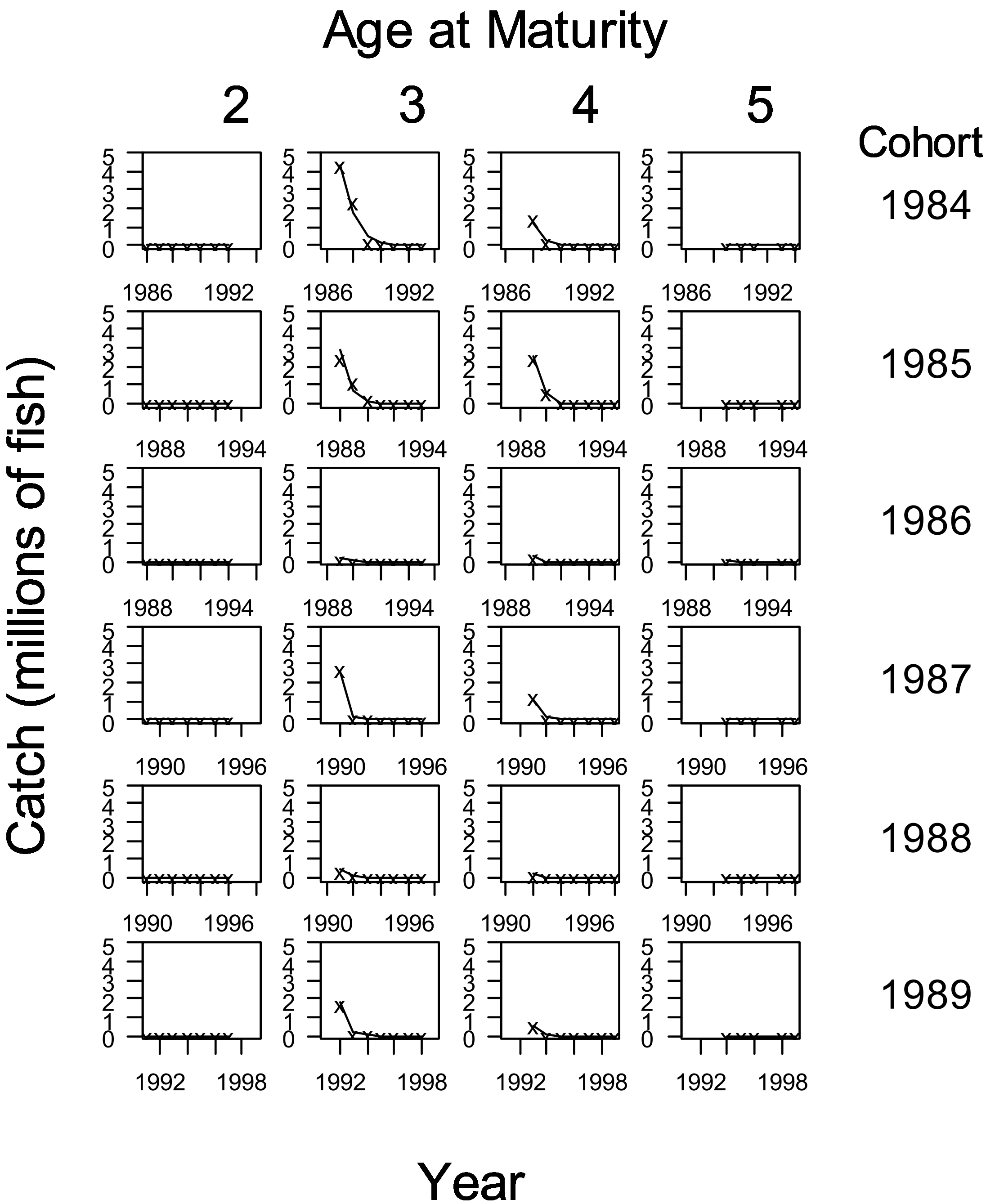

Figure 4b. The observed (x's) and predicted (lines) catch-at-age-previous-spawning arrays for the Margaree River alewife population. Catches are partitioned by cohort year (right column) and age at maturity (labels at the top). The year (bottom labels) is the year of capture.

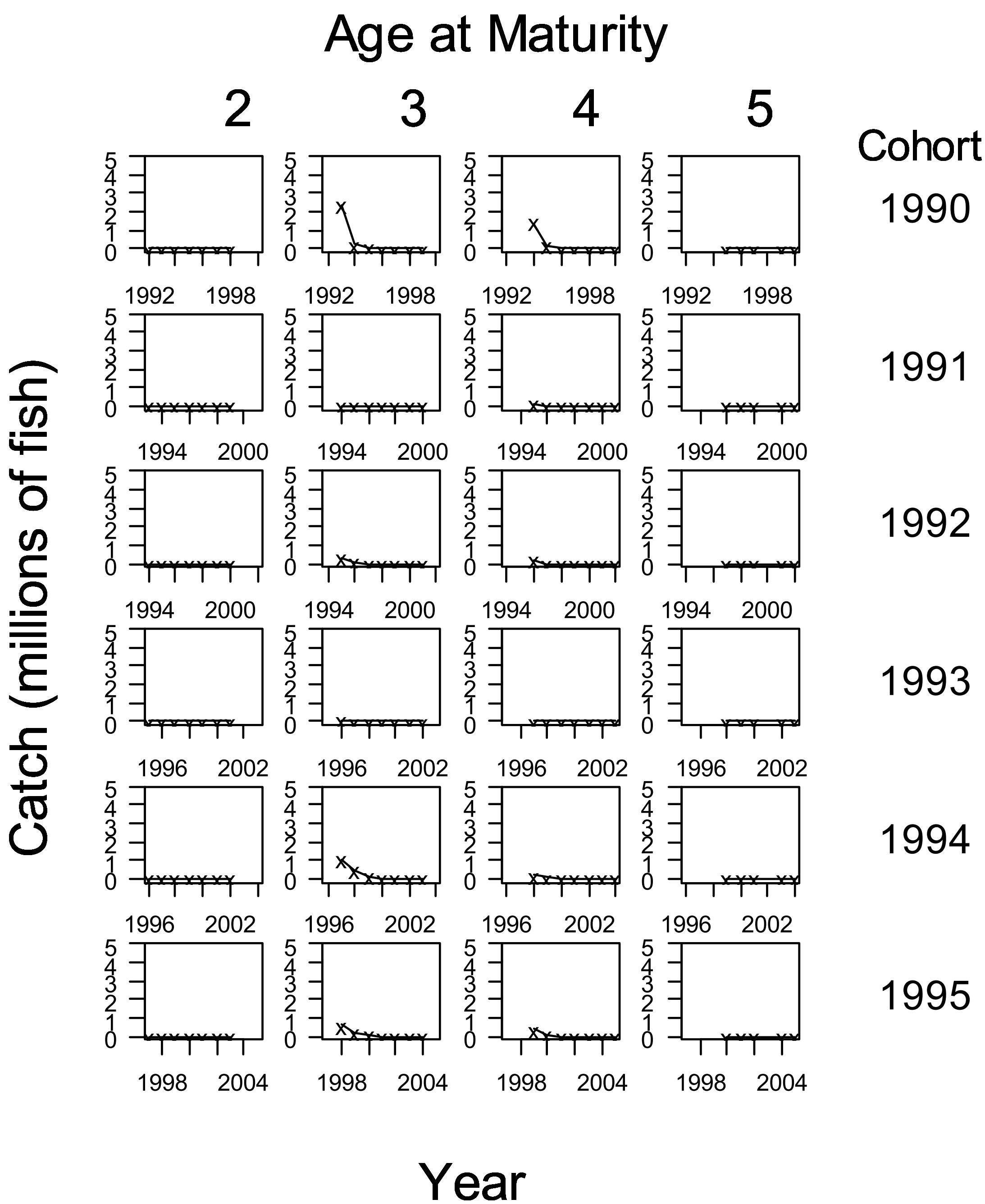

Figure 4c. The observed (x's) and predicted (lines) catch-at-age-previous-spawning arrays for the Margaree River alewife population. Catches are partitioned by cohort year (right column) and age at maturity (labels at the top). The year (bottom labels) is the year of capture.

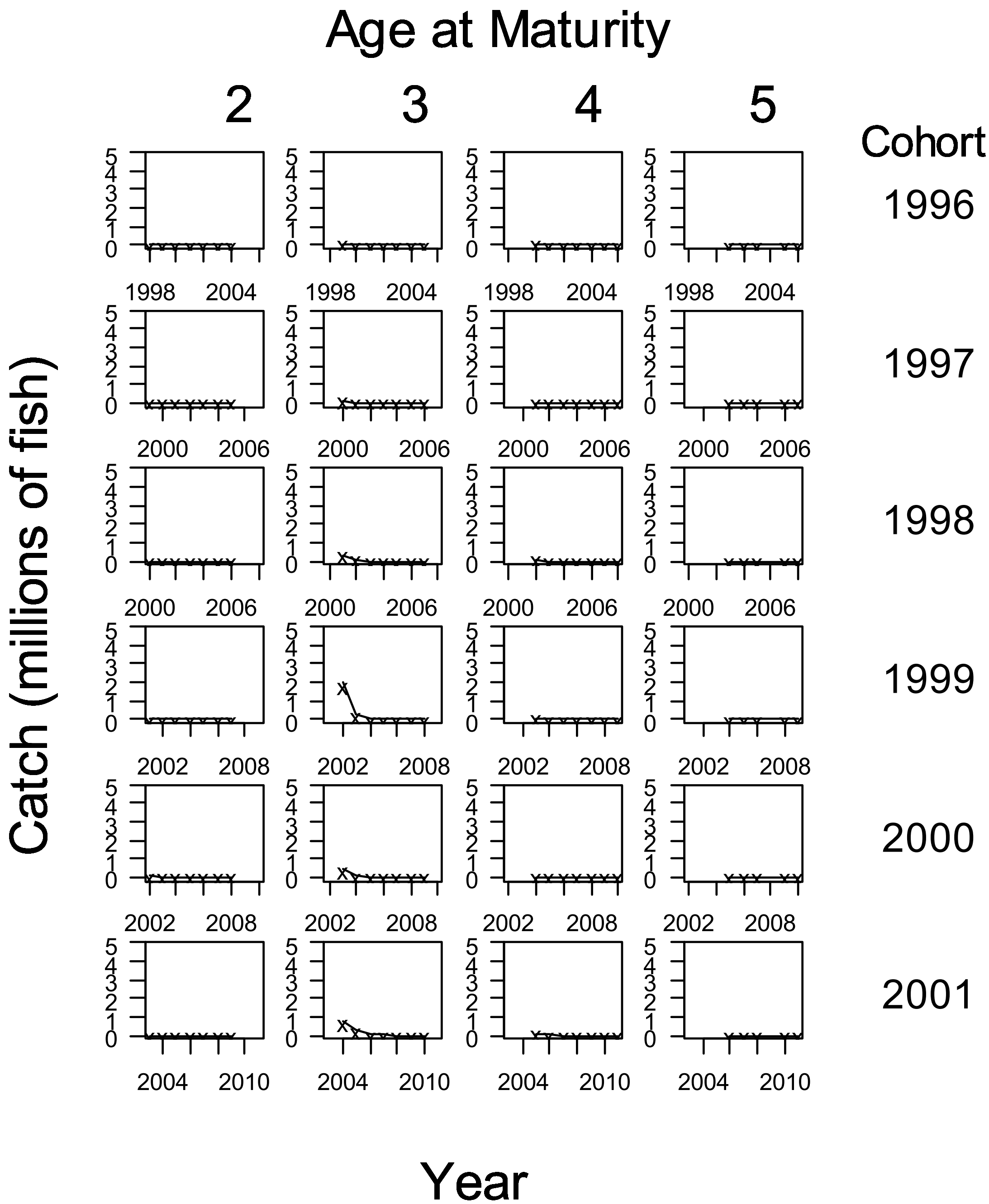

Figure 4d. The observed (x's) and predicted (lines) catch-at-age-previous-spawning arrays for the Margaree River alewife population. Catches are partitioned by cohort year (right column) and age at maturity (labels at the top). The year (bottom labels) is the year of capture.

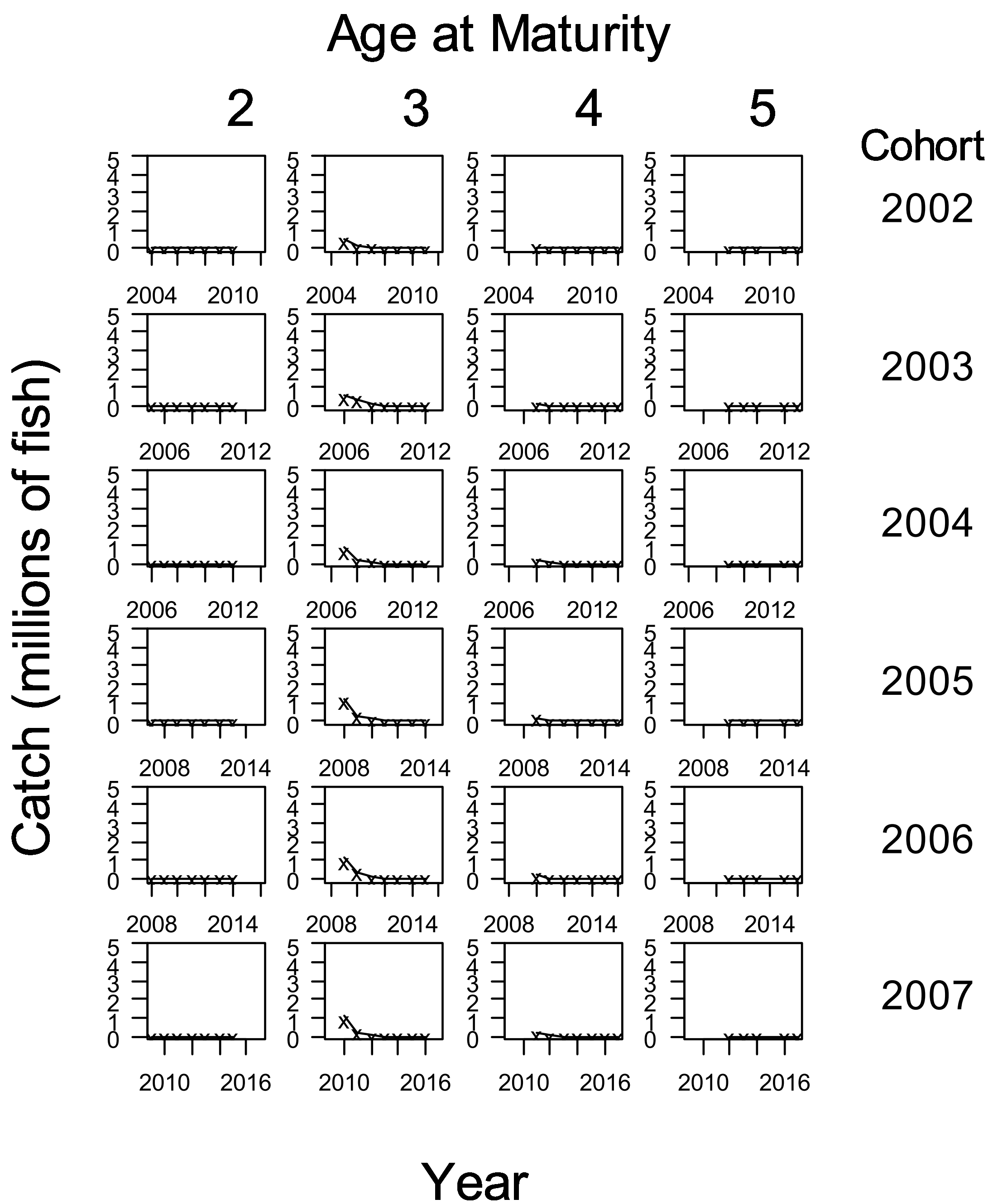

Figure 4e. The observed (x's) and predicted (lines) catch-at-age-previous-spawning arrays for the Margaree River alewife population. Catches are partitioned by cohort year (right column) and age at maturity (labels at the top). The year (bottom labels) is the year of capture.

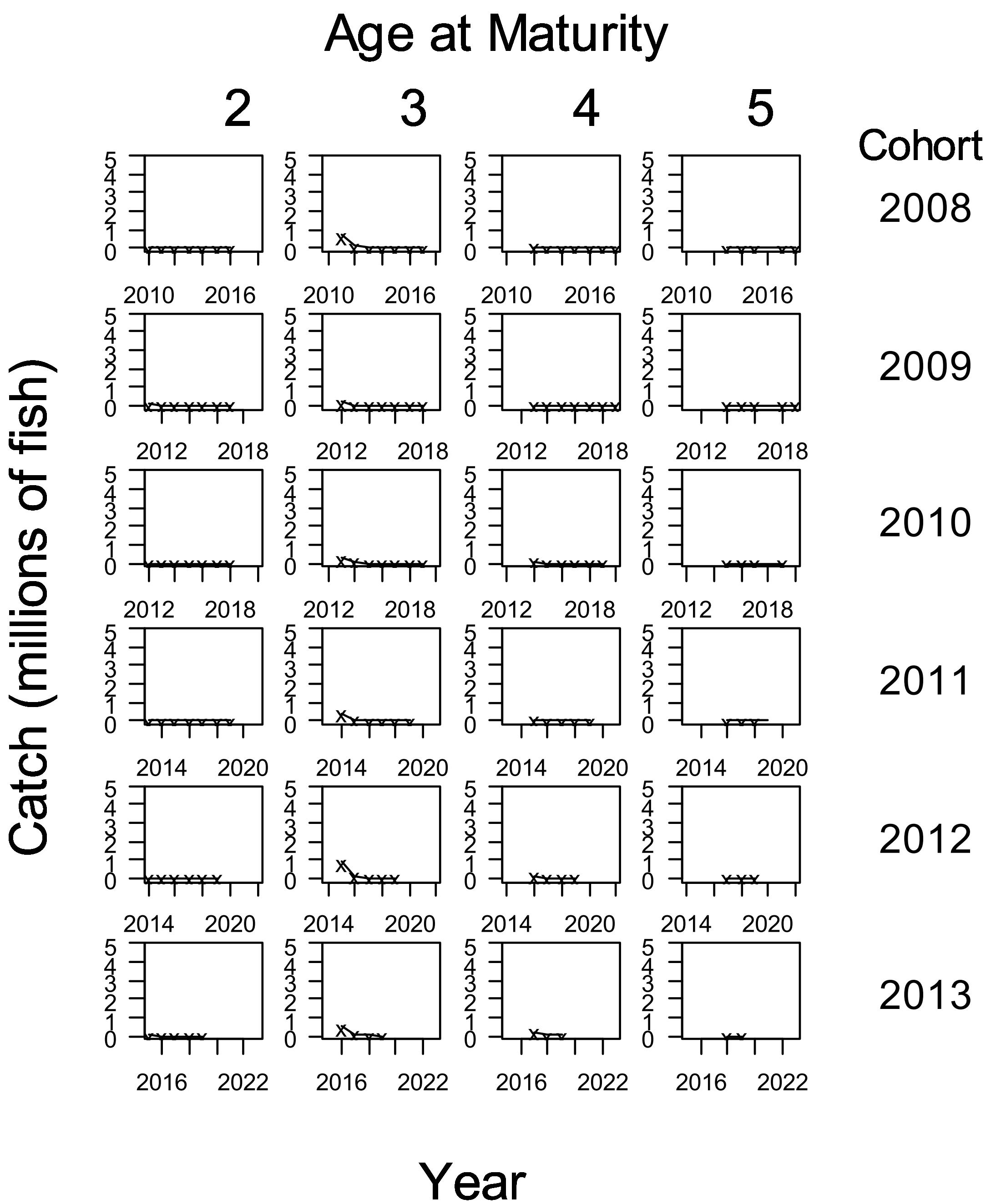

Figure 4f. The observed (x's) and predicted (lines) catch-at-age-previous-spawning arrays for the Margaree River alewife population. Catches are partitioned by cohort year (right column) and age at maturity (labels at the top). The year (bottom labels) is the year of capture.

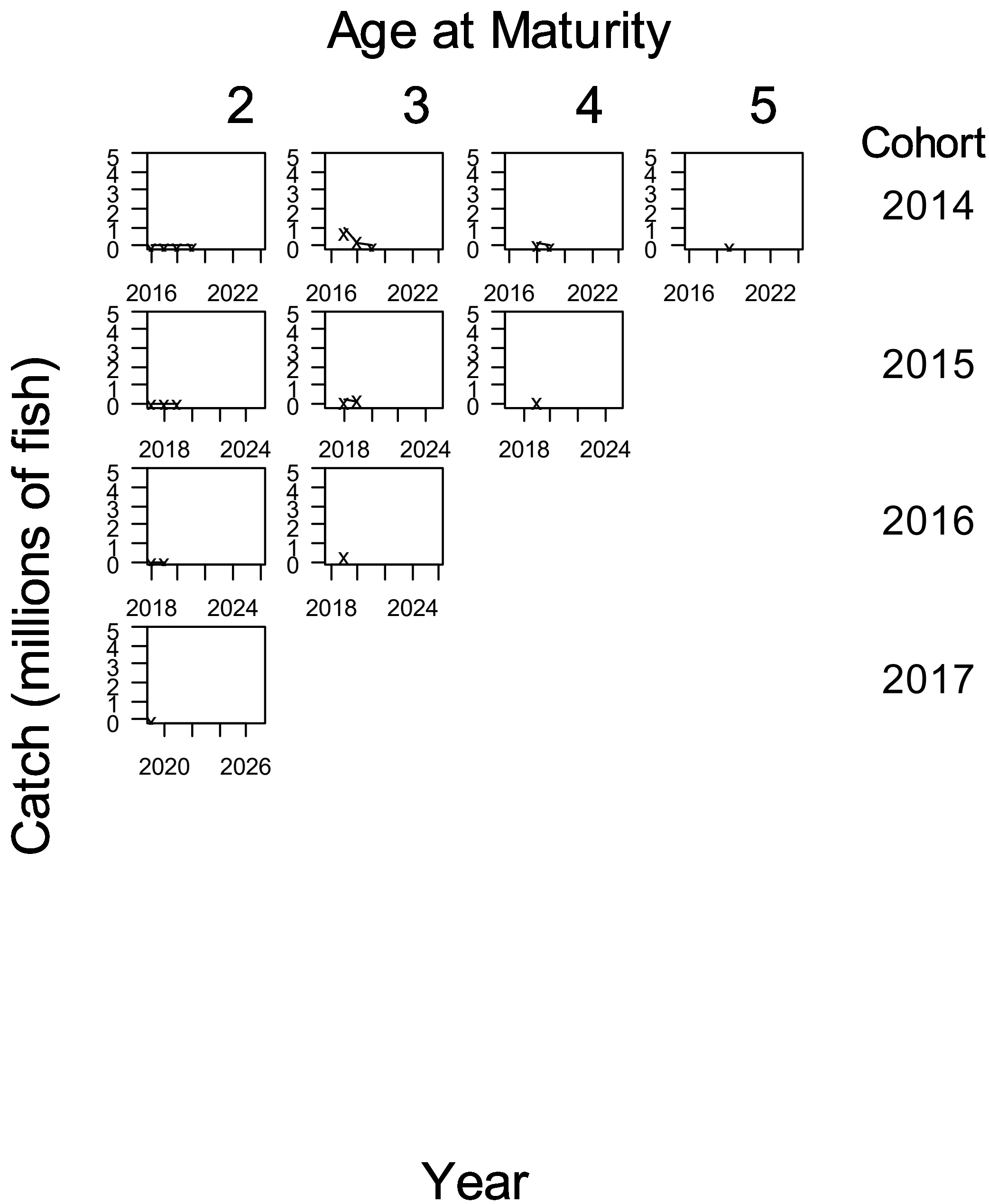

Figure 4g. The observed (x's) and predicted (lines) catch-at-age-previous-spawning arrays for the Margaree River alewife population. Catches are partitioned by cohort year (right column) and age at maturity (labels at the top). The year (bottom labels) is the year of capture.

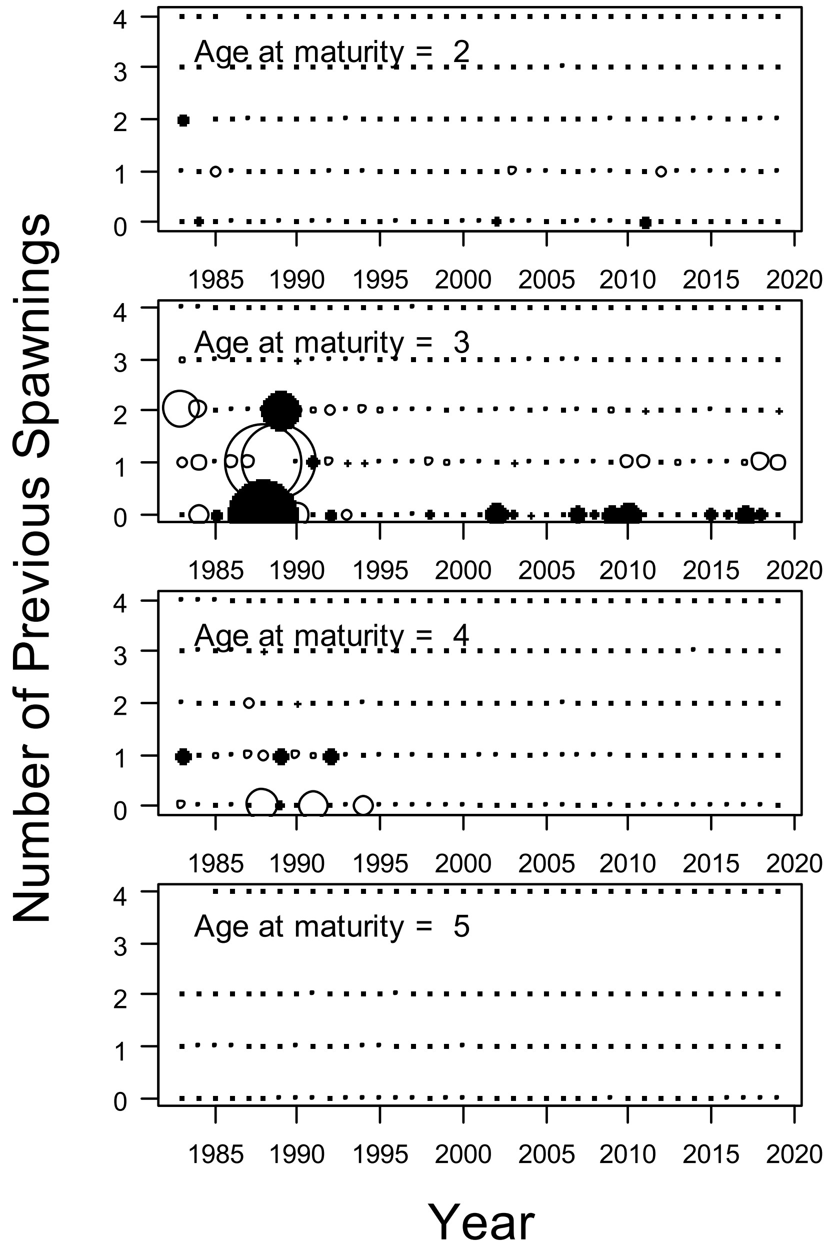

Figure 5. Raw residuals (observed - predicted) for the catch-at-age-ps from SCA 3 (CPUE index only) for Margaree River alewife. Each panel is a different age-at-maturity, representative of the age at which fish first enter the fishery. Black points indicate where the model predictions are higher than the observed value. Point size is arbitrary and scaled to highlight the pattern.

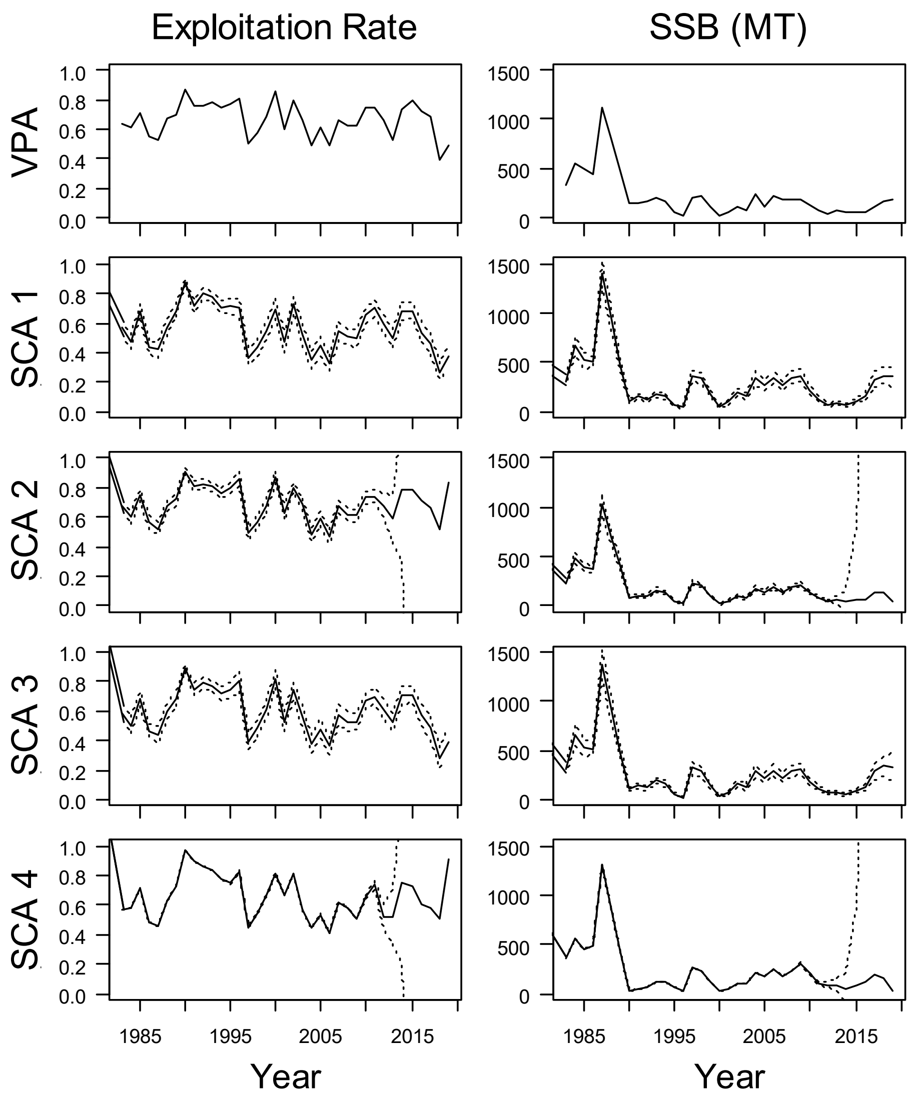

Figure 6. Comparison of the estimated exploitation rates and spawner biomasses (SSB) from five model variations used for Margaree River Alewife in this assessment. Dashed lines indicate 95% confidence intervals for the estimates.

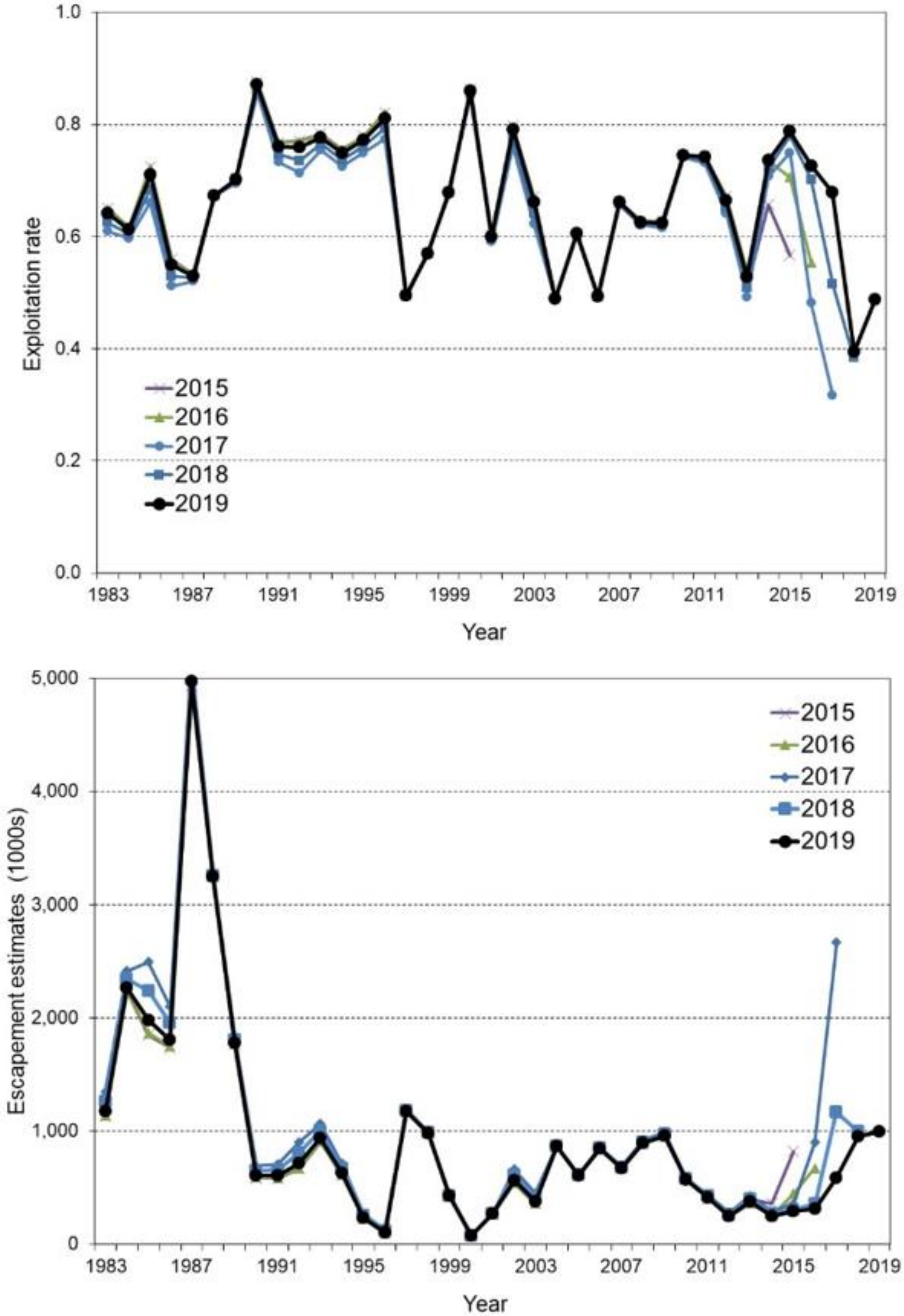

Figure 7. Retrospective patterns for the exploitation rates (upper panel) and escapements (number of spawners, lower panel) from the VPA.

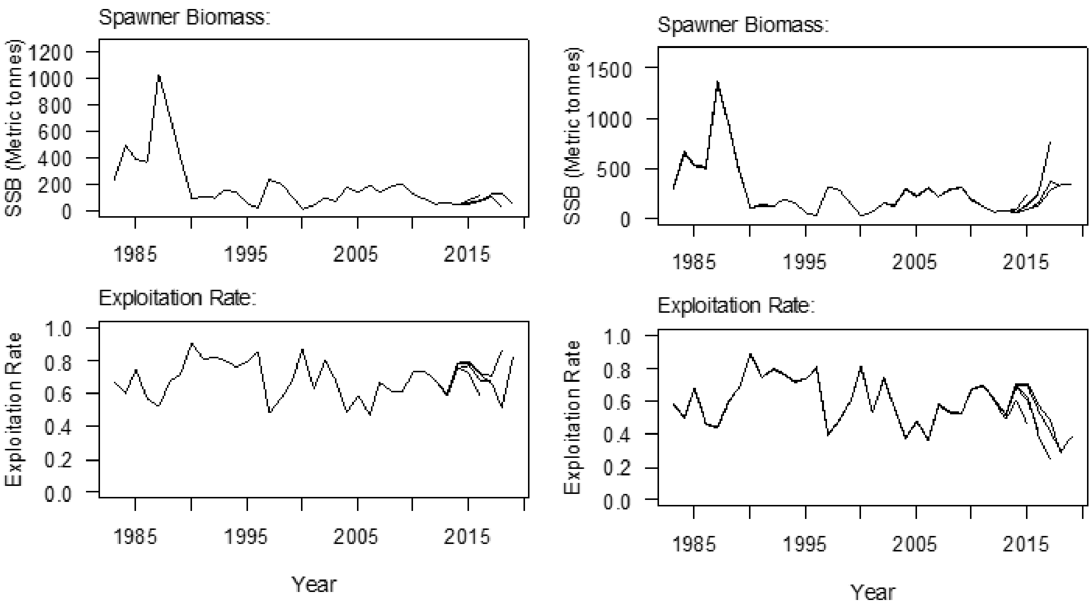

Figure 8. Retrospective patterns for the estimated spawner biomasses (top panels) and exploitation rates (bottom panels) from SCA 2 (left panel, no indices) and SCA 3 (right panel CPUE index only) fit to data for the alewife fishery on Margaree River, NS.

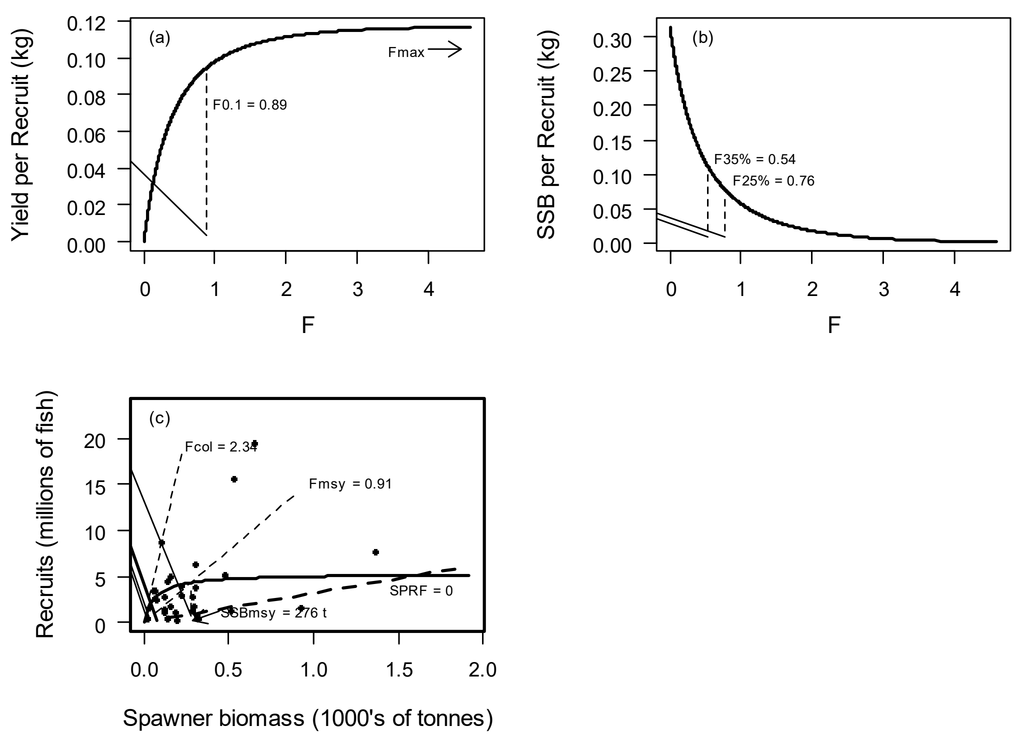

Figure 9. Yield-per-recruit (a), (b) Spawner biomass per recruit, and (c) Beverton-Holt SR models (solid line) for Margaree River Alewife population, as estimated using SCA 3. The associated reference points are also shown. The dashed lines in (c) are the replacement lines in the absence of fishing (SPRF=0), at MSY (Fmsy) and at the fishing mortality rate that extirpates the population (Fcol).

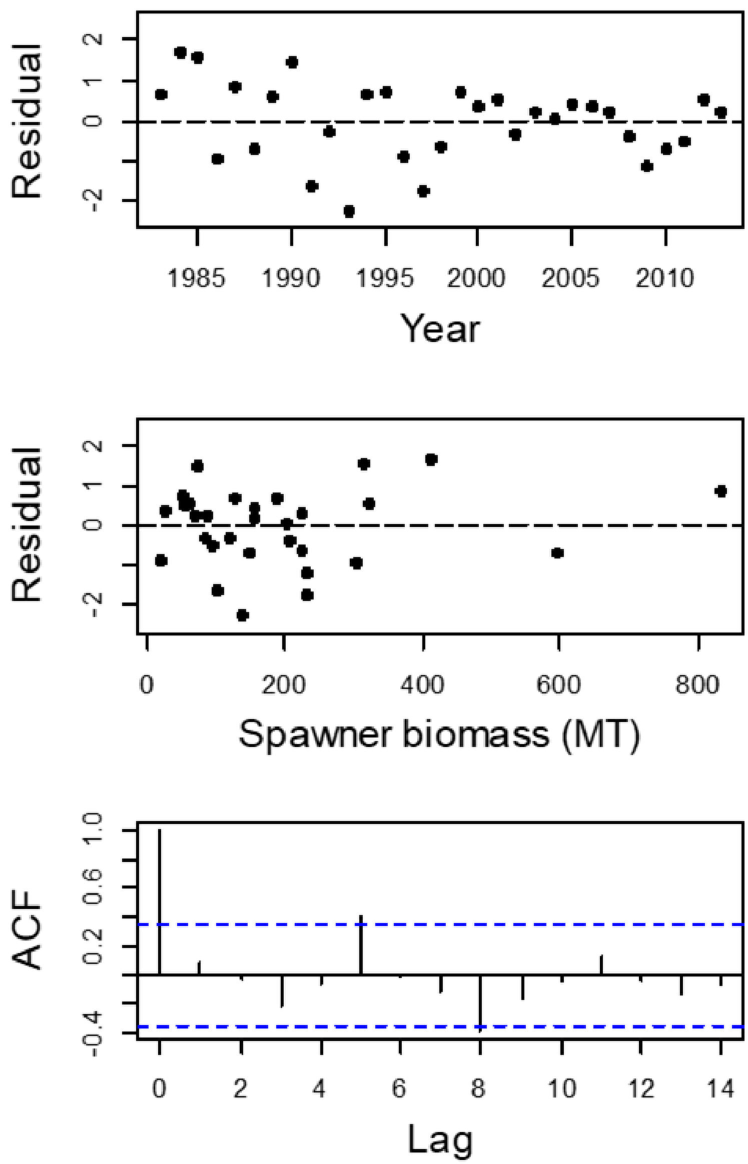

Figure 10. Log scale residuals (observed-predicted) for the SR model associated with SCA 3 for Margaree River Alewife.

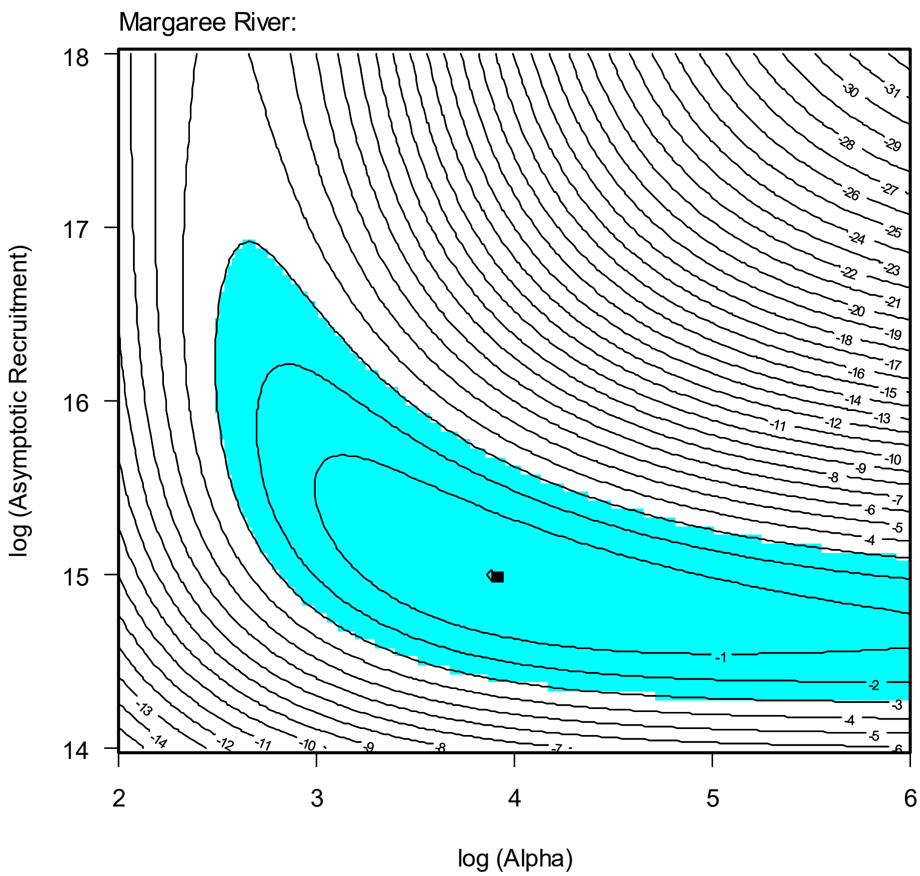

Figure 11. Contour plot showing the joint log likelihood surface for alpha and the asymptotic recruitment level for the Margaree River Alewife, associated with SCA 3. The black square indicates the point at which the log likelihood is maximized. The contour interval is -1 moving away from this point. The blue-haded region shows the likelihood ratio based 95% confidence region for the parameters.

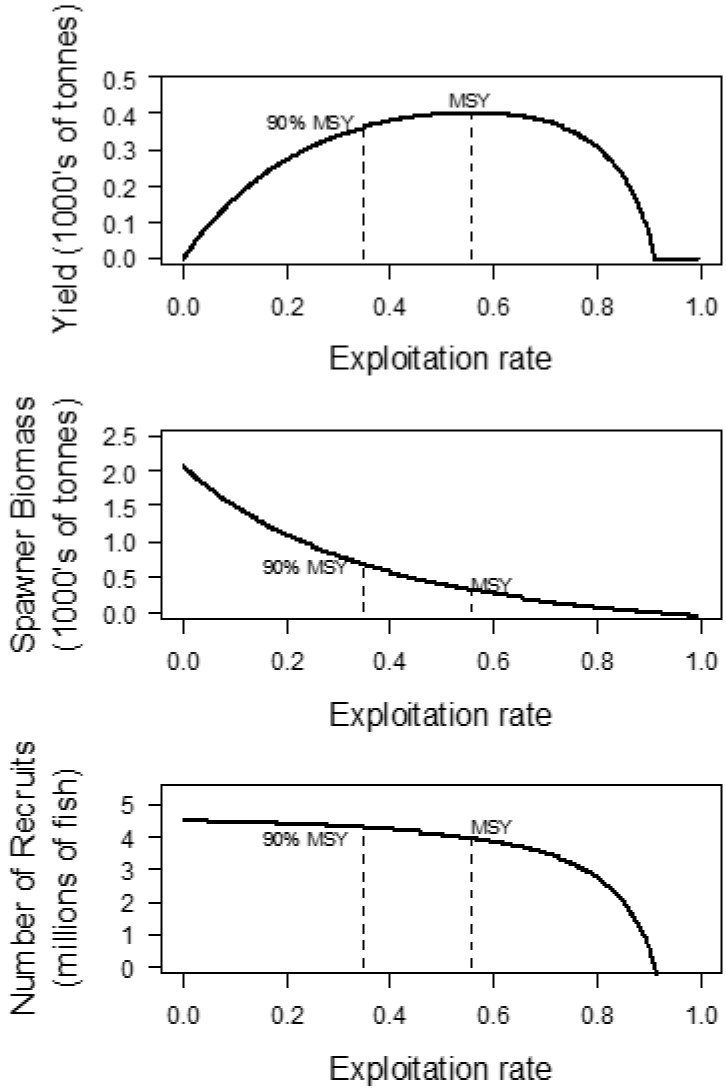

Figure 12. The relationship between yield (top panel), spawner biomass (middle panel) and the number of age-2 recruits (middle panel), and the exploitation rate for Margaree River Alewife, as estimated based on SCA 3. The dashed lines indicate the exploitation rates associated with MSY and 90% MSY.

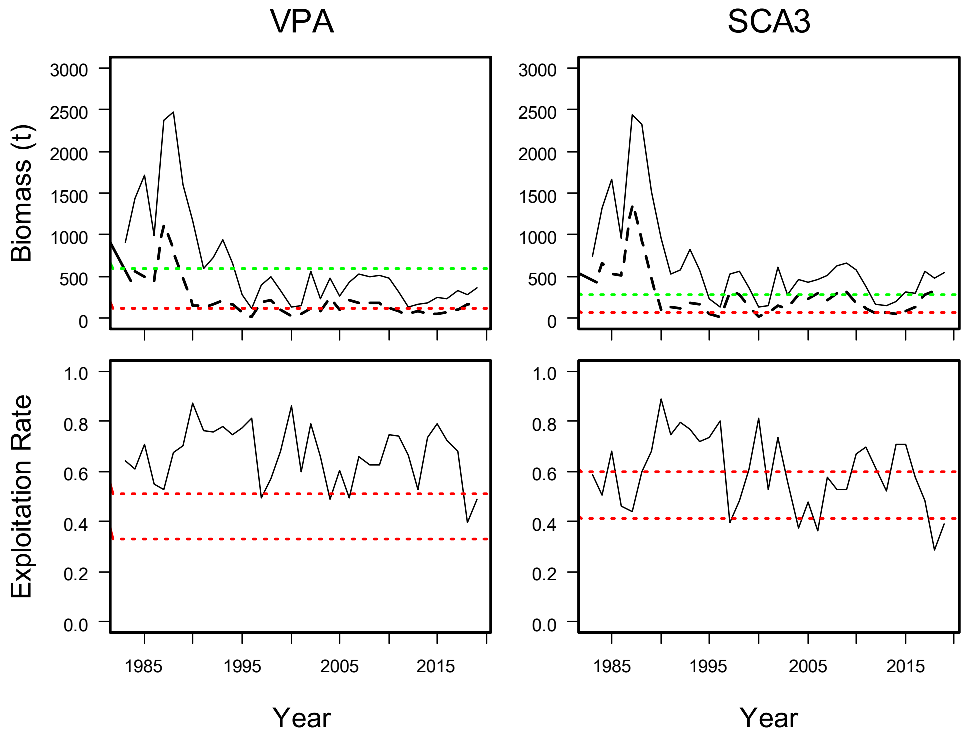

Figure 13. Time series for the Margaree River Alewife population and fishery showing the status relative to the biomass reference points (top row) and removal rate reference points (bottom row) as determined from the VPA (left column) and SCA 3 (right column). In the biomass plots, the red dotted lines show the USR (upper line) and LRP (lower line). The solid black line shows the total biomass before the fishery, whereas the dashed black line shows the spawner biomass remaining after the fishery. In the removal rate figures, the red dotted lines show the maximum removal rate (top line) and the lower removal reference rate (bottom line). Removal reference points are only appropriate when the population is in the healthy zone. The values for the last four years are questionable due to retrospective issues with the model (exploitation rates are underestimated and biomass overestimated during those years).

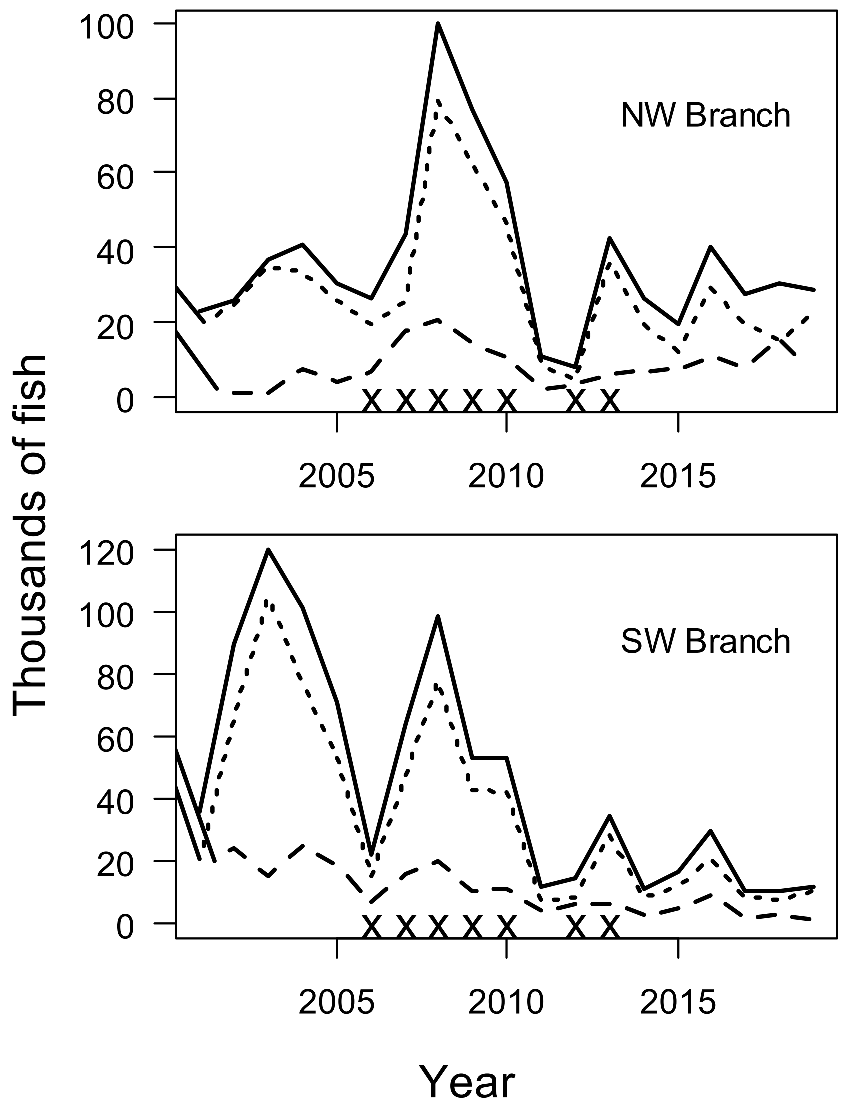

Figure 14. Annual landings of Blueback Herring (dotted line), Alewife (dashed line) from 2001 to 2019. The solid line shows both species combined. X's mark the years with age-ps composition data.

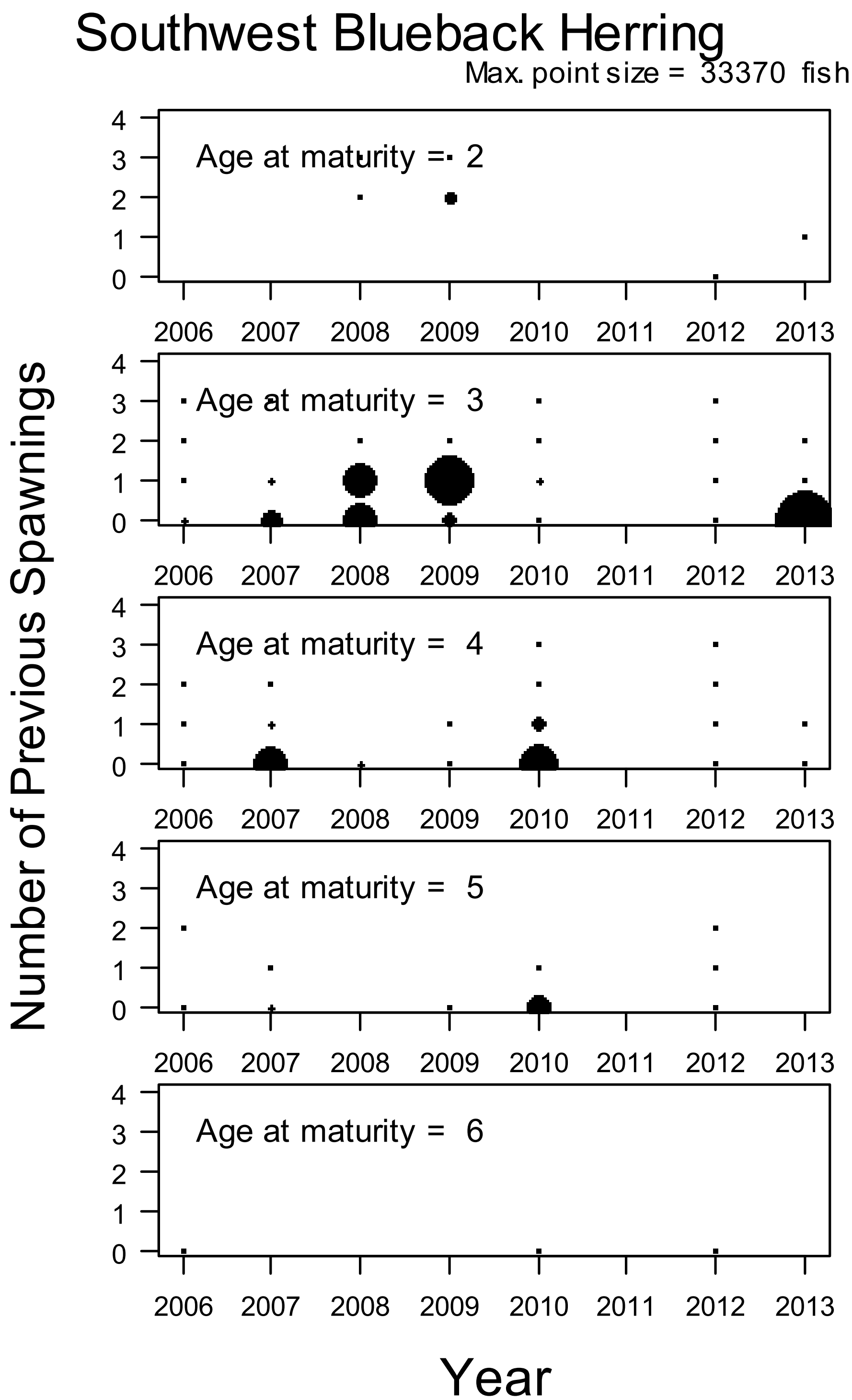

Figure 15. Bubble plot showing the annual relative abundance by age-at-maturity (panels) and number previous spawnings (y-axis) for Blueback Herring in the SW branch of the Miramichi River from 2006 to 2013 (there is no data for 2011).

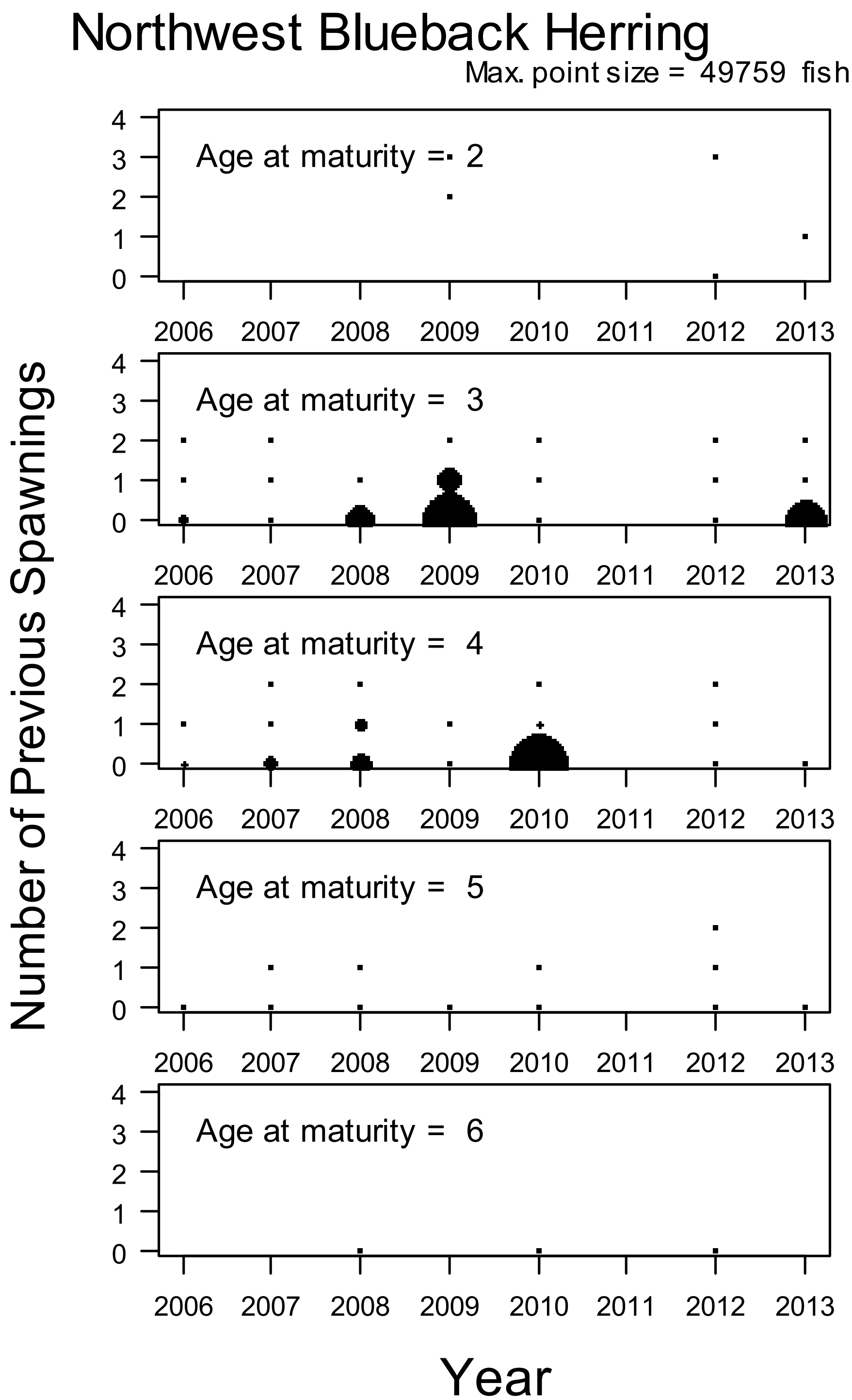

Figure 16. Bubble plot showing the annual relative abundance by age-at-maturity (panels) and number previous spawnings (y-axis) for Blueback Herring in the NW branch of the Miramichi River from 2006 to 2013 (there is no data for 2011).

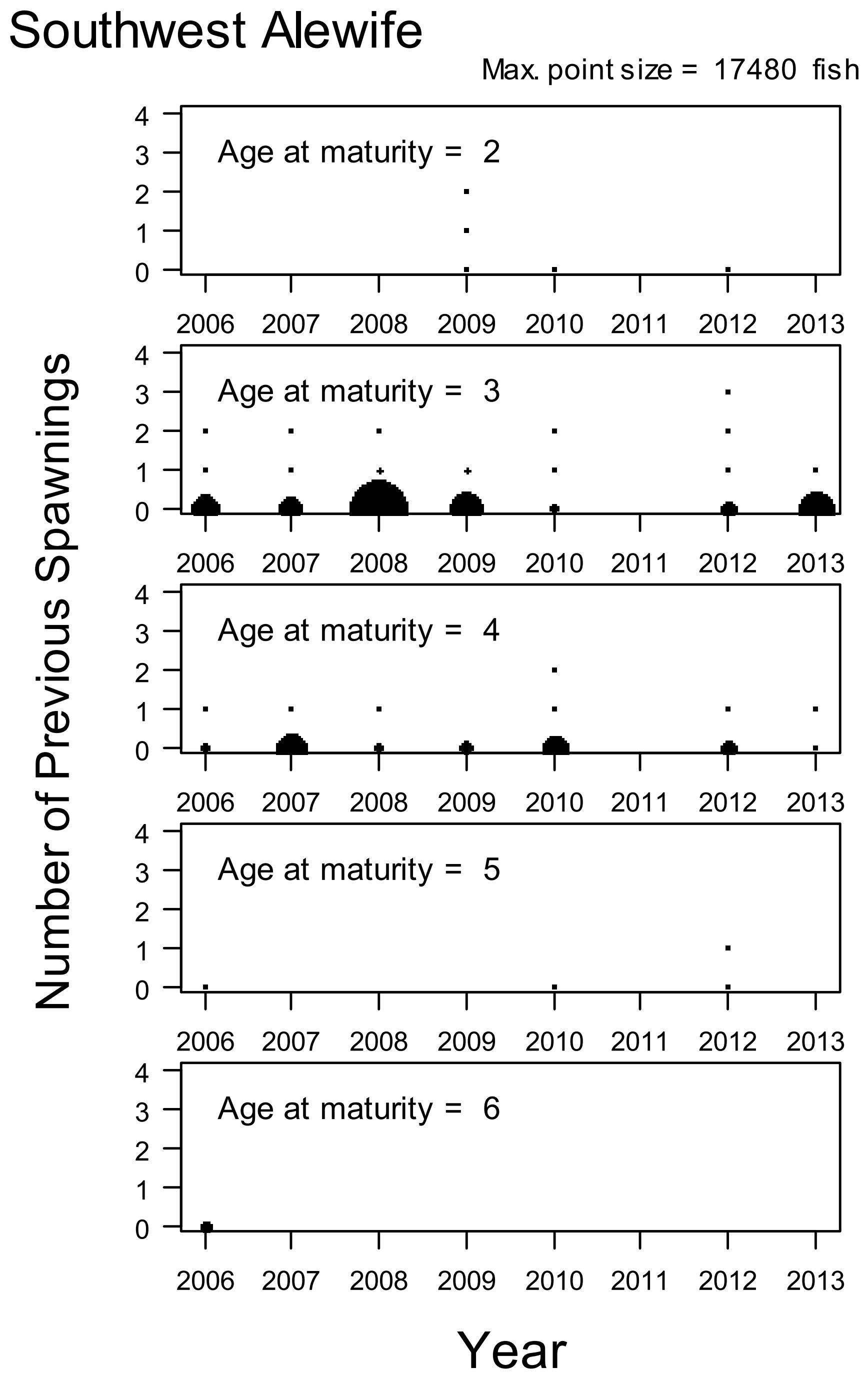

Figure 17. Bubble plot showing the annual relative abundance by age-at-maturity (panels) and number previous spawnings (y-axis) for Alewife in the SW branch of the Miramichi River from 2006 to 2013 (there is no data for 2011).

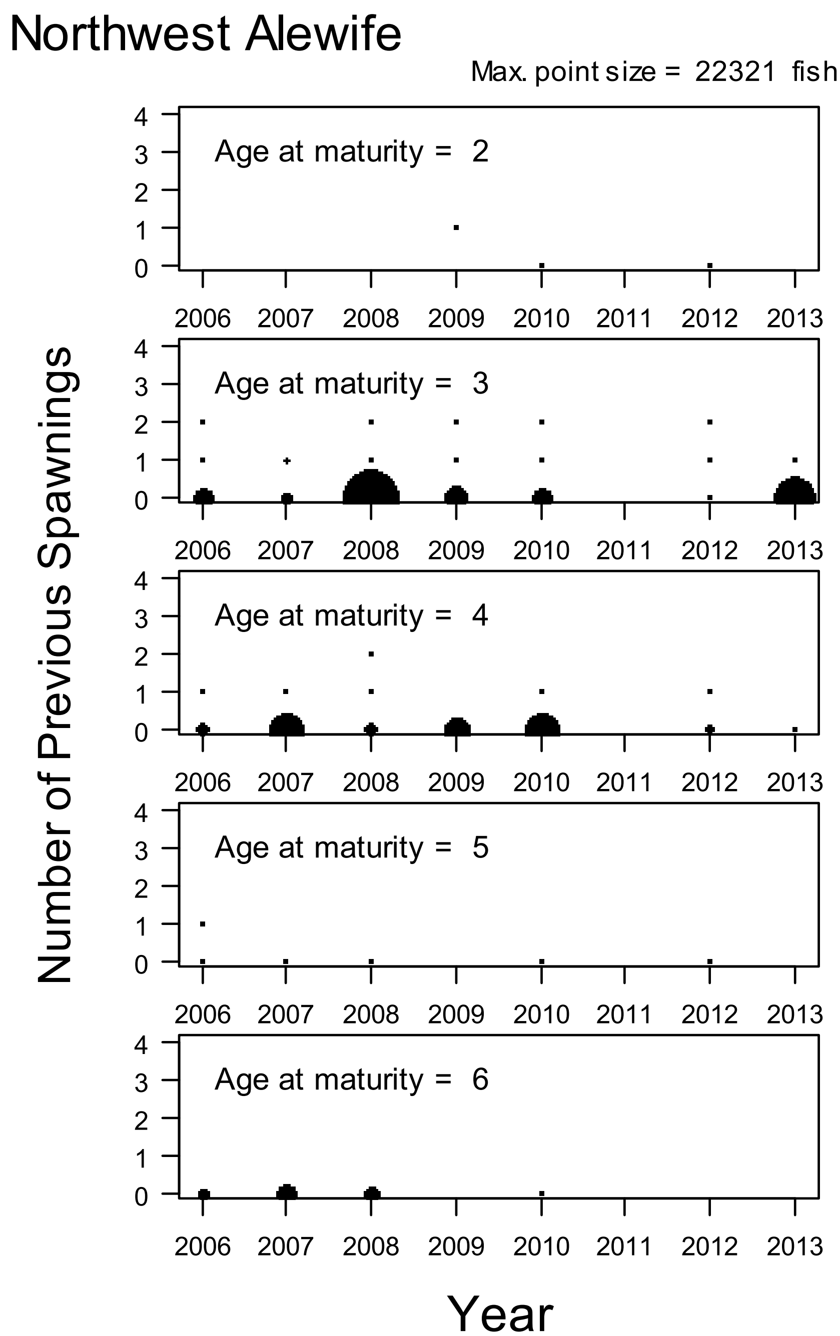

Figure 18. Bubble plot showing the annual relative abundance by age-at-maturity (panels) and number previous spawnings (y-axis) for Alewife in the NW branch of the Miramichi river from 2006 to 2013 (there is no data for 2011).

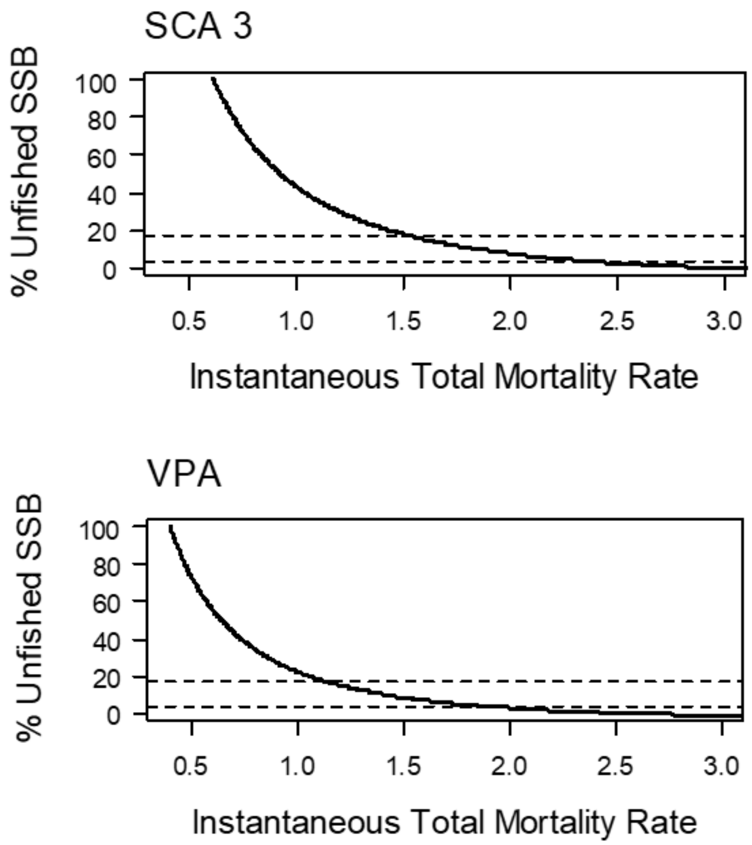

Figure 19. Relationship between the instantaneous total mortality rate and the percentage of the unfished equilibrium biomass from the Margaree River alewife models SCA 3 (top panel) and the VPA (bottom panel). The dashed lines show the percentage at SSB_{msy} (upper line) and K (lower line).The region above SSB_{msy} and the region below K is the critical zone.

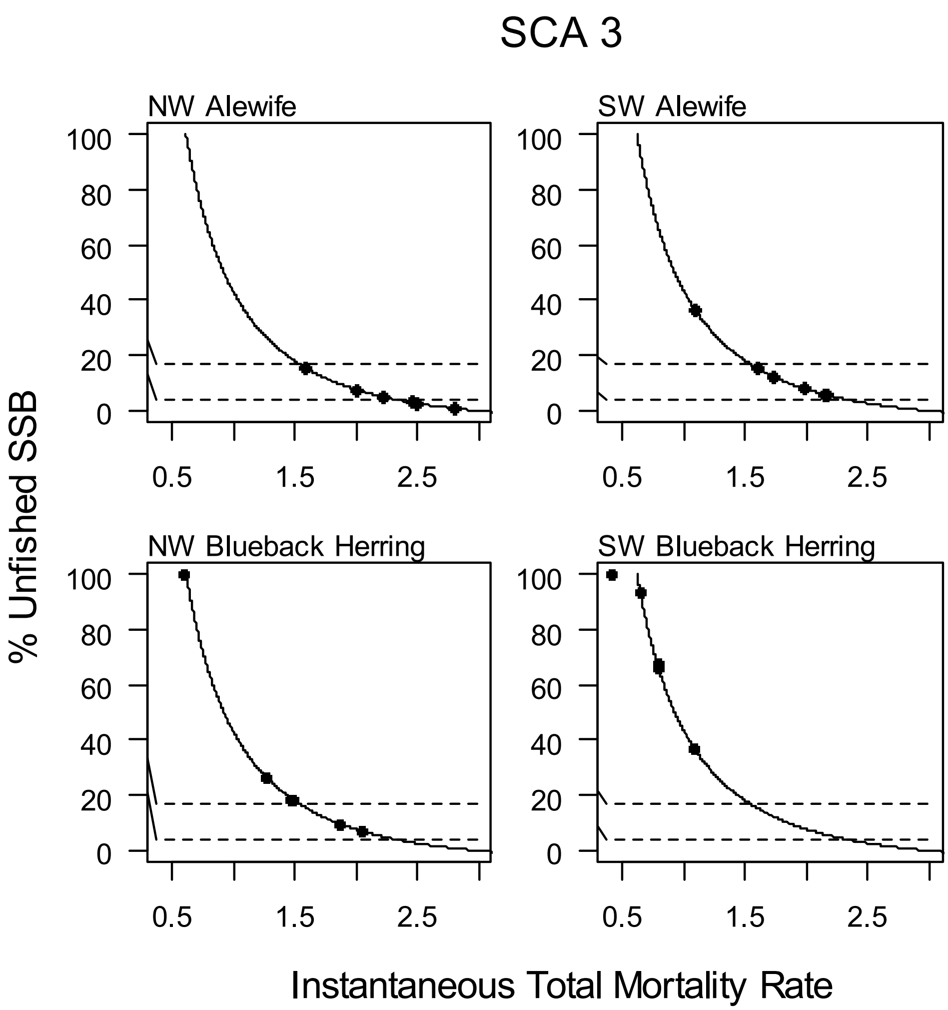

Figure 20. Relationship between the instantaneous total mortality rate and the percentage of the unfished equilibrium biomass from the Margaree River alewife models from SCA 3. The dashed lines show the percentage at SSB_{msy} (upper line) and K (lower line).The region above SSB_{msy} and the region below K is the critical zone. The points are the estimated instantaneous total mortality rates from the catch curves (Table 1). The point that is off the line for SW Blueback Herring has a mortality rate estimate that is less than the natural mortality rate estimate from SCA 3.

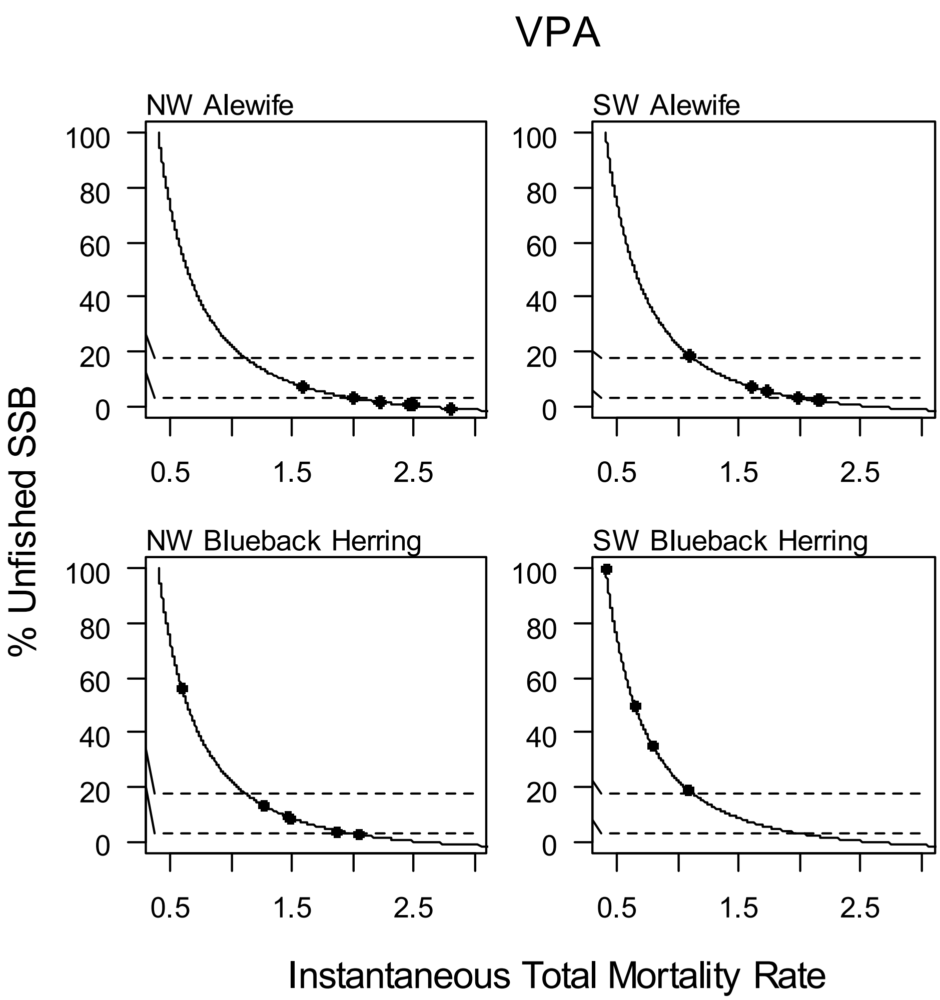

Figure 21. Relationship between the instantaneous total mortality rate and the percentage of the unfished equilibrium biomass from the Margaree River alewife models from the VPA. The dashed lines show the percentage at SSBmsy (upper line) and K (lower line).The region above SSBmsy and the region below K is the critical zone. The points are the estimated instantaneous total mortality rates from the catch curves (Table 1).

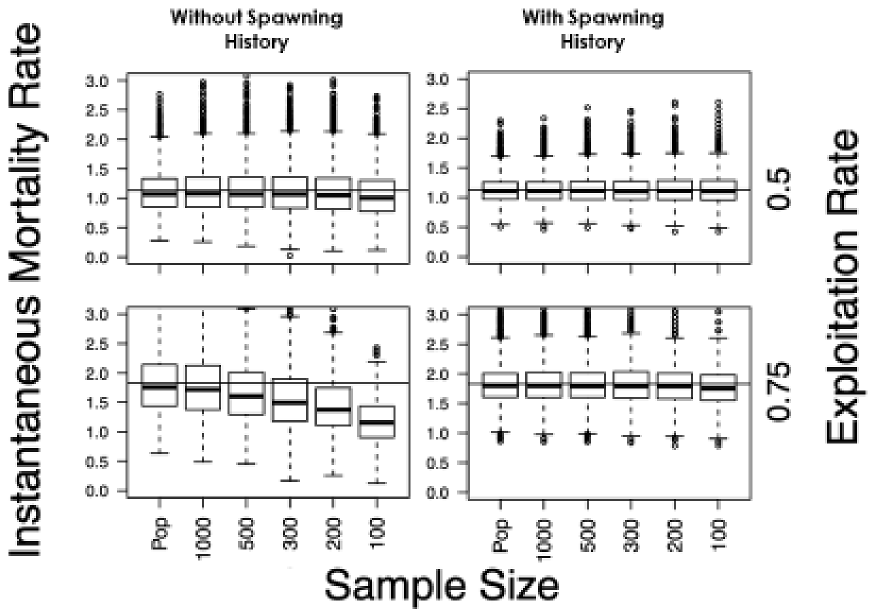

Figure 22. Boxplots comparing instantaneous total mortality rate (Z) estimates obtained by fitting to data simulated using a life cycle model. Two methods of fitting catch curves using Poisson generalized linear models are compared: using age as the independent variable (left column), and using the number-of-previous-spawnings and age-at-maturity as the independent variables (right column). The two rows show results using simulations of two exploitation rates: 0.5 and 0.75. Catch curve regressions were fit to simulated data using sample sizes of all fish (Pop), 1,000, 500, 300, 200 and 100 fish, depicted on the X-axis of each panel. Each individual boxplot shows the results of 3,750 attempted estimates of Z for each sample size and exploitation rate combination. The horizontal solid line represents the true instantaneous total mortality rate in each panel. Adapted from Billard (2020).

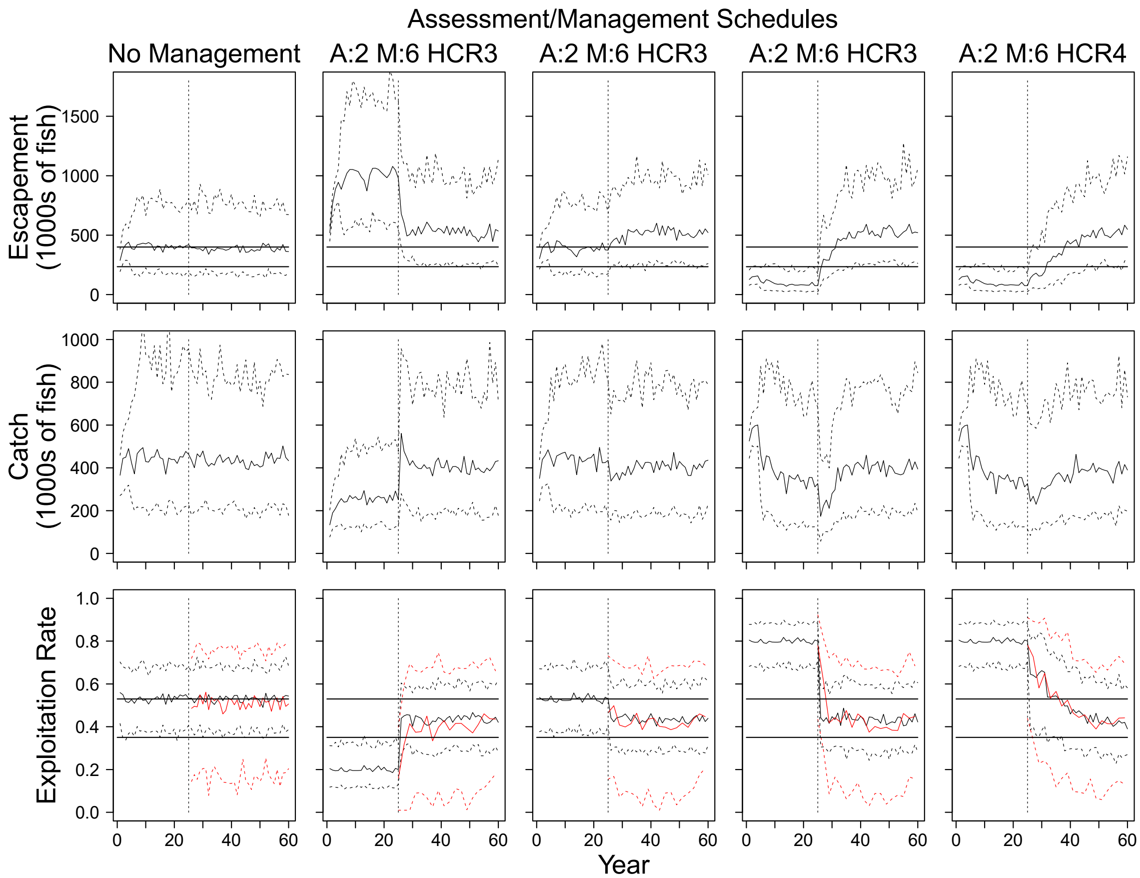

Figure 23. The distribution of annual escapement (top row), catch (middle row), and exploitation rate (bottom row) for 100 60-year projections done for five management strategies with different assessment and management schedules, harvest control rules (HCR) and starting exploitation rates in the MSE. HCR 3 involves a greater correction to adjust the exploitation rate than HCR 4. The first column shows projections of a fully-exploited population (μ=0.53) where no management changes are made. Columns two through four show projections for under-, fully and over-exploited populations (μ=0.2, μ=0.53, μ=0.8) that are assessed every two years and managed every six years under HCR 3. Column five shows projections of over-exploited populations (μ=0.8) assessed every two years and managed every six years under HCR 4. The solid lines in each panel represent the median values, while the dotted lines represent the 10th and 90th percentiles of the 100 projections. The solid horizontal lines in the top row represent the Upper stock reference point (400,000 fish) and the Limit stock reference point (235,000 fish). The solid horizontal lines in the bottom row represent the boundaries of the fully-exploited zone (0.53 and 0.35). The vertical dashed lines indicate when assessment and management commenced, at year 25. In the bottom row, the black lines show the median and spread of the exploitation rate applied to the population, while the red lines show median and spread of the exploitation rate estimated with the catch curve model (from Billard 2020).