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Fisheries Reference Points for Striped Bass (*Morone saxatilis*) from the Southern Gulf of St. Lawrence

Gérald Chaput and Scott Douglas

Fisheries and Oceans Canada
Science Branch
Gulf Fisheries Centre
343 University Avenue
Moncton, NB E1C 9B6

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Foreword

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

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ABSTRACT

The Striped Bass (*Morone saxatilis*) population of the southern Gulf of St. Lawrence, the most northern spawning population of the species distribution in eastern North America, is widely distributed in estuaries and coastal waters of the southern Gulf of St. Lawrence from the north shore of the Gaspe Peninsula in Quebec to the northern tip of Cape Breton Island, Nova Scotia. For purposes of assessment and development of fisheries reference points, the southern Gulf Striped Bass population distribution comprises the Gulf of St. Lawrence region. Following on the sustained rebuilding of the spawner abundances from the lows of the late 1990s to the current high abundances that exceed 300 thousand spawners, DFO Gulf Ecosystems and Fisheries Management requested the development of fisheries based reference points that conform to the Precautionary Approach (PA) to guide further management decisions on the development of the Striped Bass fisheries. The extensive information on the abundance and biological characteristics of the Striped Bass population of the southern Gulf of St. Lawrence is presented. An age structured population model is used to estimate stock and recruitment parameters and associated mortality rates at age based on assessed abundances of spawners for the years 1996 to 2019. Equilibrium modelling is used to define candidate Limit Reference Point (LRP), Upper Stock Reference (USR), and removal rate references that would conform to the Precautionary Approach. Despite model uncertainties, a LRP value of just over 330 thousand spawners is consistent with one of the population model results as well as with the history of the management decisions for re-opening of fisheries access since 2013. The USR value of 720 thousand spawners would represent a healthy condition for this population, based on the assessed spawner abundances to 2019 and on the potential productive capacity of this population. A number of knowledge gaps and uncertainties remain. The most important assessment and management gap is the incomplete to non-existent catch statistics for any of the Striped Bass fisheries in the southern Gulf of St. Lawrence, including Indigenous Food Social and Ceremonial fisheries and the larger recreational fisheries. In the absence of these catch and harvest data, it is not possible to provide fisheries management advice in terms of total allowable catches nor can the status of the population relative to removal rates be assessed. Striped Bass is a predator of other valued anadromous fisheries species in the southern Gulf of St. Lawrence. The reference points presented are derived based on optimizing value functions specific to Striped Bass. No multi-species reference points or management options are discussed.

1. INTRODUCTION

Striped Bass (*Morone saxatilis* Walbaum, 1792; Order Perciformes; Family Percichthyidae) is widely distributed throughout the estuaries and coastal waters of the southern Gulf of St. Lawrence (southern Gulf), from the north shore of the Gaspe Peninsula in Quebec to the northern tip of Cape Breton Island, Nova Scotia. The spawning population in the southern Gulf of St. Lawrence is at the northern extent of the species distribution (Figure 1.1).

Genetic analyses and conventional tagging studies have indicated that this population is geographically isolated within the southern Gulf of St. Lawrence and distinct from any other Striped Bass population, including the only other remaining Canadian population which spawns in the Shubenacadie River, Nova Scotia (Bradford et al. 2001a; COSEWIC 2004; Wirgin et al. 1993, 2020).

Previous to 2017, the extent of occurrence of the southern Gulf of St. Lawrence Striped Bass population was assumed to have been restricted to the southern portion of the Gulf of St. Lawrence (COSEWIC 2012). In 2017, an extraordinary expansion of Striped Bass into previously undocumented areas along the north shore of the St. Lawrence and into southern Labrador was noted (DFO 2018; Valiquette et al. 2018; Figure 1.2). The potential distribution of the southern Gulf Striped Bass population is now considered to occasionally extend into those northern areas and the estuary of the St. Lawrence River. Striped Bass sampled from the Bras d'Or Lake and Mira River areas of eastern Cape Breton have been shown to be genetically similar to Striped Bass from the southern Gulf of St. Lawrence (Bentzen, P., Mcbride, M., and Paterson, I.G. 2014. Report: Genetic analysis of Striped Bass collected in Bras d'Or Lake. Report to the Eskasoni Fish and Wildlife Commission; referenced in LeBlanc et al. 2020), however it is unknown if this is due to the contemporary migration of southern Gulf of St. Lawrence Striped Bass or due to other speculated factors that would have isolated the two groups of fish (Andrews et al. 2019a).

Striped Bass juveniles (age-0) originating from the Miramichi River were used in a re-introduction program in the St. Lawrence River beginning in the late 1990s. Successful spawning and recruitment from this program has been confirmed (DFO 2017). Tracking studies of acoustically tagged Striped Bass from the St. Lawrence group and from the southern Gulf of St. Lawrence group as well as differences in elemental composition of the otoliths of bass spawned in Miramichi and in the St. Lawrence River have indicated a general geographic isolation of the two groups. The St. Lawrence progeny are generally restricted to the St. Lawrence River itself (at least to date) whereas the Miramichi origin fish have a broader distribution, that extends into the estuary of the St. Lawrence and to the lower north shore of the St. Lawrence (Valiquette et al. 2017; Valiquette et al. 2018).

For purposes of assessment and development of fisheries reference points, the southern Gulf Striped Bass population distribution comprises the Gulf of St. Lawrence region, from the western tip of Cape Breton Island to the north shore of the Gaspe Peninsula in the St. Lawrence River and it is managed as a single biological unit.

Descriptions of Striped Bass biology and life history abound (COSEWIC 2004) and the following summary for the population of the southern Gulf is primarily taken from Douglas et al. (2003) and Douglas and Chaput (2011b).

- Striped Bass is a relatively long-lived iteroparous spawner.
- The Northwest Miramichi River estuary is the only confirmed spawning location that is annually predictable in time and space (Bradford and Chaput 1996; Robichaud-LeBlanc et al. 1996) and that has produced annual recruitment in the southern Gulf of St. Lawrence.

The Northwest Miramichi estuary possesses features that are seemingly unique and important for successful Striped Bass spawning in the southern Gulf of St. Lawrence but these are not well understood. The favourable conditions may be related to the Northwest Miramichi estuary's specific hydrology and conditions that permit the retention and successful egg and larval development.

- Spawning occurs in late May to early June in the upper estuary, at the upper extent of the salt wedge within tidal waters, of the Northwest Miramichi River, (Robichaud-LeBlanc et al. 1996; Douglas et al. 2009). Spawning activities are motivated by warming temperatures (Douglas et al 2009; Figure 1.3).
- Striped Bass is a pelagic spawner, the eggs and milt are broadcast simultaneously into the water column.
- The eggs float freely, are generally neutrally buoyant in slight saline water, and hatch in a few days depending on water temperature.
- The yolk of young larvae is exhausted within 5 to 10 days post-hatch, also conditional on temperature.
- The larvae feed on planktonic organisms (Robichaud-LeBlanc et al. 1997) and move to the near shore shallow areas of the rivers shortly after the onset of exogenous feeding.
- Young of the year Striped Bass gradually migrate downstream to Miramichi Bay in the summer and diffuse in a northwest and easterly direction from the Miramichi (Robinson et al. 2004). The confirmed coastal distribution of young of the year by the first autumn can extend from Miscou Island (NB) in the north to Pictou (NS) in the east (Douglas and Chaput 2011b).
- Growth of young of the year is quite fast, with individuals reaching of 8 to 15 cm fork length and whole weights of 10 to 50 g, by the end of the first summer (Bradford et al. 1997; Robichaud-LeBlanc et al. 1998).
- Post-spawned adults return to marine waters and undertake coastal feeding migrations through the summer and autumn, extending in some exceptional years such as in 2017 to the north shore of the St. Lawrence and to southern Labrador (DFO 2018).
- Striped Bass are generalist feeders with shifts in prey composition occurring with age and size. Larger bass are known piscivores, and consume a wide range of invertebrate and vertebrate prey. Striped Bass sampled from the spawning areas in the Northwest Miramichi consume anadromous species (Rainbow Smelt, gaspereau, Atlantic Salmon smolts) based on availability determined by timing of migrations into and out of the Miramichi (DFO 2016; Hanson 2020).
- At the onset of winter, beginning in late September to October, Striped Bass of all age and size groups re-ascend into estuaries and river mouths throughout the southern Gulf to overwinter.
- The southern Gulf of St. Lawrence population is the only population where avoidance of lethal marine conditions (sub-zero water temperatures) during winter is an obligate element of its life history and this can only be attained by overwintering in upper estuaries and river mouths (Cook et al. 2006). A literature review of locations and characteristics of overwintering habitat for Striped Bass is provided in Andrews et al. (2019b).
- In 2004, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) recognized the Striped Bass of the southern Gulf as a designatable unit (DU) and evaluated its status as 'Threatened' (COSEWIC 2004).

- Efforts to rebuild from the low spawner abundances of the mid 1990s included the introduction of restrictive fisheries management measures, most notably the closure of directed commercial fishing in 1996, and the closure of recreational and Aboriginal food, social, and ceremonial (FSC) fisheries in 2000.
- The modest increase in spawner abundance since then suggested that the management interventions had been positive for the population. In its re-evaluation in 2012, COSEWIC concluded that although it had increased strongly in abundance, it was known from only a single spawning location and the population continued to be susceptible to high rates of poaching as well as bycatch in legal fisheries, and consequently was given the status of Special Concern (COSEWIC 2012).

1.1. OBJECTIVES OF THE SCIENCE PEER REVIEW

The Striped Bass population of the southern Gulf of St. Lawrence had declined to less than 5,000 spawners in the late 1990s. Following on the prohibition of retention of bycaught Striped Bass in several commercial fisheries targeting other diadromous species in 1996, the closure of the recreational fisheries and the suspension of Indigenous Food, Social, and Ceremonial (FSC) fisheries allocations for Striped Bass in 2000, the estimated abundance of Striped Bass subsequently increased to over 200 thousand spawners in 2011 with peak abundance estimated at over 900,000 spawners in 2017 (DFO 2020). A small number of FSC fisheries were reinstated in 2012. The recreational fishery reopened in 2013 with increasing annual access for retention and a pilot Indigenous commercial fishery was licenced in 2018 and 2019.

With continued requests for additional fisheries access to southern Gulf Striped Bass, Fisheries and Oceans Canada (DFO) Gulf Ecosystems and Fisheries Management Branch requested the development of fisheries based reference points that conform to the Precautionary Approach (PA) to guide further management decisions on the development of the Striped Bass fisheries.

Striped Bass is large bodied and a piscivorous predator through most of its life. Concerns have been expressed by Atlantic Salmon fishery advocates and some gaspereau and Rainbow Smelt commercial fishery interests that the rebuilding of Striped Bass stock in the southern Gulf has contributed to declines in abundances of Atlantic Salmon and other diadromous species because of high levels of predation on these species by Striped Bass. Considering the interactions of Striped Bass with other valued fisheries species, DFO Fisheries management also requested a review of approaches and potential reference points for Striped Bass that take account of these ecosystem considerations.

The specific objectives of the science peer review are to:

- Review the available information on the abundance and biological characteristics (size at age, mortality rate estimates, size structure) of the Striped Bass population of the southern Gulf of St. Lawrence relevant for the definition of reference points;
- Review candidate fishery reference points for Striped Bass and provide estimates of these based on the available information from the southern Gulf population;
- Review and advise on the consequences of fishery management measures on the derivation of fishery reference point values;
- Consider options for incorporating species interactions considerations in the definition of reference points for Striped Bass; and
- Consider uncertainties in the definition of the reference points and management approaches for Striped Bass.

1.2. ORGANISATION OF THE DOCUMENT TO ADDRESS THE TERMS OF REFERENCE

This document is organized to sequentially to address the terms of reference.

Section 2 provides an overview of the history of fisheries for Striped Bass in the southern Gulf, with an emphasis on the management measures and fisheries situation since the re-opening of access to the resource in 2013. Particular challenges to the compilation of fisheries catch and effort data are described. Additional details on the fisheries are provided in Appendix 1.

Section 3 summarizes the assessment program and the estimates of total spawner abundances and abundances at age of spawners on the Northwest Miramichi River spawning area for the period 1994 to 2019. Information on the biological characteristics of the population are provided, including size-at-age, weight-length relationship and weight-at-age, estimated abundance of spawners at age, maturity-at-age and proportion female at age on the spawning grounds, as well as estimates of mortality-at-age and overall. Details on the size-at-age analyses and derivation of an age-length key to convert abundance of spawners at length to abundance of spawners at age are provided in Appendix 2. The biological characteristics information is used in the population modelling in section 4.

Section 4 describes the age-structured population model which was used to estimate important population dynamics parameters which are required to derive candidate reference points. The population model uses as input the estimated abundances at age from the assessments in 1996 to 2019 to make inferences on stock and recruitment parameters, mortality rates at age, and proportion of recruits that become spawners. Seven variants of the basic age-structured model are examined, with differing informative assumptions on the life history parameters and exploring different stock and recruitment functions. The input data are presented in Appendix 3, the model codes for three of the seven models are in Appendix 4, and the detailed diagnostics of the retained models are provided in Appendix 5.

Section 5 reviews some candidate reference points and describes the methods used to define these candidate reference points based on the outputs from the population model in section 4. Equilibrium approaches, which simulate population abundance trajectories based on estimated and fixed life history parameters, are used to compare abundance, age structure, and fisheries yields for different levels of fishery exploitation. Concepts of maximum sustainable yield and spawner per recruit and their associated reference points are described. Empirical driven methods that rely exclusively on past observations are also described as alternatives to model dependent approaches for defining reference points.

Section 6 describes the results of the equilibrium modelling and the corresponding values for the candidate reference points. This section also addresses the question of how the values of the reference points are modified by the assumptions on natural mortality, on the fishing management strategy when these include length based limits on retention, and the inclusion or exclusion of catch and release mortality considerations when estimating yield based reference points. The section also provides a summary of the conclusions on reference points and introduces the issue of management reference points that account for species interactions. Details on this latter point are provided in a separate document (Chaput 2022).

Section 7 addresses the uncertainties associated with the derivation of reference points for the Striped Bass population of the southern Gulf of St. Lawrence. The uncertainties discussion includes aspects of life history including size-at-age, maturation and in particular mortality rates. For mortality rates, we consider the evidence for the causes of mortality of Striped Bass, including fisheries derived, anthropogenic, and other sources of natural mortality. Other uncertainties discussed include the assumptions on the density dependent stock and recruitment relationship and considerations on the choice of models and the time series of abundance estimates that are available for characterizing the productive potential of this population.

The references cited in this report are provided in section 8.

2. FISHERIES ON STRIPED BASS

Striped Bass have been exploited in numerous fisheries of the southern Gulf of St. Lawrence for over a century of records. Catches of Striped Bass dating to 1868 and onward are available in annual reports of the Department of Marine and Fisheries but these have not been compiled for this report. Compiled annual commercial catch records for Striped Bass date from 1917 (LeBlanc and Chaput 1991) but these only account for reported commercial catches. There is an absence of reported landings from the southern Gulf of St. Lawrence during the period 1933 to 1968. This is not interpreted to be a period without harvests however, as numerous regulatory changes were made during that period to Striped Bass fisheries that likely impacted the fishing activities (Appendix 1); for example in 1949, an amendment was made to the Special Fishery Regulations for the province of New Brunswick effectively closing the commercial fishery by authorizing the retention of Striped Bass only in angling fisheries. This was followed by an amendment in 1960 that authorized the sale of Striped Bass incidentally captured in nets , traps, or weirs set for catching fish other than Striped Bass.

In 1993, the Nova Scotia Fishery Regulations, the New Brunswick Fishery Regulations, and the Prince Edward Island Fishery Regulations were revoked and replaced with the Maritime Provinces Fishery Regulations that specified regulations specific to fishing in the three Maritime provinces and in adjacent tidal waters. Of note in this amendment are the regulations specific to fishing for Striped Bass in the waters of DFO Gulf Region (Tables 2.1, 2.2; Appendix 1).

In 1996, Paragraph 4(2)b of the Maritime Provinces Fisheries Regulations which permitted the retention of unlimited bycatch of Striped Bass in commercial fishing gears for gaspereau, Rainbow Smelt, American Shad, and American Eel was repealed (Canada Gazette Part II, Vol. 130, No. 5; SOR/96-125).

Subsequent modifications to the Striped Bass fisheries management of the southern Gulf were made via licence conditions (for commercial fisheries) and variation orders for recreational fisheries. Additional restrictions to various fisheries interacting with Striped Bass were introduced from 1996 to 2000 which culminated in the closure of all legal Striped Bass fisheries (Table 2.1).

In addition to the directed fishery management measures, short-term closures to directed recreational fisheries in the spawning area of the Northwest Miramichi to preclude harm to spawning fish were instituted since 2017 (Table 2.3). The temporary closure to all recreational fisheries of the spawning area in the Northwest Miramichi during the peak spawning period was previously identified as one of several management measures that would enhance the protection of Striped Bass and promote its recovery (Appendix 1).

Although the fisheries on Striped Bass were essentially closed in 2000, Striped Bass of various life stages continued to be intercepted in a variety of illegal, commercial, and Indigenous FSC fisheries although the extent of these losses to the population is unknown (Chiasson et al. 2002; Douglas et al. 2006; DFO 2011). DFO (2011) indicated that Striped Bass of various life stages continued to be intercepted in a variety of illegal fisheries, commercial fisheries, and aboriginal FSC fisheries, with a total estimated loss of medium and large sized Striped Bass in all southern Gulf of St. Lawrence fisheries in the range of 60,000 fish per year. The total number of bass handled in the fisheries was estimated to be 152,000 fish, of which 41% were estimated to have died or been killed (DFO 2011). The activity with the greatest contribution to the total loss of Striped Bass is considered to be the illegal fishery, accounting for over 50% of the estimated adult losses, followed by the recreational fishery (illegal retention and bycatch) at about 15% (DFO 2011).

As abundance was estimated to have increased almost monotonically since the late 1990s, a number of food, social, and ceremonial (FSC) fisheries were reinstated in 2012 (Table 2.1). The recreational fishery reopened in 2013 and a pilot Indigenous commercial fishery was licenced in 2018 and 2019 (Table 2.2).

Striped Bass originating from the southern Gulf are also exploited in fisheries along the coast of Chaleur Bay and around the Gaspe Peninsula in Quebec. Fisheries management measures for the recreational Striped Bass fishery in Quebec, similar to the fisheries management measures in DFO Gulf Region, were introduced in 2013 (Table 2.2). Based on elemental composition analyses of otoliths and different characterizations of these signatures in Striped Bass originating from the Miramichi River and from the St. Lawrence River spawning areas, Valiquette et al. (2018) indicated that the southern Gulf of St. Lawrence Striped Bass distribution extended around Chaleur Bay and upstream along the Gaspe peninsula to Rivière du Loup. Occasionally, as noted in the samples of Striped Bass from 2017, southern Gulf bass were also distributed along the lower north shore of the St. Lawrence River (Valiquette et al. 2018). Tag returns of bass marked in the southern Gulf and reports of the presence of Striped Bass in southern Labrador in late summer and into the winter (DFO 2018) as well as detections of acoustically tagged Striped Bass on the receiver line at Port Hope (Labrador; Figure 1.2) confirmed the broader excursion of southern Gulf Striped Bass outside its historic range in 2017 and its exploitation in various fisheries in and outside (north) of the Gulf of St. Lawrence.

2.1. FISHERIES EFFORT AND CATCH STATISTICS

There are no complete fishery catch data for Striped Bass in the southern Gulf of St. Lawrence. Historically, fisheries statistics included only commercial harvests, exclusive of recreational and Indigenous peoples fisheries harvests. LeBlanc and Chaput (1991) summarize the reported landings of Striped Bass from the southern Gulf of St. Lawrence for the period 1917 to 1988 (Table 2.4). Peak recorded harvest was 61.4 t in 1917. There were no recorded landings for the years 1935 to 1967. Peak recorded landings in the second period of records after 1967 was 47.8 t in 1981 with 15.25 t recorded in the last year (1996) of authorized commercial landings. Detailed reported commercial harvests by statistical districts in DFO Gulf NB as well as by season and regions for the contemporary period of the fishery are provided in Bradford et al. (1995a) and Douglas et al. (2003).

Striped Bass are particularly vulnerable to capture in several fisheries in estuaries of the southern Gulf of St. Lawrence. Unregulated and directed commercial fishing up to March 1996 was attributed to have been the principal factor for the reduction in spawner abundance between May 1995 and May 1996. An estimated 14.5 t of Striped Bass were recorded harvested during January and February 1996 from the Richibucto district of New Brunswick, most likely taken in bow-net and gillnet fisheries under the ice (Bradford and Chaput 1998). Within the Miramichi system 12,300 bass were estimated to have been removed, and added to an estimated 18,800 bass (17.3 t) reported as landed and sold in districts other than the Miramichi River, the total removals were estimated to have been in excess of 40,000 fish representing 80% of the estimated spawning stock of Striped Bass in 1995 (Bradford and Chaput 1998).

The Indigenous pilot commercial fishery for Striped Bass in the Miramichi River was conducted in 2018 and 2019. The total allowable catch (TAC) was set at 50,000 fish (50-65 cm TL limit) in

2018 and 50,000 fish (50-85 cm TL limit) in 2019. Privacy rules preclude the reporting of harvests from this fishery in this report but DFO Fisheries Management indicated that the harvests were substantially below the TAC in both years.

There are no compiled reports of catches and harvests of Striped Bass in the Indigenous FSC fisheries in the southern Gulf.

In addition, young of the year (YOY) Striped Bass are susceptible to capture in the openwater fall fishing gears (boxnets and gillnets) set for Rainbow Smelt (Bradford et al. 1995b, 1997). The bycatch in the Miramichi fisheries was most important in the last half of October. Interceptions of YOY bass were estimated to have been in the hundreds of thousands annually, in the Miramichi River alone, most of which would be dead given the difficulty to sort and release them alive from the large quantities of fish captured in these fisheries (Bradford et al. 1995b, 1997). Bycatch of YOY striped bass were also reported in the Tabusintac and Richibucto River fisheries. The opening of the fall openwater smelt fishery in the Miramichi was delayed from Oct. 15 to Nov.1 in 1999.

2.2. RECREATIONAL FISHERY CATCH AND HARVEST ESTIMATES

Since the re-opening of the recreational fisheries in 2013, partial catch data from the recreational fishery for some geographic areas of the southern Gulf and in some years have been collated but they are very incomplete.

2.2.1. Year 2013

Estimates of caught and retained Striped Bass in the Miramichi River and in the southern Gulf of St. Lawrence during the two retention periods of 2013 are reported by DFO (2014) and summarized in Table 2.5. The creel survey was conducted exclusively in the Miramichi River area during the May 1-15 retention period. The estimates are considered incomplete because interviews were from incomplete fishing trips, the survey only covered a portion of the 15-day season, and not all Miramichi fishing locations nor all times of the day were surveyed (DFO 2014). Of note, DFO (2014) indicated that individual anglers reported single trip catches of Striped Bass ranging from 0 to as high as 120 fish per trip, highlighting the potential for high catch rates realized in May in the Miramichi and the extensive catch and release activities in the recreational fishery.

The estimates for the second retention period in August 2013 are also considered to be underestimates of catch and retained bass (Table 2.4). Only a few (8) of the large number of access points (bridges, wharves, public beaches etc.) along the shore of the southern Gulf were surveyed, the survey only covered the retention period in August at obvious access points and during the daily open period (two hours before sunrise, two hours after sunset) and little to none of the effort from shoreline or boats was measured in the survey. Based on the available information, and assuming a 10% hook and release mortality, there were more losses attributed to catch and release mortality then retentions although the catch and release losses occur over the entire size range of bass angled whereas the retention losses were for a slot size (DFO 2014).

2.2.2. Year 2014

In 2014, a survey was again attempted in the Miramichi River area during the May retention period. Catches of Striped Bass were again considered underestimated (Table 2.4) given that interviews only covered a portion of the 25-day season (DFO 2015a). As was the case during the 2013 fishery, catches of Striped Bass in single trips by individual anglers ranged from 0 to 111 fish per trip, with large variation in catches and success rates (DFO 2015a). During the

August and September 2015 retention periods, DFO Conservation and Protection officers conducted 434 individual interviews and documented a total harvest of 58 Striped Bass and 455 released fish. Insufficient coverage precluded the extrapolation of interviewed catches to a total for these retention periods. Angling data was also obtained from mail-in cards and a self-reporting website in 2014 (DFO 2015a). There were a low number of overall returns. For the 91 self-reporting web entries, it was indicated that 1,560 Striped Bass were released and 40 fish were retained. The data cannot be used to estimate the total catches and retentions however it does illustrate the extent of fishing activity that occurred in 2014, with a point estimate of 16 fish released per angler and with less than half the anglers retaining one Striped Bass.

The province of Quebec conducted creel surveys in 2014 at fisheries access points along the north shore (Quebec portion) of Chaleur Bay. A total of 766 interviews were completed in 2014 (DFO 2015a) resulting in an estimated total catch (released and retained fish) of 9,010 fish (5,370 to 12,650 95% confidence interval) and an estimated retention of 554 fish (299 to 809; Table 2.5). Data also included the proportion of the retained catch by size group and the proportion of the estimated released fish by size group (Table 2.6).

2.2.3. Year 2015

No creel surveys of the recreational fishery for Striped Bass in the southern Gulf of St. Lawrence were conducted in 2015.

The province of Quebec conducted creel surveys in 2015 at fisheries access points along the north shore (Quebec portion) of Chaleur Bay (Table 2.5). The estimated catches from fishing effort at the survey points in 2015 were 1,172 fish retained, 20,797 fish released with a point estimate of total losses (including catch and release mortalities) of 3,252 fish.

2.2.4. Year 2016+

No creel surveys of the recreational fishery for Striped Bass in the southern Gulf of St. Lawrence have been conducted since 2014.

Since 2016, the province of Quebec has conducted a limited survey of angling activities at four sites within two sectors during an eight week period, beginning on 1 July. Indicators of angling activity included the number of anglers per sampling unit (time, site), fishing trip duration, rate of success, probability of retention of at least one fish, and distribution of catches within length categories. The indicators of fishing success and distribution of sizes in the catches are summarized in Table 2.6.

3. ASSESSMENT AND BIOLOGICAL CHARACTERISTICS OF STRIPED BASS OF THE SOUTHERN GULF OF ST. LAWRENCE

Since 1994, monitoring of the bycatch in the commercial gaspereau trapnets of the Miramichi River has been the principal source of information for the estimation of the Striped Bass spawning population of the southern Gulf of St. Lawrence (DFO 2020). Selected biological characteristics (e.g. fork length, age, sex, and spawning stage) were recorded from fish captured in commercial gaspereau trapnets (May and June) and at index trapnet monitoring facilities operated by DFO Science (May-October). Ages are interpreted from scales.

The spawner abundance was usually estimated from mark and recapture experiments in which adult Striped Bass were tagged early in May and monitored throughout June as they were captured and released as bycatch in the gaspereau fishery of the Northwest Miramichi Estuary (Bradford and Chaput 1996; Douglas and Chaput 2011a). Catch per unit effort (CPUE) from this fishery has been used as an index of abundance for Striped Bass (Douglas and Chaput 2011a;

Figure 3.1) and estimates of catchability of the gear are used to derive the estimates of abundance. Since 2014, an adjustment to the estimation model has been made to account for the observed spawning and post-spawning behaviour of Striped Bass, using movement data of Striped Bass implanted with internal acoustic tags. The tracking of acoustically tagged Striped Bass provided information on the daily distribution of spawners in the Miramichi system and therefore their availability to the gaspereau trapnets of the Northwest Miramichi (DFO 2020).

Estimated abundances of bass spawners in the Northwest Miramichi were at or under 5,000 spawners (median) during 1996 to 2000 (DFO 2020; Figure 3.2). The decreased abundance from 60 thousand fish in 1995 to the 1996 estimate of just over 5,000 fish was largely explained by estimated removals of about 30,000 adults through unregulated and direct commercial fishing activities between May 1995 and March 1996 (Bradford and Chaput 1997). Abundance increased to between 16,000 and 26,000 during 2001 to 2006 and again to between 50,000 and 100,000 fish during 2007 to 2010. Abundances of 150 thousand to 300 thousand were estimated during 2011 to 2016 with a peak abundance in 2017 at just under 1 million fish (Figure 3.2). Striped Bass spawner abundance in 2018 and 2019 was estimated to have fallen back to approximately 300 thousand spawners.

Coincident with the high level of abundance in 2017, evidence from tag returns indicates that a component of the southern Gulf Striped Bass population migrated further north in 2017 than previously known, extending into southern Labrador (DFO 2018). In 2017, nine acoustic tag detections at the Port Hope (southern Labrador) acoustic receiver line were attributed to Striped Bass (Table 3.1). Of these, seven Striped Bass had a previous overwintering and / or spawning history in the Miramichi. Exposure to new sources of fishing mortality occurred for southern Gulf Striped Bass that migrated north in 2017 as reported by interceptions of several tens of thousands of pounds of Striped Bass in commercial gear set for cod, in herring nets and halibut trawls along the south coast of Labrador (DFO 2018). Only 3 of the 7 acoustically tagged bass detected in Labrador with a previous recorded affinity to the Miramichi were detected in the Miramichi in the winter of 2017/18, a loss of 57% of the original detections off Labrador. Losses of Striped Bass that had migrated outside the historic range to the Quebec north shore and Labrador in summer and fall 2017 may in part explain the reduced estimated abundance of Striped Bass on the spawning grounds in 2018 and 2019 relative to 2017 (DFO 2020).

3.1. AGE AND SIZE AT AGE

Ages of Striped Bass are interpreted from scales. Size-at-age has been reported previously by Chaput and Robichaud (1995) and in Douglas et al. (2006). Sampling and age determination has occurred opportunistically. There has not been any age validation nor is a reference scale set available for doing reader tests. Tagging and subsequent recaptures of tagged fish provide some information on changes in fork length over multiple years, but these are not reported here.

Striped Bass grow during the open-water season in the southern Gulf (May to October). No growth occurs through the winter when bass are overwintering and they do not feed under the ice in the upper areas of estuaries; this is evident from an examination of size distributions of bass sampled in the fall in the Miramichi at DFO index trapnets which are identical to those of bass sampled the following spring in the Miramichi (for example, see DFO 2020).

A total of 8,497 age and length data are available from sampling in the southern Gulf of St. Lawrence over all years between 1975 and 2013. From the samples available, maximum age interpreted is 15 years and maximum fork length recorded is 116 cm.

3.1.1. Von Bertalanffy Growth Model

A von Bertalanffy growth function was adjusted to the selected age and length data over all years:

$$L_a = L_\infty \left(1 - e^{-K(a - a_0)}\right) e^{\varepsilon}$$

with
L_a = length (cm) at interpreted age a,
L_∞ = predicted asymptotic length (cm),
K = predicted metabolic parameter,
a_0 = predicted apparent age at time of hatching, and
n$\varepsilon \sim N(0, \sigma^2)$.

Samples used for the von Bertalanffy model were restricted to those collected in May and June (n = 8,376), corresponding to the size at spawning time, and the start of the biological year (Table 3.2). No distinction is made between males and females.

The von Bertalanffy model parameters were estimated with OpenBugs using non-informative priors for the parameters (L_∞, K, a_0, σ) to be estimated (Lunn et al. 2013; Appendix 2). The posterior distributions of the parameters are summarized in Table 3.3 and a visualization of the data, model fits and predicted length distributions at age are presented in Figure 3.3.

3.2. SPAWNER ABUNDANCE AT AGE

Scale sampling and age interpretations are not available for all assessment years, nor are there sufficient samples of older and larger fish in any year to adequately estimate their relative abundances. There is information on the length distribution of spawners based on directed sampling by DFO Science from bycatches in the commercial gaspereau fishery and catches in dedicated science trapnets for Striped Bass assessment in the Northwest Miramichi (Figure 3.4). Consequently, the von Bertalanffy model predicted length at age distributions were used to derive an age length key which was then used to estimate the annual abundance at age of spawners (Figure 3.5) based on the assessed annual length distributions of the spawners (Figure 3.4) and the assessed total abundance of spawners (see Appendix 2 for details).

3.3. WEIGHT AT LENGTH RELATIONSHIP

A weight from length relationship was derived using data specific to the Striped Bass population of the southern Gulf of St. Lawrence. The most extensive data (N = 1,839) for whole weight (kg) and fork length (cm) were obtained from sampling during May and June, 2013 to 2015, related to the diet study of Striped Bass of the Miramichi River (Figure 3.6).

For purposes of the stock and recruitment equilibrium modelling, the coefficients of the relationship for sexes combined were used (Table 3.4).

3.4. FECUNDITY TO SIZE RELATIONSHIP

There is no southern Gulf specific fecundity to weight relationship. Data presented in Douglas et al. (2003) indicated that fecundity of Shubenacadie bass varied from 53,000 to 1.4 million eggs for bass ranging from 44.9 to 91.0 cm fork length. Goodyear (1985) presented fecundity at weight data for Striped Bass which translates to about 83,000 eggs per kg (see Figure 2 in Douglas et al. 2006). For purposes of modelling, a value of 83,000 eggs per kg was used (Douglas et al. 2006 used 83,177 eggs per kg). Based on the predicted mean length at age of bass from the Miramichi and the weight (kg) to length (cm) relationship, fecundity of an age 4 female bass (mean weight = 1.2 kg) would be 100,000 eggs whereas fecundity of age 15+ bass (mean weight = 7.1 kg) would be just under 600 thousand eggs.

3.5. MATURITY AT AGE, PROPORTION OF MATURE FISH ON SPAWNING GROUNDS

Three aspects of maturation and spawning of Striped Bass were considered by Douglas et al. (2006):

- There are no data with which to directly estimate the age or size at 50% maturity because no representative sampling of bass at age and maturation assessment is available. Based on studies elsewhere, the maturation schedule of male and female bass was assumed to differ, with males maturing earlier than females. Based on available samples of sex at age during May and June, there is evidence of higher proportions of males at ages 2 to 4 and more balanced sex ratios at ages 6 and older (Table 3.5). It was assumed that male bass first mature at age 3 years and female bass first mature at age 4 years, and all bass are mature by age 6 years (Douglas et al. 2006). This is supported by the observations of increased estimated abundances at ages 3 to 5 of spawners when following cohorts.
- Not all mature Striped Bass are considered to be on the spawning grounds in the Northwest Miramichi. This inference is based on reports of adult sized Striped Bass, some in ripe condition (males and females), in other estuaries of New Brunswick and Nova Scotia in May and June.
- There is also the possibility of skipped spawning in Striped Bass, particularly of larger fish. Rideout and Tomkiewicz (2011) review the evidence for and causes of skip spawning in fish, in which fish forego egg production until the subsequent year, as a potential plastic response of individual fish to low levels of stored energy or unsuitable environmental conditions. Secor (2008) and Gahagan et al. (2015) report on non-annual spawning of Striped Bass. Secor et al. (2020), using tracking of acoustically tagged Striped Bass, reported skip spawning percentages of 14-15%, with a higher percentage for bass in the year of tagging. The authors indicated that skip spawning could occur due to energetic constraints and seasonal movements and attributed the higher non-spawning behaviour in the year of tagging as the result of a residual tagging and handling effect.
- In 2017, nine acoustic tag detections at the Port Hope (southern Labrador) acoustic receiver line were attributed to Striped Bass (Table 3.1). Of these, seven Striped Bass had a previous overwintering and / or spawning history in the Miramichi. Of note, are the three Striped Bass acoustic tags detected in Labrador which were subsequently detected in the Miramichi (i.e., returned from Labrador) in the winter of 2017/18 and 2018/19 and the spawning that had occurred in the Miramichi in 2017, not in 2018, but spawning again in 2019, providing evidence of skipped spawning for those three fish.

Insights into the proportion female at age on the spawning grounds is available from the directed sampling as part of a diet study of Striped Bass in the estuary of the Miramichi River conducted during May and June of 2013 to 2015. Figure 3.7 shows the proportion female by cm fork length bin. Overlain on the plot are the 95% confidence interval range of the predicted fork length at age from the von Bertalanffy model. For bass less than 32 cm fork length, there is a varying but generally equal proportion of males and females in the samples; we interpret this as representative of immature fish. There is a low proportion female for bass ranging from 33 to 48 cm, roughly equivalent to age 3, increasing proportion female in the size range of age 4 bass with the proportion female levelling off at around 0.5 for size ranges of bass aged 5 and older (Figure 3.7).

The assumptions regarding the proportions mature at age and the proportions of mature bass on the spawning grounds result in estimates of the proportions of recruits by age, sexes combined, that are on the spawning grounds in the Miramichi. If the proportion of mature recruits present on the spawning grounds is the same for male and female bass at all ages, then the proportion female at age of spawners depends only on the ratio of the maturation schedules (Table 3.6).

3.6. MORTALITY

We assumed similar mortality at age for male and female bass.

3.6.1. Estimate of Natural Mortality of Ages 0 to 3

Estimates of natural mortality (M) for age-0, and ages 1 to 3 were derived using the empirical relationship published in Gislason et al. (2010) that relates instantaneous natural mortality rate to von Bertalanffy growth characteristics of the species. The equation derived by Gislason et al. (2010) is:

$$ln(M) = 0.55 - 1.61 * ln(L) + 1.44 * ln(L_{\infty}) + ln(K)$$

with
M = instantaneous natural mortality rate,
L = length of fish (mm),
L_{∞} = predicted asymptotic length (mm) from von Bertalanffy growth function, and
K = metabolic parameter from von Bertalanffy growth function.

Based on the point estimates of L_{∞} (907 mm), and *K* (0.1685) from the von Bertalanffy fit to the Striped Bass data (Table 3.2), estimated size at age of age 0 bass at the end of the growing season, and predicted mean sizes at ages 1 to 3 in mid-year (mean of $L_{a,t}$ and $L_{a+1,t+1}$), the model derived values of M for these age groups are summarized in Table 3.7.

Douglas et al. (2006) assumed an instantaneous rate (M) of 1.5 (survival = 0.22) for YOY in the first winter. Derivation of M based on the empirical relationship of Gislason et al. (2010) gives an M of 1.9. Mortality of young of the year bass in the first winter is expected to be high for this northern population. Size distribution of YOY bass in the fall, at the end of their first growing season, is annually variable with modal fork lengths varying between 9 and 15 cm (Bradford et al. 1997; Douglas et al. 2006; Figure 3.8). Chaput and Robichaud (1995) backcalculated fork lengths at age 1 (after the first winter) ranging from 10 to 15 cm depending on year class. Like adults, juveniles do not feed in the winter and no food items have been found in stomachs of juvenile bass sampled from the open water smelt fishery in November at low water temperatures (R. Bradford pers. comm.). The period of fasting likely extends from late October to late April in most years. There is limited empirical evidence that small bodied Striped Bass have a lower fitness than large bodied juveniles during the first winter. Some juvenile bass have been found frozen in surface ice in the Miramichi (Douglas pers. comm. or previous section). Variations in quantity of optimal habitat in the winter has been suggested as a possible factor contributing to variations in recruitment of the Hudson River striped bass population (Hurst and Conover 1998).

Douglas et al. (2006) had assumed that M for age 1 bass was 1.0, less than the overwinter mortality rate of YOY (1.5) but higher than the assumed value of 0.8 for age 2 bass. Values for M based on the empirical relationship of Gislason et al. (2010) and the mean size at age mid-season, are 0.82 for age 1 bass and 0.45 for age-2 bass.

Based on these values, the predicted cumulative survival rate from age-0 in the summer to age 3 is 0.039 ($exp^{-(1.97+0.82+0.45)}$).

3.6.2. Mortality of Age 4 and Older Bass

3.6.2.1. Cohort Decline Analysis

Estimates of total mortality (Z) over age were calculated as the change in natural log of the assessed abundance at age of spawners by cohort:

$$\log(N_{y,a}) = \beta + Z * Age_a + \varepsilon;\ \varepsilon \sim N(0, \sigma_\varepsilon^2)$$

with
y the cohort,
a the age,
Z the slope of the natural log of the assessed abundance at age by cohort, and
β the intercept (log of abundance for the first age in the regression).

Z was calculated over ages 5 to 12 because it is assumed that Striped Bass from the southern Gulf of St. Lawrence are not fully mature until age 5 for males, age 6 for females and we wanted a sufficient number of cohorts in the time series to derive estimates of Z. Cohorts were retained for which there was a minimum of six available estimated abundances over the age range 5 to 12 years.

The estimated abundances at age and the estimates of Z for the 1989 to 2009 cohorts are shown in Figure 3.9. The absolute values of Z range from a low of 0.16 for the 2005 cohort to a high of 0.58 for the 1989 cohort. The 1993 cohort is the first fully assessed cohort for this population. For the fully assessed cohorts (cohorts 1993 to 2007 covering the full age range 5 to 12), the absolute values of Z ranged from 0.16 to 0.43, with a median value of 0.33.

Catch curve analyses reported in Douglas and Chaput (2011a) indicated that the total instantaneous mortality values (Z) ranged from a low of 0.08 to a high of 2.86 and corresponded to annual mortality rates of 7% to 94%. Year on year negative estimates of Z were frequent at age 3 and were not unexpected given the presumed maturity schedules for male and female bass at ages 3 to 5 resulting in partial recruitment to the spawning population of age-3 and age-4 bass. Based on the average abundance at ages 3 to 9 years over the period 1997 to 2010, the total mortality rate of adult Striped Bass was estimated at 0.47 (Z = 0.63; Douglas and Chaput 2011a), marginally lower than estimates of Z (0.8-0.9) and A (0.5-0.6) previously calculated for southern Gulf Striped Bass between the ages of 3 and 7 (Douglas et al. 2006).

Cohort decline analysis indicates variable but relatively high total mortality for Striped Bass aged 5 to 12; for the fully assessed cohorts (cohorts 1993 to 2007 covering the full age range 5 to 12), the absolute value of Z ranged from 0.16 to 0.43, with a median value of 0.33. The high mortality rate for the southern Gulf was considered consistent with the relative rarity of Striped Bass older than 10 years of age in the southern Gulf (Douglas et al. 2006).

3.6.2.2. Mortality inferred from tagging data

Acoustic tagging and tracking programs of Striped Bass conducted in 2003 to 2004, 2008 to 2009, and during 2013 to 2017 provide independent data to estimate annual mortality (converse survival) rates of adult Striped Bass to the Miramichi River. Striped Bass, ranging in size from 40.4 to 88.0 cm fork length (size data were not available for all tagged fish in all years) were tagged with acoustic transmitters and released from three locations: the Gaspe area (Quebec side of Chaleur Bay; MFFP Quebec), the Miramichi River, and a small effort from Pictou (Nova Scotia; C.F. Buhariwalla, pers. comm.). Both Vemco V13 and V16 acoustic tags were used with the majority of fish tagged with V16 tags. Anticipated battery life of the tags varied with tag type over years, and tag detections included in the survival estimates account for the expected battery life of the tags. Acoustic receivers were deployed throughout the Miramichi River and estuary year round (see Douglas et al. 2009 for details).

In this analysis, only sequential detections of tagged bass from acoustic receivers in the Miramichi River are used. It is assumed that fish detected in the Miramichi one year would be expected to return to the Miramichi the following year. Generally, survival rates are provided for the years after the year of tagging and corresponding to the open water period, i.e. survivals for the year 2017 are derived from fish tagged in 2016, that were detected in the Miramichi over the winter 2016/17 and again in the Miramichi over the winter 2017/18. The exception is for the bass tagged in 2003, 2004, 2008 and 2009; these fish were tagged and released in the spring and the survival estimates are derived from detections in the winter and spring of the following year, hence survivals correspond to the year of tagging and release.

Details on the number of bass tagged and subsequent detections, by location, tag type and size group at time of tagging are provided in Table 3.8.

3.6.2.3. Estimating the probability of survival

Over all tags available for detection, the probabilities of survival were estimated independently by tag group assuming a binomial distribution with a non-informative beta prior for the probability of survival:

$$N.tags(j,t) \mid N.tags(j,t-1), \emptyset_{j,t}, p \sim Binomial(\emptyset_{j,t} * p, N.tags(j,t-1))$$

$$\emptyset_{j,t} \sim Beta\left(a_{j,t}, b_{j,t}\right);\ prior\ a_{j,t} = b_{j,t} = 1$$

with

parameter $\emptyset_{j,t}$ the probability of survival of tag group j over the period t-1 to t, and

p the probability of detection of acoustically tagged fish in the Miramichi.

Striped Bass return and overwinter in the upper portion of the Miramich River estuary and the probability of detection of these acoustic tags is considered to be 100%; total detections of individual tags generally totaled in the 100s or more.

These survival rate estimates include both natural and fishing mortality because these fish would have been vulnerable to legal and illegal fisheries over those years. To determine the extent to which survival rates in recent years may be size dependent and affected by the introduction of the retention size limit in the recreational fishery, we estimated and compared survival rates by size group for the year immediately after tagging, when the length of the fish would be expected to be most similar to their size relative to the size limits for the fishery. We also examined the survival rates over sequential years of fish in each size group, with the expectation that fish below the size limit would grow into the size limit and fish within the size limit at tagging would grow out of the size limit over time. Based on predicted fork length mid-season from von Bertalanffy model fits, the current retention size limit of 47 to 61 cm fork length in the recreational fishery results in selectivities to the recreational fishery of 0.12 for age 3 years, peaking at 0.76 to 0.79 at ages 4 and 5 years old and falling to 0.1 or less by age 10 years (Figure 6.3). Bass would be strongly selected by the fishery for two years but expected to grow through the slot over a period of 4 to 5 years.

3.6.2.4. Estimates of survival rate

Posterior distributions of the estimated probabilities of survival by tagging group (location, year of release, tag type) for sizes combined are shown in Figure 3.10. With few exceptions, annual survival rates are greater than 0.6. The estimated probabilities of survival (pooled values) were lowest during 2003 to 2009 and higher since 2014 (Figure 3.10, bottom panel).

The extent to which the estimated survival rates from tagged bass include fishing mortality is considered by examining survival rates by size group and sequential changes in survival rates for these groups (Figures 3.11, 3.12). Few bass of fork length less than the minimum retention limit were tagged in the recent years. There is an impression that survival rates of tagged bass within the retention size limit at time of tagging were lower than for bass which were outside the retention size slot, although there are notable exceptions such as the bass tagged in Gaspe for which estimated survival of bass in the slot size was better than for bass larger than the slot size for the 2014 year (Figure 3.11).

Estimates of instantaneous mortality rates (Z) ranged from 0.41 (median) during the period 2003 to 2009 to 0.22 for the period 2014 to 2018 (Figure 3.10). It is not possible to partition the natural mortality rates from fishing mortality rates with these data however considering that fishery removals would have in part contributed to the estimated mortalities, natural mortality of adult sized (> 47 cm) Striped Bass should be less than 0.2.

4. POPULATION MODELS

Estimates of key life history and population dynamics parameters are required to derive Maximum Sustainable Yield and other reference points. An age structured population model, as described in Walters and Martell (2004) and Walters et al. (2008) with an underlying stock and recruitment relationship (Beverton-Holt, power) is used to model the population dynamics of Striped Bass.

The time series of assessed abundance of spawners in the Miramichi and estimated abundances at age for the period 1996 to 2019 are used (Appendix 3; Figure 3.2). The data series begins in 1996 because prior to 1996, there was an active harvest of Striped Bass on the spawning grounds in the gaspereau fishery that was removing fish concurrent with the assessment program; the assessed population estimates for 1994 and 1995 are considered to be potential spawners rather than realized spawners. The same situation may apply since 2013 concurrent with the reopening of the Indigenous FSC fisheries and recreational fisheries, however, the harvest of Striped Bass during the assessment period (mid-May to mid-June) for those years is considered to be substantially less than what occurred prior to 1996.

4.1. MODEL SPECIFICATIONS

4.1.1. Model Equations

The life cycle population dynamic equations account for the estimated and/or assumed life history characteristics of the Striped Bass population of the southern Gulf. The beginning of the year is the spawning period, mid-May to mid-June, corresponding to the assessment period. The model assumes similar life history characteristics for male and female Striped Bass in terms of fork length-at-age, weight-at-age, and mortality-at-age.

The general model equations are described below. Modifications to these are made according to the model considered; those details are described specific to the model.

Recruitment (number) at age is calculated as:

$$N.0_y = \frac{\alpha * Eggs_y}{1 + \frac{\alpha * Eggs_y}{K}} \text{ (Beverton-Holt) or}$$

$$N.0_y = \gamma * Eggs_y^{\beta} \text{ (Power function)}$$

with
$N.0_y$ = recruitment abundance (number) at age 0 in the summer in year y,
$Eggs_y$ = total eggs spawned in year y
α = Beverton-Holt density independent mortality rate (0,1),

K = Beverton-Holt asymptotic abundance of age 0 in the summer,
γ = survival rate (0,1) at the origin of the power stock and recruitment function, and
β = the density dependent compensatory survival rate of the power stock and recruitment function (if β = 1, recruitment is a proportion of eggs; if β < 1, recruitment is a decreasing proportion of increasing eggs; if β > 1, recruitment is an increasing proportion of increasing eggs).

$$N_{y+1,1} = N.0_y * e^{-Z.0}$$

with
$N_{y+1,1}$ = recruitment abundance at beginning of year y at age 1,
$N.0_y$ as defined above, and
$Z.0$ = instantaneous overwinter mortality rate of age 0,

$$N_{y+1,a+1} = N_{y,a} * e^{-(Z_a)} \text{ for a = 1 to 13}$$

with
Z_a = instantaneous mortality rate at age a

Age 15 is the oldest age and included as a plus group. Abundances of the plus group are calculated as:

$$N_{y,a} = N_{y-1,a-1} * e^{-(Z_{a-1})} + N_{y-1,a} * e^{-(Z_a)} \text{ for a = 15+.}$$

Spawner abundances (number) at age and total eggs are calculated as:

$$Sp_{y,a} = N_{y,a} * p.rec.sp_a$$

with
$Sp_{y,a}$ = abundance (number) of spawners of age a at beginning of year y,
$N_{y,a}$ = recruitment abundance of fish of age a at beginning of year y,
$p.rec.sp_a$ = proportion of mature recruitment at age a present on the spawning grounds.

$$Eggs_y = \sum_{a=3}^{A} Sp_{y,a} * p.fem_a * fec * u.Wt_a$$

with
$Eggs_y$ = total eggs spawned in year y calculated as the sum of eggs at age a, a = 3 to A (15+ group)
$Sp_{y,a}$ = abundance (number) of spawners of age a in year y,
$p.fem_a$ = proportion female of spawners at age a,
fec = 83,000 eggs per kg of female bass
$u.Wt_a$ = mean weight (kg) at age a (Figure 3.6; Appendix 3).

4.2. EGG TO YOY FUNCTIONAL RELATIONSHIP

We assumed that there is a density dependent compensatory function between eggs spawned and production of young-of-the-year (YOY) in the first summer (Goodyear 1985). We modeled this dynamic as a Beverton-Holt function (Hilborn and Walters 1992) or as an alternate power function.

The combination of high fecundity and iteroparity of Striped Bass are indicative of a species with high mortality in the early stages. Inter-year class variability in Striped Bass has been observed to be high, largely determined during the egg and larval stages and influenced by environmental factors (see references within Richards and Rago 1999; Uphoff 1989; Rutherford et al. 2003). Instantaneous daily rates of mortality (M d^{-1}) between the egg and the 8 mm larval stage have been estimated to vary between 0.11 and 0.34, with overall survival after 20 days varying between 0.03% and 11% (Rutherford et al. 1997). Increased juvenile production is not guaranteed by increased spawning stock but the chances of producing a strong year class are improved at high spawner abundances.

For the southern Gulf of St. Lawrence Striped Bass population, the life stage at which the carrying capacity limit is defined is assumed to be during the early juvenile (age-0, summer) stage as the habitat and food base for the larvae and post-metamorphosis juveniles is constrained to a relatively small tidal spawning and rearing area in the Northwest Miramichi (Robichaud-LeBlanc et al. 1996, 1997; Douglas et al. 2009). Cowan et al. (1993) contend that the year-class strength of Striped Bass is determined prior to metamorphosis (larval stage) as a combination of factors including maternal effects (larger females spawn more and larger eggs which contribute to larger larvae at hatch and better survival), prey abundance and quality.

Douglas et al. (2006) used a rate of 0.1% for survival to the end of the growing season for this population at the northern limit of the species distribution. Although there are no measures of absolute abundance of age-0 bass at the end of the first summer, the mean asymptotic abundance (K) was assumed to be in the order of a few million fish with 10s of millions of individuals possible for strong year classes (Douglas et al. 2006). Estimates of bycatch in the fall open water fishery of the Miramichi were over half a million fish in a year when spawner abundance was low (Bradford et al. 1997).

4.3. DATA

The data (observations) for model fitting are provided in Appendix 3. The observations include the assessed estimates of total spawner abundances and estimates of the number of spawners at age calculated from the assessed size distribution and an age-length key. Empirical data on weight-at-age and assumptions of maturation schedules by age for males and females are also shown in Appendix 3. Specifically, the observations for model fitting are:

- Assessed (median) total spawners (number) 1996 to 2019 (excluding 2012)
- Estimated abundance at age of spawners 1996 to 2019 (excluding 2012) based on:
  - Fork length distribution of spawners by year, 1996 to 2019 (excluding 2012), and
  - Age and length data to develop an age-length key based on von Bertalanffy growth model.

4.4. LIKELIHOODS

Lognormal likelihoods for abundance (number of fish) included:

- Median spawner abundance at ages 3 to 8 by year ($Sp.obs_{a,y}$) as

$$Sp.obs_{a,y+a} \sim LogN\left(log.\mu.Sp_{a,y+a}, log.\sigma_a\right) \text{ for a = 3 to 8, y = 1996 to 2019-a.}$$

with
$log.\mu.Sp_{a,y+a}$ the predicted mean (natural log scale) abundance of spawners age *a* in year *y+a*.

The sequence *y+a* is used for the appropriate cohort link; the 1996 cohort (1996 spawning) is first observed as 3-year olds in 1999, 4-year olds in 2000, etc. By age 8, the cohorts included in the model are 1996 to 2011. In all cases, the 2012 data are missing (but the missing data are included in the likelihood).

- Median total spawner abundance (age 3 to 15+) by year ($Sp.tot.obs_y$) as

$$Sp.tot.obs_{y+12} \sim LogN\left(log.\mu.Sp.tot_{y+12}, log.\sigma_{sp.tot}\right) \text{ for y = 1996 to 2008.}$$

with

$log.\mu.Sp.tot_{y+12}$ the predicted mean (natural log scale) total abundance of spawners, ages combined, year *y+12*. In this case, the sequence y+12 corresponds to the predicted spawners for the 2008 to 2019 assessment years. Although the 2008 (1996+12) to 2010 assessment years include spawners at ages 13 to 15+ from the 1993 to 1995 cohorts for which there are no originating spawner abundances (hence resulting from sequential survivals from initial abundances at age 3 in 1996 to 1998 and unrelated to the stock and recruitment function), the percentage of these age groups to total spawners in any of those years is small (< 1%) and considered to have minimal consequence on the likelihood.

4.5. INITIAL YEAR 1996

Estimated recruitment at age and spawners at age for the first year, 1996, are derived directly from the assessed and estimated spawner abundances at age in 1996.

Recruitment at age was estimated as:

$$N_{1996,1} = \frac{Obs.sp_{1996,3}}{p.rec.sp_3} * e^{(Z_1 + Z_2)}$$

$$N_{1996,2} = \frac{Obs.sp_{1996,3}}{p.rec.sp_3} * e^{(Z_2)} \text{ and}$$

$$N_{1996,a} = \frac{Obs.sp_{1996,a}}{p.rec.sp_a} \text{ for a = 3 to 15+.}$$

Total spawners, total eggs, and recruitment at age 0 are as defined above.

Depending on the model, Z_1 and Z_2 above are either given informative priors or are not used because the life cycle transition goes directly from age-0 to age-3 (Model 5) or from eggs to age-3 (Model 6, 7).

For models 5, 6 and 7 described below, the predicted recruitment abundance at age 3 is derived from either eggs or age-0 recruitment in year-3. Therefore, initial values for age-3 recruitment for 1997 and 1998 are derived from the assessed spawner abundances at age 3 for those years adjusted by the proportion of recruitment that become spawners at age 3 (as was the case for age 3 in 1996).

$$N_{y,3} = \frac{Obs.sp_{y,3}}{p.rec.sp_3} \text{ for y = 1997 and 1998.}$$

4.6. MODEL VARIANTS

Seven age-structured life cycle models with differing assumptions and parameters to be estimated were examined. Some life history characteristics (mean weight-at-age, proportion female at age of spawners, eggs per kg of spawner) were set at fixed values in all models. For the other life history parameters (Beverton-Holt stock and recruitment parameters, survival, proportion of recruits that are spawners), prior distributions were used for the parameters (Table 4.1). Time varying parameters were not considered in the models.

The model predictions of abundances at age and total spawner abundance were fitted to the point estimates of abundances of spawners at age and estimated total spawners from the assessments conducted in the Miramichi over the period 1996 to 2019.

The models were coded in OpenBugs with posterior distributions derived from Monte Carlo Markov Chain simulations with Gibbs sampling (Lunn et al. 2013; Appendix 4).

4.6.1. Model 1

The initial model assumed informative prior information for most of the life history parameters with the exception of the parameters of the stock and recruitment Beverton-Holt function and the precision parameters of the likelihoods (Table 4.1).

Parameters in the model to be estimated are:

- α (survival rate at the origin);
- K, asymptotic carrying capacity of age 0 in the first summer;
- σ, for ages 3 to 8 and for total spawners;
- Z for ages 0 (overwinter survival), 1, and 2 from the Z to length relationship of Gislason et al. (2010; informative priors);
- Z at age assumed similar for ages 3 to 15+ at median value (0.33) of the cohort decline analysis of estimated spawners at ages 5 to 12 (informative prior); and
- Proportion of recruits at age that are spawners (sexes combined), based on assumed maturation schedule of males and females (informative priors).

4.6.2. Model 2

In the second model, the mortality rates at ages 3 to 8 were estimated independently but with informative priors with the same rates over years; the mortality rate for ages 9 to 15 was set at the mortality rate at age 8 (Table 4.1).

Parameters in the model to be estimated are:

- α (survival rate at the origin);
- K, asymptotic carrying capacity of age 0 in the first summer;
- σ, for ages 3 to 8 and for total spawners;
- Z for ages 0 (overwinter survival), 1, and 2 from Z to length relationship of Gislason et al. (2010; informative priors);
- Z for ages 3 to 8; Z for ages 9 to 15+ = Z at age 8 (informative prior); and
- Proportion of recruits at age that are spawners (sexes combined), based on assumed maturation schedule of males and females (informative priors).

4.6.3. Model 3

In the third model, the mortality rates at ages 3 to 8 were given independent and weakly informative priors (Table 4.1).

Parameters in the model to be estimated are:

- α (survival rate at the origin);
- K, asymptotic carrying capacity of age 0 in the first summer;
- σ, for ages 3 to 8 and for total spawners;
- Weakly informative priors for Z for ages 3 to 8; Z for ages 9 to 15+ = Z at age 8;
- Z for ages 0 (overwinter survival), 1, and 2 from the Z to length relationship of Gislason et al. (2010; informative priors); and

- Proportion of recruits at age that are spawners (sexes combined) for ages 3 to 6. Proportion for ages 7 to 15 set equal to proportion at age 6.

4.6.4. Model 4

In the fourth model, the proportion of recruits that are spawners at ages 3 to 6 and the survivals at age-0, 1, and 2 are given weakly informative priors, to be estimated (Table 4.1; Appendix 4a).

Parameters in the model to be estimated are:

- α (survival rate at the origin);
- K, asymptotic carrying capacity of age 0 in the first summer;
- σ, for ages 3 to 8 and for total spawners;
- Z for ages 3 to 8; Z for ages 9 to 15+ = Z at age 8;
- Weakly informative priors for Z for ages 0 (overwinter survival), 1, and 2 centered on Z to length relationship of Gislasson et al. (2010); and
- Weakly informative priors for proportion of recruits at age that are spawners (sexes combined) for ages 3 to 6. Proportion for ages 7 to 15 set equal to proportion at age 6.

4.6.5. Model 5

In the fifth, the cumulative survival from age 0 (summer) to age 3 was estimated, excluding the need for priors on survivals at age 0, 1, and 2 (Table 4.1; Appendix 4b).

Parameters in the model to be estimated are:

- α (survival rate at the origin);
- K, asymptotic carrying capacity of age 0 in the first summer;
- σ, for ages 3 to 8 and for total spawners;
- Z for ages 3 to 8; Z for ages 9 to 15+ = Z at age 8;
- Cumulative Z for age 0 (summer) to age 3; and
- Proportion of recruits at age that are spawners (sexes combined) for ages 3 to 6. Proportion for ages 7 to 15 set equal to proportion at age 6.

4.6.6. Model 6

In this model, the Beverton-Holt stock and recruitment parameters were estimated for eggs to recruitment at age 3 (Table 4.1; Appendix 4c).

Parameters in the model to be estimated are:

- α (survival rate at the origin; cumulative survival eggs to age-3);
- K, asymptotic carrying capacity at age 3;
- σ, for ages 3 to 8 and for total spawners;
- Z for ages 3 to 8; Z for ages 9 to 15+ = Z at age 8; and
- Proportion of recruits at age that are spawners (sexes combined) for ages 3 to 6. Proportion for ages 7 to 15 set equal to proportion at age 6.

4.6.7. Model 7

In the final model, a power function for the spawner to recruitment relationship to age 3 was examined, that defines a density dependent survival but no carrying capacity limit. Given the relatively short time series of stock and recruitment data and the one way trip of increasing abundance observed, this model was used to examine the strength of evidence of a compensatory relationship with an asymptote for carrying capacity for recruitment measured at age 3.

$$N_{y+3,3} = \gamma * Eggs_y^{\beta}$$

with
$N_{y+3,3}$ = recruitment abundance (number) at age 3 in year y+3,
$Eggs_y$ as defined above,
γ = density independent mortality rate (0,1), and
β = density dependent component, expected to be < 1 if there is density dependence.

Parameters in the model to be estimated are (Table 4.1):

- γ proportional survival from eggs to age 3;
- β the density dependent compensatory parameter for age 3;
- σ, for ages 3 to 8 and for total spawners;
- Z for ages 3 to 8; Z for ages 9 to 15+ = Z at age 8; and
- Proportion of recruits at age that are spawners (sexes combined) for ages 3 to 6. Proportion for ages 7 to 15 set equal to proportion at age 6.

4.7. MODEL RESULTS

Model diagnostics for variants 4, 5, and 6 are detailed in Appendix 5 and summarized in Table 4.2.

The time series of increasing abundance of spawners for the Striped Bass population during 1996 to 2019 follows a one way trajectory and the observations provide limited information to clearly define the population dynamics. Despite this, a number of conclusions can be drawn from these analyses:

- There is sufficient evidence that survival rates at age for the time series of observations differ with the lowest estimated survival rates for ages 4 to 6 and the highest rates for ages 8 plus.
- Estimated survival rates of Striped Bass of ages 7 and older, appear to have increased over the time period 1996 to 2019 (based on positive temporal trend in residuals), although such a change was not incorporated in the model.
- The proportion of recruits at age that become spawners increases from age 3 to 6, as expected.
- There is a negative correlation between the estimated survival rate at the origin of eggs to age-0 summer abundance of the Beverton-holt relationship and the density independent survival rate estimated for other ages (age-0 and age-3 in Models 3 and 4, age 0 to 3 in Model 5). This trade-off in parameter estimates occurs because of an absence of observations allowing for the partitioning of survival for the intermediate age groups (ages 0, 1, and 2).

- There is insufficient evidence to unequivocally conclude or reject the assumption of a density-dependent compensatory stock and recruitment relationship for this population. There is little difference in the fit to observations of the power function model compared to models with assumed Beverton-Holt stock and recruitment functions. The power function of eggs to recruitment at age 3 provides the lowest deviance value of all the models but with a density dependent parameter that encompasses unity, hence a proportional relationship.

A priori, a density dependent Beverton-Holt stock and recruitment function is assumed and models with this stock and recruitment function were considered further.

4.7.1. Beverton-Holt SR Model Results

There is no difference in fits to observations of the model with a Beverton-Holt stock and recruitment function between eggs and age-0 abundance in the summer (followed by density independent survival to age-3; Models 4 and 5) and the model that fit the stock and recruitment function from eggs directly to age-3 (Model 6; Table 4.2; Appendix 5).

In terms of the models that estimate survival at the origin and carrying capacity to age-0, the following are noted:

- The first model (model 4) that incorporated an egg to age-0 stock and recruitment function considered weakly informative priors on the overwinter survival rates at age-0 and the survival rates at ages 1 and 2 to estimate the abundances at age-3, the first age of spawners with observations.
- The alternate model (model 5) directly estimated a cumulative survival rate from age-0 to age 3.
- There is a strong negative correlation in the estimates of survival at the origin from eggs to age-0 and the estimates of survival at age 0 and at age 3 in model 4 and in the estimates of survival from age-0 to 3 in model 5 (Appendix 5).
- The estimated survival at the origin (eggs to age-0) for model 4 is approximately three times higher than the estimate for model 5 (Table 4.3). The cumulative survival from age-0 to 3 in model 4 (based on priors for survival rates for overwinter survival at age-0 and survivals at age 1 and 2) is much lower (by a factor of 4) than for model 5 which directly estimates a cumulative survival from age-0 to 3.
- The cumulative survival from egg to age-3 at the origin, in the absence of density dependent compensatory survival, is quite low at 3 to 4 fish per 100,000 eggs. The scaled egg to age-3 survival for model 5 (median = 3.65 E-5) is similar to that of model 4 (median = 3.34 E-5) and with large uncertainties; consequently, there is no difference in the estimated density independent survival rates from eggs to age-3 between the models ($p = 0.26$; Table 4.3).
- The lifetime reproductive rate, expressed as the cumulative production of age-3 recruits in absence of density-dependent compensatory survival over the lifetime of a spawner (sexes combined), is approximately 5.0 to 5.5 recruits at age-3, and similar for these two models (Table 4.3).
- The estimate of K at age-0 is higher for model 4 than for model 5 ($p = 0.06$) however the age-3 asymptotic abundance estimated by correcting K at age-0 by cumulative survival between age-0 and age 3 results in a significantly higher asymptotic abundance value at age 3 for model 5 compared to model 4 ($p < 0.001$; Table 4.3).
- Beverton-Holt K at age-0 and scaled to age-3 are not attainable with the assumed and estimated life history parameter values from these models as shown by the equilibrium

asymptotic values which are lower than the theoretical asymptotic values from the Beverton-Holt model. Equilibrium modelling using the assumed life history characteristics (weight at age, maturation schedule, fecundity) and the estimated population dynamic parameters (survivals, proportion of recruits that become spawners, Beverton-Holt stock and recruitment parameters) result in asymptotic abundance values at age-0 that are 81% of Beverton-Holt K from models 4 and 5, respectively (Table 4.3).

Model 6 estimated the Beverton-Holt stock and recruitment parameters directly from eggs to age -3.

- The median estimate of eggs to age-3 survival from this model (median = 4.09 E-5) is much lower than the density independent survival at the origin (eggs to age-0) from models 4 and 5.
- The survival from eggs to age-3 for model 6 is higher than the scaled survival from eggs to age-3 from model 4 and model 5 but with large uncertainties that overlap among models resulting in no significant differences in the scaled survival rates among the models ($p = 0.20, 0.42$, respectively; Table 4.3).
- The lifetime reproductive rate is similar for the three models considered (Table 4.3).
- The estimated carrying capacity at age-3 from model 6 is approximately nine times and four times higher than the scaled carrying capacity to age -3 for model 4 and model 5, respectively, and despite large uncertainties, the distributions do not overlap among the models ($p < 0.001, 0.01$, respectively; Table 4.3).
- Equilibrium modelling of asymptotic abundance at age-3 for model 6 gives a value of 2.9 million recruits and 815 thousand spawners at age-3, 78% of the Beverton-Holt derived carrying capacity value for recruitment at age-3.

4.7.2. Choice of Model

The choice of model has consequences on the interpretation of population abundance and trends as well as on the derivation of the reference points.

- A priori, a density dependent Beverton-Holt stock and recruitment function with density dependence occurring between eggs and age-0 summer abundance is assumed so these models are retained (models 4 and 5). Model 6 (Beverton-Holt stock and recruitment function with density dependence occurring between eggs and age 3) is not retained; in its recruitment profile, model 6 is very close to a proportional relationship.
- There is little information to support preferentially selecting Model 4 over Model 5. Diagnostics of model fits suggest a slight improvement in the predicted to observed total spawner abundances for model 5 but the difference is very minor (Figures 4.1, 4.2; Appendix 5). Deviance values from the two models are essentially identical. There are fewer prior requirements (fewer parameters) for model 5 compared to model 4 as only cumulative survival from age-0 to age-3 is estimated but other than that, the estimates of survival at ages 3 to 8 and the proportion of recruits that are spawners are similar between models (Figure 4.3).
- Model 4 parameter estimates indicate the population has a higher survival rate at the origin and a higher carrying capacity to age-0, however, the carrying capacity at age-3 is lower for model 4 compared to model 5 due to the lower cumulative survival from age-0 to age-3 inferred from model 4 (Figure 4.4).

- The lower carrying capacity at age-3 and the higher survival rate at the origin from model 4 will in turn result in lower reference values for maximum sustainable yield and other reference points compared to model 5.
- Estimates of maximum sustained yield and candidate reference values are presented for both models 4 and model 5.
- More detailed diagnostic and summaries for models 4 and 5 and summaries for model 6 are available in Appendix 5.

5. REFERENCE POINTS FOR STRIPED BASS

5.1. RECOVERY OBJECTIVES FROM THE RECOVERY POTENTIAL ASSESSMENT

Following on the first status assessment by COSEWIC (2004) of the southern Gulf of St. Lawrence Striped Bass Designatable Unit as threatened, a Recovery Potential Assessment was conducted that included proposals for abundance recovery objectives (DFO 2006; Douglas et al. 2006). Mortality, fecundity, and stock and recruitment dynamics were modeled using general life history information of the species and observed or assumed values specific to southern Gulf Striped Bass. The choice of parameter values in the model were supported by observations on characteristics of the population and balancing of life stage abundances. The characteristics of the southern Gulf population considered included:

- prior for expected abundance of adult bass and spawners,
- relative age structure of the spawners, and
- sex ratio of spawners.

5.1.1. Prior Expectation of Striped Bass in an Exploited State

An estimate of historical maximum abundance was stated as a reasonable expectation of a recovered population. The maximum recorded annual fishery landing of southern Gulf Striped Bass since 1917 was 61.4 t (in 1917). The maximum commercial landing during 1968 to 1996 was 47.1 t. Using the historical maximum landing of 61.4 t, an assumed weight for the exploited Striped Bass population of 1.9 kg, and an assumed (without information) exploitation rate of 50%, the abundance of adult-sized (3 year and older) Striped Bass in the southern Gulf was considered to have been between 65,000 and 200,000 fish (Douglas et al. 2006).

A deterministic life history equilibrium model was run over a range of egg depositions to derive four spawning stock reference levels: spawners at equilibrium in the absence of fisheries (Seq), the spawning stock which produced the maximum gain (Sopt), and spawning stocks at a fishing rate which resulted in 50% and 30% spawning per recruit (50%SPR, 30%SPR). The mortality rate and life history parameters were assumed as:

- Beverton-Holt stock and recruitment relationship with α = 0.001 and K expressed as abundance of age-0 at the end of the summer = 1.5 million fish;
- M = 1.5 for the six months of overwintering for YOY;
- M = 1 for age 1 bass;
- M = 0.6 for age 2 and older bass;
- Maturation schedule of males and females (or proportion of bass at age on spawning grounds); and

- Fecundity based on mean weight at age.

Sopt (spawners that produce C_{MSY}) was proposed as the recovery limit for the southern Gulf Striped Bass and spawners for 50%SPR as the recovery objective for directed fisheries. Since the parameters for the Beverton-Holt compensatory function were not known, simulations under lower and higher average YOY production (1, 1.5, 2 million; K) and for lower and higher density independent survival (0.0005, 0.001, 0.002; α) were run. Based on the prior expectation of adult abundance being in the range of 65,000 and 200,000 bass, the YOY productive capacity of 1.5 million and the density independent survival rate of 0.1% were retained as suitable values for deriving the reference levels. The Seq value (spawners at replacement in terms of lifetime egg production) was estimated at 63,000 fish. The proportion female in the spawners was 0.34.

The Sopt value was calculated at 21,600 spawners and the 50%SPR value was 31,200 spawners. These were proposed as the recovery limit and the recovery target, respectively, the latter being the value for considering any directed fisheries. Compliance rules were also proposed for assessing whether the population was recovered; for 5 of 6 consecutive years for the recovery limit and once this was attained, attainment of the recovery target in 3 of 6 consecutive years. It was also indicated that the assessment of spawner abundance relative to the recovery objectives would be based on the 5th percentile of the annual abundance, keeping with the premise that there should be a low probability of the abundance indicator being below the recovery limit (Douglas et al. 2006). The expectation of reasonable abundance, i.e. adult Striped Bass of 100 thousand, and the recovery objectives were exceeded after 2010.

5.2. FISHERY REFERENCE POINTS

Striped Bass is a valued Indigenous FSC, recreational, and previously commercial fish and it was assumed that the reference points of interest to DFO Fisheries Management would be used to manage harvest fisheries. A large number of reference points have been proposed and discussed in the literature (Goodyear 1993; Mace 1994; Myers et al. 1994; Gabriel and Mace 1999). We focused on a limited number of possible reference points that could be derived from equilibrium modelling of maximum sustainable yield, from spawner potential per recruit (SPR) and reference values based on historical observations.

5.2.1. Methods

Given the iteroparous nature of Striped Bass, the concepts of Maximum Sustainable Yield (MSY) and associated metrics including B_{MSY} (biomass at MSY), C_{MSY} (catch at MSY) and F_{MSY} (fishing rate at MSY) are relevant. With carrying capacity in units of juvenile stages, B_{MSY} is calculated using the assumed life history characteristics that include a stock recruitment relationship, natural mortality-at-age, partial recruitment to the fishery at age, weight-at-age, proportion female spawners at age, and fecundity. Important population dynamics parameters, in particular the stock and recruitment parameters, were obtained from model fitting to observations. MSY reference points are derived using an equilibrium model that incorporates the joint probability distributions of these life cycle model parameters.

Reference points corresponding to Spawner per recruit (SPR) concepts were also considered. SPR is presented as a proportion of the spawner potential which remains when fished relative to a population that is not fished (Goodyear 1993). There is no spawner to recruitment function in SPR calculations. SPR reference point values discussed in literature include: 30%SPR (fishing rate that reduces the spawner production to 30% of the unfished condition) as a maximum fishing rate (Mace and Sissenswine 1993; ICES 1997) and 50%SPR (fishing rate that reduces the spawner potential to 50% of the unfished condition) as a target fishing rate, presented as F_{pa} in ICES (2001). These fishing rate reference points can be converted to abundance reference points using a stock and recruitment function. Equilibrium modelling is used to calculate the equilibrium abundance at fishing rates corresponding to 30%SPR and 50%SPR. Spawner per recruit reference points are derived using the joint probability distributions of the life cycle model parameters for spawners of ages 3 to 15+.

MSY and SPR reference point are context specific. The reference point values derived depend not only on the parameter estimates of the population dynamics (survival, prop. recruits to spawners) but also on the fisheries management scenarios, particularly those that have size limits for harvest retentions. The size limits, combined with the size distributions at age, define the partial recruitment at age to the fishery and hence the proportion of the total annual losses at age attributed to fishing.

We also considered a traffic light approach that relies exclusively on past observations without a model as a simple and naïve alternative to define potential precautionary approach status zones. The traffic light approach was proposed for the integration of multiple indicators and for simplifying the communication of information to support management decisions (Caddy 2002).

MSY and SPR abundance reference points are calculated in terms of eggs and converted to numbers of spawners on the spawning ground of the Northwest Miramichi because this is the component that is monitored and assessed (DFO 2020).

5.2.2. Upper Stock Reference (USR)

The USR points examined include:

- Spawner abundance at 80% B_{MSY};
- Spawner abundance at equilibrium when the stock is fished at F corresponding to 50%SPR; and
- Traffic light green zone that characterizes a high abundance state.

5.2.3. Limit Reference Point (LRP)

DFO (2009) provides guidance for candidate LRPs. The LRPs examined include:

- Lowest spawner abundance that resulted in recovery of the stock (Brecover);
- Spawner abundance at equilibrium corresponding to 40% B_{MSY};
- Spawner abundance at equilibrium when the stock is fished at F corresponding to 30%SPR; and
- Traffic light reference boundary that defines a zone of low abundance based on history of assessed values.

Additionally LRPs based on the abundance of spawners (or eggs) that results in 50% of K (carrying capacity) or 50% of equilibrium asymptotic abundance are also considered:

- Spawner (number) abundance or eggs that result in 50% chance of attaining 0.5 K (at age 3); and
- Spawner (number) abundance, eggs that result in 50% chance of attaining 0.5 equilibrium asymptotic abundance (at age 3).

Density dependent effects are assumed to occur during the early life stage, i.e. from eggs to early summer recruitment. Mortality at all other life stages was assumed to be density-independent hence K can be defined for any life stage of interest that is first measured. K is presented as the spawner abundance at age 3 years, the first age of maturity that is assessed on the spawning grounds.

Previously, Douglas et al. (2006) summarized the information related to an abundance index of YOY from monitoring of catches in the rainbow smelt (*Osmerus mordax*) open water fishery in the fall during 1991 to 1998 and a summer beach seine index from 2001 to 2005. The mean annual catch rate (CPUE) of YOY bass in the open-water smelt fishery was positively correlated (R = 0.66) to the female spawner estimates derived from mark and recapture and less so for the total spawner abundance. When female spawner abundance was at or above 5,000 fish, there was a high YOY index in the fall smelt fishery supporting the premise that spawner abundance is an important component of recruitment to the fall YOY stage of striped bass (Bradford and Chaput 1997; Douglas et al. 2006).

Beach seining surveys at five to six index sites of the Miramichi were conducted during 2001 to 2005. Catch per unit effort analyses were restricted to the July sampling period because:

- YOY are readily captured in nearshore habitats of the Miramichi by this time,
- most YOY have not yet extended their distribution outside of the Miramichi system, and
- catches of YOY by beach seine in the Miramichi substantially decreased by August.

Mean CPUE estimates were highly variable between years ranging from a high of 139 YOY per sweep to a low of 4 YOY per sweep in 2003 and 2004, respectively. Douglas et al. (2006) indicated that several more years of beach seine data would be required to determine the correlation between YOY and spawners. The limited data from the Miramichi indicates that environmental factors may play an important role in year-class success, as shown in several US studies that have demonstrated that recruitment is largely determined in the first few days after spawning as a result of variable environmental conditions affecting survival (Richards and Rago 1999).

5.2.4. Removal Rate Reference Point

The fishing rate reference points considered are:

- F_{MSY} from equilibrium modelling;
- F corresponding to 30%SPR as a maximum fishing rate; and
- F corresponding to 50%SPR as a target fishing rate.

6. DERIVATION OF CANDIDATE REFERENCE POINTS

6.1. TRAFFIC LIGHT APPROACH

The traffic light approach is used to coarsely assign estimates of annual abundance of Striped Bass to three status zones, or traffic light colours. A substantial amount of work was undertaken by DFO in the early 2000s to consider what kind of indicators could be used, how to integrate multiple indicators, and how to establish the thresholds that define the zones (Halliday 2001; Halliday and Mohn 2001). Halliday and Mohn (2001) discuss a number of considerations for setting boundaries including the scale of the indicator (natural scale vs log scale) and how the observations considered may change the boundary thresholds.

The 24 year time series of spawner abundance estimates for the period 1994 to 2019 is characterized by an approximately monotonic increase in abundance. We were interested in aggregating the time series of spawner abundances into three status categories roughly equivalent to critical, cautious, and healthy zones of the PA.

6.1.1. Methods

The categories, defined as the centroids for three groups of observations, were estimated using the optimization function “kmeans” in R. This R utility uses an objective function that minimizes the sum of squares of individual points to the assigned group centers.

We examined how the definition of the groups depended on three considerations:

- the scale of the observations i.e. the natural scale versus the log scale;
- the effect of excluding the exceptional 2017 observation on the estimates of the groups; and
- the variability of the attribution of status based on the time series of observations considered. The change in estimated group centroids and the attribution of the annual observations to status zones is examined beginning with the 1994 to 2008 time series and sequentially adding one year to the data series to 2019 (excluding 2012 with no data).

Proxy values equivalent to the boundaries between the critical and cautious zones (LRP) and between the cautious and healthy zones (USR) were calculated as the means of respectively the lower and middle centroids and the middle and upper centroids.

6.1.2. Results

Log transformation versus the natural scale for observations prior to optimization of three group centroids has a large effect on the assignment of status and the calculation of proxy reference values (Figure 6.1). Using the entire time series of assessment values (medians) from 1994 to 2019 (excluding 2012), the interpretation of status is as follows (Figure 6.1, upper row):

- Based on the log scale, the abundance was in the critical zone during 1996 to 2000, has been in the healthy zone since 2011, and was in the cautious zone in all other years.
- Based on the untransformed values, the abundance was in the critical zone during 1994 to 2010 as well as in 2012, and has only been in the healthy zone in 2017.
- Following on this, the proxy LRP based on the log transformed data would be 13 thousand spawners compared to 162 thousand spawners based on untransformed data.
- The proxy USR values are similarly different, at 105 thousand based on log transformed values and over 600 thousand based on the untransformed values.

There is a large effect on the interpretation of status zones for individual years with incremental additions to the time series of observations (Figure 6.1, middle rows):

- There is similar interpretation of status, based on log transformed data and untransformed data, when the status categories are defined based on the initial short time series of observations, 1996 to 2009. In both cases, the population was assigned to the critical zone during 1996 to 2000, and to the healthy zone during 1994, 1995, 2007 to 2009.
- Sequentially adding a year to the analyses has the largest effect on the interpretation of status when the observations are on the natural scale. The status of the 1994, 1995, and 2007 to 2009 assessed years declines from healthy, through cautious and into critical as observations for the 2011, 2013 to 2015 assessment years are included in the estimation of groups.

- The interpretation of status is however much more stable when the observations are log-transformed prior to assignment to groups. At most, the status for some years declines from healthy to cautious.
- In almost all cases, the status changes from healthy to cautious or cautious to critical. It is never consistently in the opposite direction. This is expected given the almost monotonic increase in assessed abundance of this population during the period 1996 to 2019.
- The proxy LRP values based on the log transformed data are in the same range based on the initial 15 years of data (10 thousand fish) compared with the entire time series (13 thousand fish). This is not the case when the untransformed data are used; an LRP proxy value of 13 thousand fish is calculated for the initial 15 year time series whereas the proxy LRP value based on the entire time series is more than a factor larger, at 162 thousand fish.
- The proxy USR values are similarly different, based on the transformation or not of the observations. Based on the initial 15 year time series, the proxy USR values are approximately similar between the data treatments (36 versus 43 thousand for log transformed and untransformed, respectively). Using the entire time series, the proxy USR values increase to 105 thousand for log transformed and over 600 thousand for the untransformed data.

The assessed median abundance of spawners of 990 thousand fish is an exceptional observation in the relatively short time series of assessment. Excluding the 2017 observation has interesting consequences on the assessment of status and the derivation of proxy reference values (Figure 6.2):

- The status zones and the interpretation of status for the initial time series are not affected by excluding the observation for the 2017 assessment year because the groups are defined based on data from 1994 to 2009.
- For the time series extending from 1994 to 2019, the interpretation of status and the calculation of the proxy reference values based on the log transformed data are essentially similar whether 2017 is included or excluded. The proxy LPR values are 10 thousand when 2017 is excluded versus 13 thousand when 2017 is included. The proxy USR values are 87 thousand when 2017 is excluded versus 105 thousand when 2017 is included.
- In contrast, for the observations on the natural scale, the interpretations of status through time and the calculation of proxy reference values are sensitive to the inclusion versus exclusion of the 2017 value. Note that when the 2017 data point is included, the upper centroid and zone are defined exclusively by the single observation of 2017. When 2017 is excluded, the upper centroid is defined by 6 observations (Figure 6.2). When 2017 is excluded, the interpretation is that the population was in the critical zone during 1996 to 2006 and has been in the healthy zone since 2011 with the exception of the assessed abundance in 2014. The proxy LRP value for the whole time series is 44 thousand fish when the 2017 observation is excluded (Figure 6.2), compared to 162 thousand fish when the 2017 observation is included (Figure 6.1). The proxy USR value is similarly strongly affected by the 2017 observation; when the 2017 observation is excluded, the proxy USR value is 181 thousand fish in contrast to a proxy USR value of 639 thousand fish when the 2017 point is included (Figures 6.1, 6.2).

6.2. EQUILIBRIUM MODELLING

Equilibrium modelling is used to simulate predicted abundances at age and overall for different fishing rates. The equilibrium model uses the same life cycle equations as in the estimation model (section 3) with modifications as described in the next sections. Values of the population dynamics and life history parameters are taken from individual MCMC draws from the joint posterior distribution from the population model. The model in its equilibrium form is coded in R with runs forward 150 years to ensure attainment of equilibrium conditions, at fixed levels of fishing and for specific management regimes.

Maximum sustainable yield (MSY) is derived by searching over a range of fully-recruited F for the fishing rate (F_{MSY}) that results in maximum yield (in weight). Biomass at MSY (B_{MSY}), spawner abundance (number of fish) at B_{MSY}, catch (C_{MSY}; in number and weight), and age structure of the catch and of the spawners at MSY are retrieved from the simulation outcomes. Management strategies based on size limits are also examined with the model.

The MSY values are provided for the abundance (number, biomass) of spawners (ages 3 to 15+) on the spawning ground, thus the values do not represent the entire population as not all Striped Bass of ages 3 to 15+ are considered to be present on the spawning ground. The spawning period (May) is considered to be the start of the year.

6.2.1. Natural Mortality (M) At Age

Estimates of M at ages 3 to 15+ are required for the equilibrium analysis to derive fishing rate and MSY reference values.

In the age structured population model, applied to the estimated spawner abundances at age for the years 1996 to 2019, Z at age is estimated for ages 3 to 8, with Z at ages 9 to 15+ being set equal to Z at age 8. These are estimates of total mortality (sum of natural mortality and fishing mortality) as there were fisheries removals of Striped Bass over the entire time series, despite the closures of all harvest fisheries between 2000 and 2012 (DFO 2011).

Based on acoustic tagging and tracking data, estimates of instantaneous mortality rates (Z) were 0.41 (median) during the period 2003 to 2009 and 0.22 (median) during the period 2014 to 2018 (Section 3.6.2.2; Figure 3.10). It is not possible to partition the natural mortality rates from fishing mortality rates with these data however considering that fishery removals would have in part contributed to the estimated mortalities, the instantaneous natural mortality rate of adult sized (> 47 cm) Striped Bass would not be greater than 0.2.

In the coastwide assessment model for Striped Bass of the eastern seaboard of the US, M for adult bass age 4 and older is set at 0.15 (NEFSC 2019).

For purposes of equilibrium modelling and to define reference points, two scenarios for M were examined:

- Assuming M = Z as derived from the population model for ages 3 to 15+ (Figure 4.3);
- M at age 3 based on Z from the population model and M for ages 4 to 15+ from acoustic tagging information (M = 0.20 with a 5^{th} to 95^{th} percentile range of 0.13 to 0.28 based on S ~ beta(82,18)).

6.2.2. Fishery Selectivity at Age (s_a)

Fishery selectivity at age (s_a) to fully-recruited F is determined using the predicted fork length distribution at age from the von Bertalanffy model and relative to a defined management strategy based on fork length (Table 6.1). The proportion of the age group vulnerable to the fishery was calculated as the proportion of the area under the normal density curve contained within the lower and upper size retention limits. The proportion of the area at age is calculated as (in R code):

$$s_a = pnorm(FL.max, u.fl_a, sd_a) - pnorm(FL.min, u.fl_a, sd_a)$$

with
s_a being the selectivity at age a (range 0 to1) to fully-recruited fishing rate ,
FL.max and FL.min are the fork length size limits (cm) for a specific management strategy,
$u.fl_a$ = mean fork length (cm) of bass at age a at the time of fishery taken as mid-season, and
sd_a = mean standard deviation of the mid-season size distribution at age a (Figure 6.3).

For a management strategy with no size limits, a minimum size of 30 cm was assumed to be the smallest sized bass that would be retained. If there is no maximum size limit defined, FL.max was set to 150 cm.

6.2.3. Catch Equation

The standard Baranov catch equation was used to calculate the number and weight of fish lost due to fishing activities, assuming F and M occur simultaneously, i.e. between May and October. It is assumed that a fish that is captured and within the management size limit is retained, all other fish are released.

Total loss of fish at age resultant of fishing includes fish retained and harvested and fish lost due to catch and release mortality. A catch and release mortality rate of 9% is assumed corresponding to the catch and release mortality value used in the coastwide assessment of Striped Bass of the eastern seaboard of the US (NEFSC 2019).

$$FLoss.N_a = N_a * (1 - e^{-(M_a + s'_a F)}) * \frac{s'_a F}{s'_a F + M_a}$$

with
$FLoss.N_a$ the number of bass at age a that die from fishing activities,
N_a the estimated recruitment abundance (sexes combined) of bass at age a,
M_a is the natural mortality at age a,
F is the fully recruited fishing rate,
$s'_a = s_a + (1 - s_a) * A.CR$, s_a is the vulnerability at age to fully recruited F, and *A.CR* is the catch and release mortality rate set at 9% when losses from catch and release are accounted for in the model. Setting *A.CR* = 0 is equivalent to ignoring mortality from catch and release.

Yield in terms of retained catches, to define maximum sustainable yield, is calculated as:

$$C.N_a = N_a * (1 - e^{-(M_a + s'_a F)}) * \frac{s_a F}{s'_a F + M_a}$$

with
$C.N_a$ the retained catch in number at age a, and other components as described above.

$$C.Wt_a = C.N_a * u.wt_a$$

with
$C.Wt_a$ is the retained catch weight-at-age a, and $u.wt_a$ is the mean weight at age a at the time of the fishery (mid-year) based on $u.fl_a$.

6.2.4. Equilibrium Modelling Results

An example of the equilibrium modelling results and the reference values from model 5 is presented in Figures 6.4a to 6.4d. For illustrative purposes, the management strategy corresponding to no size limits and no accounting for catch and release mortality (*A.CR* = 0) is considered the default strategy. The summaries are presented for the assumptions on M of Striped Bass aged 3 to 15+ and include:

- Plot of survival rates at age (e^{-M}) assumption;
- Plot of proportions of recruits at age that become spawners;
- Plot of selectivity at age to fully recruited F (s_a; specific to a management scenario);
- Plot of catch at age proportions at F = (F_{MSY}, 50%SPR, 30%SPR);
- Plot of age distribution of recruitment at F = (0, F_{MSY}, 50%SPR, 30%SPR); and
- Plot of age distribution of spawners at F = (F_{MSY}, 50%SPR, 30%SPR).

MSY estimation summary outputs include:

- The equilibrium total recruitment abundance (ages 3 to 15+) over a range of fully recruited fishing rates;
- The equilibrium total spawner abundance (ages 3 to 15+) over a range of fully recruited fishing rates;
- Yield in weight over a range of fully recruited fishing rates;
- Yield in number of fish over a range of fully recruited fishing rates; and
- Posterior distributions (boxplots) of C_{MSY} (weight), C_{MSY} (number), F_{MSY}, B_{MSY} (recruitment), B_{MSY} (spawners), and eggs at B_{MSY}.

Illustrative plots of abundance (number of fish) trajectories over 150 years including:

- Predicted total recruitment at F=0 and F= 0.09; and
- Predicted recruitment at age-3 at F = 30%SPR and F = 50%SPR.

6.2.4.1. Equilibrium results for model 5 and model 4

Equilibrium modelling results based on life history parameter inferences from model 5 are summarized in Table 6.2a and Figures 6.4a to 6.4d. Results for model 4 are summarized in Table 6.2b. Abundances are summarized in terms of total abundance for ages 3 to 15+, referred to as recruits, and in terms of spawners which would be the component assessed on the spawning grounds (DFO 2020). The spawner abundance values are lower than the total abundance because not all fish at ages 3 to 15+ are spawners. Fishing occurs on recruitment, or total abundance, and catch and fishing rate references refer to the removals and removal rates from the entire stock.

As expected, total equilibrium recruitment abundance (ages 3 to 15+) is higher for the equilibrium model with lower assumed values of M at age and abundance decreases with increasing fishing mortality rates (Figures 6.4b, 6.4c; Tables 6.2a, 6.2b). The yield curve is not symmetric, rising more steeply on the ascending limb at F less than F_{MSY} and declining more slowly on the decreasing side of the yield curve (Figure 6.4b). The equilibrium abundances and yields have large uncertainty, due to the combined uncertainties in the life history parameter estimates from population modelling.

Maximum lifetime reproductive rate, defined as the cumulative production of recruits at age-3 in absence of density-dependent compensatory survival over the lifetime of a spawner (sexes combined), is 15.7 fish (median; 5^{th} to 95 percentile range 11.1 to 23.0 fish) for the lower M at age values, and 5.0 fish (median; 5^{th} to 95 percentile range 3.7 to 7.5 fish) for M=Z from population model 5 (Table 6.2a). Approximately similar values are calculated from model 4 (Table 6.2b).

F_{MSY} values are similar for the equilibrium models with differing assumptions for M (Figure 6.4b; Tables 6.2a, 6.2b). The population crashes (N <= 100 fish) when fully recruited F exceeds 0.70 (M = Z, panel A) and 0.87 (for lower values of M, panel B; Figure 6.1a; Table 6.2a). Spawner per recruit fishing rate reference values of 30%SPR and 50%SPR are higher for the model with higher values of M (panel A, Figure 6.4d). F at 30%SPR is higher than F_{MSY} for both scenario values of M. Approximately similar values are calculated from model 4 (Table 6.2b).

The age structure of the population is modified by the fishing activity, with a strong bias towards younger ages in the total population and in the spawners:

- the higher the fishing rate, the faster fish die because mortality at age is the sum of fishing mortality and natural mortality;
- as fishing rate increases (for a constant M), the age structure of the spawner population gets younger, the mean weight of spawners decreases, and because younger fish have a lower proportion female as spawners (before age 6), the number of eggs per spawner declines.

The MSY and SPR reference values are higher for model 5 compared to model 4 (Figure 6.5). Based on M for ages 4+ inferred from observations, B_{MSY} from model 5 is approximately twice as high compared to the estimate from model 4. F_{MSY} estimates of F = 0.17 are similar between models resulting in higher C_{MSY} values, by a factor of two, from model 5 compared to model 4 (Tables 6.2a, 6.2b; Figure 6.5).

6.2.5. Reference Points From Equilibrium Modelling

6.2.5.1. Reference points dependent on assumptions for M

MSY reference values and reference points derived from equilibrium modelling are dependent upon the assumptions of natural mortality. The reference points are defined in terms of the number of spawners on the spawning grounds, the life stage and time period corresponding to the assessments (DFO 2020). The following summaries present the results from models 4 and 5 for the default fishing strategy with no size limits for retention and no accounting for catch and release mortality (Table 6.3a, 6.3b).

The USR values (80%B_{MSY}, abundance at 50%SPR) from the equilibrium model are higher for the scenario with lower assumed natural mortality rates (Tables 6.3a, 6.3b). For model 5, spawner abundances at 80%B_{MSY} are 530 thousand fish for the M = Z scenario and 1.2 million fish for M based on observations. The spawner abundances corresponding to 50%SPR are higher yet, at 620 thousand and 1.8 million fish for scenarios of M = Z and M based on observations, respectively (Table 6.3a). In all cases, the uncertainties for the reference values are large.

USR values from model 4 with M based on observations are comparatively lower than those from model 5, at 720 thousand for 80%B_{MSY} and 1 million for 50%SPR (Table 6.3b). The uncertainties for these reference points are equally high as in model 5.

The values of the respective candidate LRPs differ substantially. Brecover, the lowest spawner abundance from which the stock recovered, is calculated as the mean estimated abundance for the period 1996 to 2000, which was 4,500 spawners (Figure 3.2; Table 6.3a). This contrasts sharply with the values for spawners at 40%B_{MSY} and spawners that produce half of asymptotic equilibrium abundance. For model 5 with M inferred from observations, these candidate LRPs equal 700 thousand and 510 thousand spawners, respectively (Table 6.3a). There is large uncertainty in these estimates. LRP values from model 4 with M informed from observations are lower by just under half compared to model 5 values, 420 thousand and 300 thousand, for 40%B_{MSY} and half asymptotic abundance respectively (Table 6.3b).

Differences in reference point values in currencies of fish between the two scenario assumptions on M are consistent with the consequences to the age structure of the spawners as affected by fishing and conditioned by assumptions on M. For example, the 40%B_{MSY} spawner abundance for the scenario with M = Z in model 5 is less than half the value for the scenario with M informed from observations (Table 6.3a).

Spawner per recruit fishing rate reference values at 30%SPR and 50%SPR are higher for the model with higher values of M (Table 6.3a). F at 30%SPR is higher than F_{MSY} for both scenario values of M. For this management strategy without size limits on retention, fully-recruited F at MSY is 0.17, compared to F = 0.12 for 50%SPR, and F = 0.24 for 30%SPR (Table 6.3a). Fishing rate reference values are similar for model 5 and model 4 (Tables 6.3a, 6.3b).

6.2.5.2. Reference points dependent on fishing strategy

Fishing strategies have a consequence on the reference point outcomes in terms of numbers of fish because fishing changes the age structure of the population at equilibrium relative to the unfished condition. Reference point values based on the life history and population dynamics parameters of model 5 are summarized in Table 6.4a and values for model 4 are presented in Table 6.4b, both with the assumption on M for ages 4 to 15+ informed from observations. Three potential fishing strategies are contrasted with all three excluding catch and release mortality.

The choice of the USR can be based on objectives related to fishery outcomes, consistent with principles of the Precautionary Approach which states that the USR value would be determined by productivity objectives for the stock, broader biological considerations, and social and economic objectives for the fishery (DFO 2009). The values from model 5 corresponding to 80%B_{MSY} range from 940 thousand to 1.2 million spawners, dependent upon the fishing strategy with near complete overlap of the 5^{th} to 95^{th} percentile ranges among the three fishing strategies. For model 5, the USR corresponding to 80%B_{MSY} ranges from 960 thousand to 1.2 million spawners (Table 6.4a). For model 4, the USR corresponding to 80%B_{MSY} ranges from 570 to 720 thousand spawners, dependent on fishing strategy (Table 6.4b).

Other than spawners for 40%B_{MSY}, the candidate LRPs examined and corresponding to the life history characteristics of Striped Bass from the southern Gulf, are generally invariant to fishing strategy. Brecover is not affected by fishing strategy, being based upon similar years of abundances and independent of fishing strategy simulations. The eggs for half of asymptotic abundance to age 3 are unaffected by fishing strategy because it is assumed that eggs are equivalent regardless of age of spawners and fish younger than age 3 years are generally not subject to fishing mortality and are not spawners. Differences in spawner numbers for half Beverton-Holt K and half equilibrium asymptotic abundances among the fishing strategies are due to the effects of fishing that modifies the age structure of spawners toward younger ages. Spawners for half of asymptotic equilibrium abundance from model 5 are approximately 500 thousand spawners, with large uncertainty, such that there is essentially no difference in the number of spawners among the fishing strategies (Table 6.4a). For model 4, spawners for half asymptotic abundance are quite similar among fishing strategies, rounded off to 300 thousand spawners (Table 6.4b).

We cannot make a compelling argument for using spawner abundance at F corresponding to 30%SPR as a LRP. In these analyses, spawner abundances at 30%SPR are higher than spawner abundance at 80%B_{MSY}.

Fully-recruited fishing removal reference values are very dependent on the fishing strategy and any choice of a removal rate reference would be specific to the fishing strategy for the stock. The exploitation rates on total recruits, aged 3 to 15+, vary from 14% with no size restrictions, to 18% for the slot limit of 47 to 61 cm fork length to 20% for the maximum size limit of 65 cm (Tables 6.4a, 6.4b).

6.2.5.3. Reference points accounting for catch and release mortality

The effects of including or excluding catch and release mortality on MSW reference values are generally inconsequential in these analyses given the large uncertainties in population dynamics (Table 6.5). The only exception is the estimate of F_{MSY} for the management strategy with a slot size of 47 to 61 cm which is higher when catch and release mortality is excluded compared to when it is included (Table 6.5).

When catch and release mortality is included, MSY values are lower than if catch and release mortality is excluded, i.e., similar to assuming higher natural mortality on the population (Table 6.5). Of the two management scenarios examined that have catch and release implications, the scenario with a slot size of 47 to 61 cm fork length has the largest proportional loss of fish through catch and release and the largest relative decrease (14%) in the retained catch at MSY. The retained catch represents 86% of total fishery losses for the management strategy with a slot size of 47 to 61 cm, 97% for the strategy with a maximum size limit of 65 cm, and no effect for the management strategy without size limits for retention.

Catch and release effects as modelled here do not fully account for recreational fishing practices in the southern Gulf and would underestimate the consequences of the practice on the resource. The recreational fishery for Striped Bass in the southern Gulf has a large component of catch and release, in part due to the mandatory slot size restrictions for retention and the fishing practices of individual anglers that favour a lot of angling activity without intent to retain. There is a community of recreational users that practice catch and release regardless of the retention allowances; they will catch and release fish that are within the retention limits and at peak periods of aggregation during the spring and fall some anglers have reported catching and releasing upwards of 100 fish or more per daily fishing trip (see Section 2.2). The analysis of consequences of these fishing practices on MSY and other reference values would require a different model and data inputs.

6.3. CONCLUSIONS ON REFERENCE POINTS

6.3.1. MSY and SPR Based Reference Points From Population Modelling

We used equilibrium modelling to explore candidate reference points based on life history and population dynamics parameters informed from a population model for Striped Bass of the southern Gulf of St. Lawrence. A priori, two population models with a Beverton-Holt stock and recruitment function with density-dependence occurring between the egg and age-0 life stage in the summer are considered for estimation of MSY reference values. The two models differ in the prior assumptions for the density independent survival from age-0 to age-3, 3 year olds being the first age group that is monitored as spawners. The two model variants provide similar estimates of lifetime reproductive rate to age-3 in the absence of density dependent compensatory mortality, however the estimates of carrying capacity at age 3 differ by a factor of two between the models. This has consequences on the derivation of reference points and we present candidate reference point values for both models (Figure 6.8) and suggest a choice of reference points based on population trajectory over the past two decades and the risk to population sustainability and persistence.

Information on natural mortality (M) at age is crucial in the equilibrium model and reference point calculations. The expectation from life history theory is that natural mortality is inversely related to size, and hence age. Based on sequential observations of acoustically tagged and tracked Striped Bass, instantaneous natural mortality for adult bass >= 47 cm fork length is concluded to be less than 0.2, equivalent to an annual survival rate of 0.82 or higher. Population modelling also indicates a relatively high annual survival rate of 0.77 (median) for Striped Bass aged 8 and older but with large uncertainty (5^{th} to 95^{th} percentile range 0.44 to 0.93). A relatively high survival rate (median = 0.67; percentiles range 0.47 to 0.86) is estimated for fish at age 3 years, an age and size group that may be outside the size preference for retention in historical and contemporary fisheries. For purposes of equilibrium modelling and MSY reference calculations, M for Striped Bass aged 4 and older is assumed to be 0.18 (5^{th} to 95^{th} percentile range of 0.13 to 0.28) and M for younger ages are taken from population model estimates.

Fishing strategies can have a consequence on the reference point outcomes in terms of numbers of fish because fishing changes the age structure of the population relative to the unfished condition. An USR point conditional on a fishing strategy is consistent with principles of the Precautionary Approach which states that the USR value could reflect socio-economic considerations, for example reference points that consider maximizing yield, in terms of weight or in terms of number of fish harvested. Of the two USR candidates discussed above, the spawner abundance corresponding to 80%B_{MSY} has been most frequently used in fisheries management and examples from marine fish and invertebrates assessments and management abound.

To conform to the principles of the PA policy, the LRP should be determined by biological considerations and thus preferably be invariant to fisheries exploitation strategies. LRP candidates including 40%B_{MSY} and abundance at 30%SPR are not invariant to fishing strategy. Candidate LRPs that are invariant to fishing include Brecover (although not entirely) and reference points associated with egg abundances that result in half of Beverton-Holt carrying capacity or half of maximum asymptotic abundance of recruitment at age-3.

Brecover, the lowest historical spawner abundance that did not prevent rebuilding of the population, is quite clearly the low spawner abundances estimated during 1996 to 2000, at a mean value of just under 5,000 spawners (Figure 3.2; Table 6.4). The fact that the Striped Bass population of the southern Gulf was able to monotonically increase from those low abundances to several hundred thousand spawners in less than 20 years reflects the improved survival conditions of juvenile and adult Striped Bass over this period. The carrying capacity for this population, as estimated from modelling assuming a Beverton-Holt stock and recruitment relationship with M < 0.2 for bass aged 4 and older and no fishing is estimated to be 2.7 to 4.7 million fish aged 3 to 15+, with the abundance of spawners at 1.8 to 3.1 million fish, dependent on model (Tables 6.2a, 6.2b). A Brecover value of 4,500 spawners represents 0.1% to 0.2% of this estimated unfished equilibrium value (B_0), substantially less than proposed LRP values equivalent to 20% of the unfished abundance at equilibrium (Myers et al. 1994; DFO 2009). A reference value equivalent to 20%B_0 would be in the range of 360 to 620 thousand spawners. Despite the abundance of spawners having been as low as 5 thousand spawners in recent history, given the indications of the potential size of this unfished population Brecover does not seem appropriate.

Candidate LRPs defined in terms of spawners or eggs that result in half asymptotic abundance (Myers et al. 1994) have been applied to Atlantic Salmon populations in eastern Canada (DFO 2015b). These candidate LRPs can be invariant to fisheries management strategy if the recruitment stage being maximized is not subject to fishing mortality and if the spawning stock is expressed in terms of eggs. They are however modified by fishing strategy when expressed in terms of number of fish. This is because fishing strategies modify the age and size structure of the spawning population; regardless of strategy, fishing disproportionally reduces the relative abundance of older fish resulting in a younger mean age of spawners and consequently fewer eggs per spawner. The LRP and the assessment of attainment of the LRP could be presented in currencies of eggs. This is a trivial exercise for the most part as biological characteristics of the spawners have been obtained annually and the quantity of eggs spawned could be calculated using the same life history characteristics as were used to derive the reference points.

F_{MSY} and F at 50%SPR are potential candidate removal rate references but their values depend on the fisheries management strategy. These removal rate references are expressed in terms of fully recruited instantaneous fishing rates which are not easily understood. The fully recruited fishing rate values were converted to exploitation rates, calculated as the ratio of catch at MSY to total abundance at MSY for ages 3 to 15+. The fishing strategy without any size limits has the lowest exploitation rate at F_{MSY} of 14%, whereas the strategy with a maximum size limit of 65 cm fork length result in an exploitation rate at F_{MSY} of 20%, with an intermediate rate of 18% for the strategy with a slot limit of 47 to 61 cm fork length (Table 6.4). Exploitation rate at F_{MSY} for the three fishing strategies of this population of Striped Bass is at or less than the assumed annual natural mortality rate of 18% ($1\text{-}e^{-M}$).

6.3.2. Proxy Reference Points Based on Traffic Light Approach

The Striped Bass stock of the southern Gulf of St. Lawrence has demonstrated a monotonically increasing abundance trajectory, with an annual rate of increase during 1996 to 2019 of 25%. Candidate reference points based exclusively on past observations and independent of a population dynamic model are attractive. Note that Brecover is such a reference point. However, such reference point definitions are dependent on a number of less desirable considerations including whether the data are log transformed, the time series of observations considered, and the inferences may be sensitive to outlier / exceptional observations. Overall, reference points defined on observations which are log transformed prior to cluster identification were less dependent upon time series considerations (Figure 6.1) and less sensitive to exceptional high or low observations (Figure 6.2) than those based on the natural scale. Using the entire time series of observations, the proxy reference points derived from log-transformed data are 13 thousand and 105 thousand for the LRP and USR respectively. Based on the natural scale of observations and conditional on there being at least five observations within individual clusters, which is the case when the 2017 value is excluded, the LRP and USR are 44 thousand and 181 thousand spawners, respectively (Figures 6.1, 6.2).

This is not a good approach as the decisions on scale of data to use are subjective and there is instability in reference values as additional years are added. The approach may have more utility if the time series of observations included the full range of potential abundances of the stock to define the groups

6.3.3. Summary of Candidate Reference Points and Corresponding Stock Status

The fishery decision-making framework that incorporates the precautionary approach (DFO 2009) was developed to guide management of fisheries exploitation in order to reduce the risk of the stock falling into the critical zone and that promotes growth of the resource into the healthy zone. As the intention within the policy is to avoid the stock falling to the LRP and the critical zone, the objective is not to manage the stock to the LRP.

The proposed candidate reference points in terms of eggs and approximate spawner abundance number equivalents are summarized in Tables 6.4a, 6.4b (DFO 2020). Consistent for both model 4 and model 5, the model derived USR value is two times the LRP value. The stock status relative to these model derived reference points, over the period of assessment 1994 to 2019 is shown in Figure 6.6. The spawner abundance has been in the healthy zone only once (in 2017) and dependent on the model, the spawner abundances were either above the LRP and below USR (model 4) or at approximately the LRP (model 5) since 2013.

There is no consensus LRP value from the two retained models; whereas the modelled LRP values are 17.3 billion eggs, equivalent to 330 thousand spawners from model 4 and 30.0 billion eggs, equivalent to 560 thousand spawners from model 5. Based on the trajectory of the population over the relatively short period of assessment, maintaining a spawner abundance that exceeds 330 thousand spawners should be more than sufficient to avoid serious harm to the population.

The carrying capacity for the Striped Bass population from the southern Gulf of St. Lawrence is unknown. Modelling informed by observations from this population suggests total abundances of age-3+ Striped Bass at B_{MSY} of 1 to 2 million fish with abundances at B_{MSY} of 860 thousand to 1.5 million spawners. Potential removals when the stock is at B_{MSY} are in the range of 200 to 400 thousand fish annually.

As an alternative, the posterior distribution of the spawner assessed values could be used to assess the probabilities of the spawner abundances being below the LRP or above the USR. From looking at the distribution of boxplots relative to the point estimates of the LRP and USR in Figure 6.6, one can see that the probability of the assessed spawner abundance being below the LRP is > 75% for all years except in 2017 for the reference derived from model 5 but the probability is just under 50% since 2015 for the LRP derived from model 4. Similarly, the probability that the spawner abundance was above the USR in 2017 was just over 50% for model 4 but < 75% relative to reference points from model 5. This interpretation of status that incorporates the uncertainty in the assessed abundance relative to point estimates of reference points would conform to the directives of the Precautionary Approach policy for characterizing uncertainty and risk.

In the eastern US Striped Bass assessment, a number of reference points have been defined and used to assess the status of the stock. A spawning stock biomass reference point ($SSB_{Threshold}$) is defined as the assessed female SSB for 1995 when the stock was declared recovered with an expanded age structure. The revised value from the most recent assessment is an $SSB_{Threshold}$ value of 91,436 t (NEFSC 2019). An SSB_{Target} is also defined, equivalent to 125% of the female $SSB_{Threshold}$, equivalent to 114,295 t (NEFSC 2019). Fishing mortality threshold and target values are also defined based on the fishing rate applied to the current estimate of SSB that results in $SSB_{Threshold}$ and SSB_{Target}. These values, from the recent assessment, are $F_{Threshold}$ = 0.24 and F_{Target} = 0.20.

6.3.4. Guidance on Choice of Reference Points and Management Strategies

The first consideration for the development of the PA framework is the definition of the LRP. The recent fisheries management history is informative of the management decision making process and provides insights into what could be a publicly acceptable LRP. Fisheries access was responsive to the rebuilding of the Striped Bass population beginning initially with the re-opening of the Indigenous FSC fisheries in 2013, the retention recreational fisheries in 2014, and a pilot commercial fishery in 2018. The re-opening of the Indigenous fishery occurred following the conclusion that the population had first met both the limit and target recovery objectives in 2011, at a median abundance of 200 thousand spawners and a 5th percentile value of 90 thousand spawners (DFO 2013), values of abundance corresponding to the LRP value from one of the models and consistent with a harvest decision rule that allows fisheries exploitation when the stock is above the LRP. A cautious recreational fisheries strategy (two short retention seasons, 1 fish per day, slot size limit of 55 to 65 cm TL) was chosen in 2014 following on the 2013 median spawner assessment value of 250 thousand fish. Further increases in abundance in 2015, to a median estimate of 300 thousand spawners, resulted in an extended retention period in the recreational fishery for 2016. The largest change in the recreational fishery occurred in 2018 with an authorization to retain 3 fish per day within a slot size of 50 – 65 cm TL; this increased access followed on the exceptional return estimate in 2017 of just under 1 million spawners. The pilot commercial fishery was also first authorized in 2018.

The risk to the Striped Bass stock of an underestimate of the LRP from either the population models (330 to 560 thousand) is considered low. The lowest spawner abundances of the late 1990s did not preclude the rebuilding of the population at an average rate of 25% per year. Curtailing fishing mortality was an important factor in this rebuilding, with assessed abundances of recent years that are almost two orders of magnitude higher than the lowest assessed values of the late 1990s. This increase in abundance was sustained even with increased fisheries access beginning again in 2013. However, Brecover is not prudent as a LRP, given that its value of < 5 thousand spawners is less than 1% spawners at B_0, regardless of the population model considered, and would certainly place it in the at risk criterion for small population size used by COSEWIC. COSEWIC (2004) assessed the Striped Bass population as threatened despite the more recent abundances at that time that exceeded 20 thousand spawners.

An USR value of 720 thousand to 1.2 million spawners is seemingly within the scope of potential spawner abundance for this population. A healthy stock would minimally be at a population abundance that exceeds 720 thousand spawners (80%B_{MSY} under model 4). This may be an underestimate of the production potential of this population, as indicated by outputs from model 5, however full exploitation to rates equivalent to F_{MSY} and potential removals at MSY (C_{MSY}) would likely only be considered once the trajectory of the population abundance had placed it in that healthy zone. When this does occur, a re-assessment of population dynamics with additional observations could be undertaken to determine the appropriateness of the defined USR. The 2017 value of just under 1 million spawners was exceptional, and the decline in 2018 and 2019 to estimated values of just over 300 thousand spawners provides a cautionary note on the variations in size of the stock under new population dynamics conditions (extensive migration of Striped Bass beyond its historic distribution range with associated mortalities) and increasing fisheries exploitation. Some of the annual variation in abundance estimates are also likely related to the difficulties and uncertainties in assessing the abundance on the spawning grounds, i.e., year effects.

At a LRP value of 330 thousand spawners and an USR value of 720 thousand spawners, we note that increasing fisheries access on Striped Bass from the southern Gulf has been provided during a period when the stock has been situated in the cautious zone (with exception of 2017) but with a trajectory of increasing abundance towards the healthy zone.

If the assessed abundance was to increase above a proposed USR value of 720 thousand fish, this may result in requests for new and alternative fisheries access. The fisheries exploitation potential on this species is high. Historically and even now, Striped Bass are readily captured in large numbers in gaspereau trapnets in the spring during the spawning aggregations in the Miramichi; catch rates (fish per trapnet per day) in 2017 exceeded several thousand fish per net haul (Figure 3.1). Striped Bass are also reportedly captured in gaspereau fishery trapnets in other estuaries of DFO Gulf New Brunswick.

The recreational fishery is increasing in popularity throughout the Gulf of St. Lawrence including into the western portion of the Gulf. The current recreational fisheries management plan for Striped Bass in the Gulf is very generous, i.e. aggressive, relative to management of the Striped Bass stocks of the eastern US. The retention season extends from mid-April to the end of October, essentially the open water season, with a daily retention and possession limit of three bass within a defined slot limit. In the eastern US, there is a diversity of management measures tailored to stock units and management sectors, with fishing area specific seasons, daily limits and size limits for retention, however, daily retention limits along the entire eastern US seaboard are either one or two fish per day (ASMFC 2019). In the southern Gulf Striped Bass fishery, the pool of recreational anglers is unknown and unrestricted since there is no licence requirement to fish in tidal or marine waters. Relaxing the slot limits may provide more opportunity for individual anglers to retain the daily limit however in the absence of catch and effort data and monitoring of the recreational fishery, it is not possible to assess the extent to which the current recreational fisheries rules are limiting the harvests of Striped Bass in the recreational fishery.

A slot size is currently used in the recreational (and pilot commercial) fishery for Striped Bass which inevitably leads to catch and release of fish that are outside the slot for retention. Catch and release fishing is likely to be practiced regardless of size limit strategies. According to creel survey data and from anecdotal reports, some anglers in the southern Gulf will release upwards of 100 fish or more in a daily fishing trip particularly when bass are aggregated prior to or at spawning time in the Miramichi River. A catch and release mortality rate of 9% is used in the coastwide Striped Bass assessment of the US but it is recognized that the mortality rate depends upon fishing gear, water temperature, maturity state and angler practices (Millard et al. 2005; NEFSC 2019). When examined in these analyses, the consequence of including or excluding catch and release mortality on the development of MSY references and reference points was inconsequential; reference point values were indistinguishable between fisheries strategies (Table 6.5) due to the large uncertainties in the estimated population dynamics parameters. That does not mean however that catch and release has no effect on survival and abundance of Striped Bass. The mortality consequences of the catch and release fishery are unknown since there are no estimates of catches or harvests in the recreational fishery for Striped Bass (DFO 2011). In addition, a large amount of catch and release fishing occurs on fish during a stressful period as they come out of a winter fast and are physiologically switched to spawning.

The intent of the slot size is to a) to provide an opportunity for the fish to spawn once before being vulnerable to retention, and b) to protect older fish with high fecundity and hence guard against successive year classes of poor recruitment. Gwinn et al. (2015) discussed fishing strategies for competing objectives of different fishery users, as for example, when the number of fish harvested, rather than total weight, is the fishery preference. This could be the case in recreational fisheries where the preference is access to a high number of acceptably sized fish rather than maximizing the weight of fish captured; the latter objective may be more relevant for commercial fisheries. Gwinn et al. (2015) concluded that a slot size was superior to a minimum size strategy as a compromise regulation for achieving these competing objectives. Ahrens et al. (2020) assessed the performance of minimum size and slot size strategies relative to competing conservation and fisheries objectives and concluded that harvest slots were the optimal harvest regulation under multiple fisheries objectives (biomass yield, yield in number, trophy catch, and catch rates). The tradeoff between yield in weight and yield in number is shown in the results of the equilibrium analysis of fisheries strategy effects (Table 6.4); the slot size of 30 to 65 cm FL results in the highest catch number but the lowest catch weight at MSY of the fishery strategies examined. Indeed the lower the minimum size, the more yield in number can be extracted. Of importance in the discussion about reference points is that, with the available data and models, there was no difference in the reference point outcomes among the three management strategies examined. The uncertainty intervals greatly overlapped among the fisheries strategies, however, this would not be the case if the population dynamics information was more precisely known.

Based on the currently available information on the proportion female by fork length (Figure 3.7), a minimum slot size of 47 cm FL provides substantial protection from harvesting for male bass but less protection for females. A minimum size of 55 cm FL would provide better protection to first spawning of female bass.

The protection of larger and older Striped Bass, achieved through a maximum size for retention, is important for several reasons. Although it was assumed in our analyses that fecundity of Striped Bass is a linear function of weight and that egg value was similar regardless of female size, it has been widely discussed in literature that maternal effects on early life stage survival and recruitment are important in fish and in particular the value of older and larger females in the spawning population may be disproportionate to their numerical egg contribution (Barneche et al. 2018). The combination of high fecundity and iteroparity of Striped Bass are indicative of a species with high mortality in the early stages. Inter-year class variability in Striped Bass has been observed to be high, largely determined during the egg and larval stages and influenced by environmental factors (see references within Richards and Rago 1999; Uphoff 1989; Rutherford et al. 2003). Hence the importance of maintaining an abundance of older and larger spawners to take advantage of intermittent favourable environmental conditions that can produce large year classes, which can be realized with a maximum size limit fishing strategy. A maximum slot size of 61 cm FL reduces the selectivity to the fisheries to values less than 10% for Striped Bass 8 years and older (Figure 6.3).

6.3.5. Multi-Species Considerations

DFO (2019) developed a policy to support rebuilding plans under the precautionary approach framework for stocks that are in the critical zone. DFO (2019) states that in cases where rebuilding of a stock has the potential to negatively impact the status of another, as in the case of rebuilding a predator species that could result in a decline of a prey species, rebuilding objectives need to be carefully developed through a balanced approach to ensure neither is depleted to a point of serious harm. Most importantly DFO (2019) acknowledge that it is not possible to simultaneously achieve yields corresponding to MSY predicted from single-species assessments for a system of multiple, interacting species and rebuilding efforts should be approached within an ecosystem context to the extent possible.

The reference points and management strategies discussed in this working paper are based on single species management approaches for the purpose of optimizing utility functions specific to Striped Bass. The Striped Bass population of the southern Gulf has increased in abundance, out of the critical zone as presently proposed. Striped Bass is large bodied and a piscivorous predator of other valued anadromous fisheries species in the southern Gulf of St. Lawrence. Concerns have been expressed by Atlantic Salmon fishery advocates as well as some gaspereau and Rainbow Smelt commercial fishery interests that the rebuilding of Striped Bass stock in the southern Gulf has contributed to declines in abundances of Atlantic Salmon and other diadromous species because of high levels of predation on these species by Striped Bass. Similar concerns were expressed about the impact of the recovered Atlantic Coast Striped Bass on its prey-base and NEFSC (2019) summarize a number of analyses that examined the potential for Striped Bass to deplete prey populations along the Atlantic Coast. To date, no multi-species reference points or management plans have been proposed for the US situation.

One of the objectives of this review was to consider approaches and potential reference points for Striped Bass that take account of these ecosystem considerations. This objective is considered by Chaput (2022). The cautionary note from DFO (2019) is worth repeating here: it is not possible to simultaneously achieve yields corresponding to MSY predicted from single-species assessments for a system of multiple, interacting species. Thus, any multi-species management approach will be a compromise of competing single species objectives.

7. UNCERTAINTIES AND KNOWLEDGE GAPS

Although there are substantial empirical observations to characterize the life history parameters of the population of Striped Bass from the southern Gulf including the weight at length relationship, the size at age relationship, and mortality rates, a number of knowledge gaps and uncertainties remain.

7.1. ASSUMPTIONS AND OBSERVATIONS OF LIFE HISTORY

7.1.1. Size at Age Information

Age of Striped Bass in this population is determined based on interpretations from scales. Age interpretations from scales are considered to be sufficient for fish that are less than 8 or 10 years old whereas otoliths are considered more reliable at estimating the age of older fish (Secor et al. 1995; Liao et al. 2013). The oldest age interpreted using scales from samples of the southern Gulf to date is 15 years. The oldest reported age of Striped Bass in eastern US seaboard is 31 years (NEFSC 2019). If scale age interpretations underestimate the ages of Striped Bass, then the growth rates from the von Bertalanffy model would be overestimated, which would have the consequence of underestimating the abundance of older fish in the population and underestimating the fishery selectivity at age profiles. The consequences of this bias on modelled estimates of total mortality and subsequently on derivation of reference points has not been examined. There is limited information from tagging and recaptures of Striped Bass that validates the relatively slow growth rate of fish after age 7: for example a Striped Bass tagged in 2006 measuring 67.6 cm with an age interpretation of 7 years was recaptured and sampled in 2013 and was measured as 83.7 cm, an increase of 16 cm over 7 years (DFO 2014). Other tag and recapture data can provide validation for the growth rate of bass of different sizes and ages from the Miramichi.

The longest recorded Striped Bass from sampling in the Northwest Miramichi is 116 cm fork length. There are anecdotal reports of catches of very large bass in the southern Gulf of St. Lawrence. In the eastern US populations of Striped Bass, fish exceeding 180 cm total length are not considered exceptional (NEFSC 2019). Size distributions of spawners are described from sampling of bycatches of Striped Bass from commercial gaspereau fishery trapnets and at DFO index trapnets in the Northwest Miramichi (DFO 2020). The commercial gaspereau and DFO trapnets are not considered size restrictive; catches of large bodied Atlantic salmon exceeding 100 cm fork length are frequent and there are a few recorded catches of Atlantic Sturgeon in the 4 foot (120 cm) length range. The trapnets are set from shore and do not cover the deeper channel areas of the Northwest Miramichi. If larger and older Striped Bass preferentially use these deeper areas, then they would not be available for capture in the trapnets. The extent of the potential undersampling of larger fish is not known but there is some evidence that this not an important issue. Since 2015, there has a Striped Bass fishing derby in the Miramichi River in late May that targets the pre-spawning and spawning aggregations of Striped Bass. Tournament participants are allowed to high grade the catches before submitting them for registration and so those catches would be biased to the larger fish angled by parties. Extensive fishing effort by recreational fishing parties in 2019 recorded some catches of relatively large bodied fish. The data provided by the tournament organizers was aggregated by fishing party into total weight and number of fish. Based on these data, the highest mean weight per fish recorded was from an aggregate of two fish weighing 22 kg giving a mean weight of 11 kg which would be equivalent to an average fork length of 97 cm. Of the 262 fish submitted by parties, approximately 10 were estimated at mean lengths exceeding 90 cm and 70% of the average weights of fish were less than 6 kg (equivalent to 79 cm fork length).

There is evidence from literature that growth rate and size at age profiles differ for males and females, particularly after the attainment of maturity for which males are comparatively smaller at age than females (Chaput and Robichaud 1995; NEFSC 2019). The population model used in this study does not track abundance at age by sex nor does the assessment model for Striped Bass for the eastern seaboard of the US. At least in the context of estimating egg production at age, it is the mean size at age of females which would be important and using a growth function that ignores sex would result in an underestimate of size at age for females, and therefore eggs at age if females are larger at age than males. Selectivity at age to the fishery, used in equilibrium modelling to derive MSY reference values, would also be affected by differences between the sexes in growth rate and size at age. The amount of bias introduced to the estimates of spawner abundances at age and to the equilibrium model assumptions of ignoring differences in size at age by sex is not known. Incorporating differences in size at age by sex would require a different model structure from one used in this analysis.

Estimation of the von Bertalanffy growth parameters was based on samples of length and age of Striped Bass collected in May and June with the majority sampled from the spawning area in the Northwest Miramichi. Within an age group, if the probability of maturing is size dependent, with faster growing fish maturing earlier, then the use of size and age data from samples of spawners may result in an overestimation of size at younger ages, particularly ages 3 and 4. The consequences of this sampling bias on von Bertalanffy model growth parameters has not been examined.

7.1.2. Age at Maturity and Proportions of Recruits on the Spawning Grounds

There are no data with which to directly estimate the age or size at 50% maturity because there are no representative samples of bass at all states of maturity in the spring. The maturation schedule of male and female bass was assumed with males maturing earlier than females. The earlier maturation at age of male bass is supported by observations of the sex ratio of fish on the spawning grounds which indicate a predominance of males at age 3 and age 4 and equal male to female proportions for fish age 6 and older. In the population model, the parameter that is estimated is the proportion of the recruits at age that are on the spawning grounds. This parameter is a combination of proportion at age that are mature by sex and the proportion of mature individuals by sex that are spawners in the Miramichi. If such information was available and there was evidence of differences between males and females, then this could be considered but it would require a different age structured model than the one considered here.

The proportion female at age is assumed known in the model and is calculated directly from the assumed maturation profiles of male and female bass. This proportion seems appropriate as it corresponds to the proportion female at length from sampling of fish in May and June of 2013 to 2015.

It is assumed and modelled that not all mature Striped Bass are on the spawning grounds in the Northwest Miramichi. This inference is supported by observations of Striped Bass, some in ripe condition (males and females), in other estuaries of New Brunswick and Nova Scotia in May and June. It also includes the phenomenon of skipped spawning in which fish forego egg production until the subsequent year. Skip spawning has been reported in eastern US Striped Bass populations (Secor 2008; Gahagan et al. 2015; Secor et al. 2020) and inferred for fish from the Miramichi that had been detected off the coast of Labrador in 2017, had returned and overwintered in the Miramichi in 2017/2018 and subsequently based on behaviours from acoustic tag detections had left the Miramichi in early spring 2018 prior to spawning. These fish survived, overwintered in Miramichi in 2018/2019 and were inferred to have spawned in 2019 but not in 2018.

7.1.3. Assumptions of Fecundity at Age

The fecundity at age used in the model is a coarse approximation of fecundity values reported elsewhere. There have been efforts to collect fecundity estimates from the southern Gulf of St. Lawrence population but the analysis of these data is incomplete. Bias in the assumed fecundity at age values would bias the estimation of the Beverton-Holt stock and recruitment parameters; if fecundity was underestimated, this would result in a positive bias for the slope at the origin whereas if fecundity was overestimated, there would be the opposite effect. The direction of bias of the assumed fecundity values relative to population specific fecundities for this population is not known.

7.2. ASSUMPTIONS ON NATURAL MORTALITY AND CONSTRAINTS

Natural mortality (M) rates are difficult to estimate in most circumstances.

The acoustic tagging and tracking data provide estimates of total mortality of larger Striped Bass. It is recognized that those estimates may also include some fishing related mortality however the estimates of Z at a median value of 0.22 in recent years is strongly indicative that instantaneous natural mortality is very likely no higher than 0.2. The natural mortality value of 0.15 used in the assessment of Striped Bass on the eastern seaboard of the US is lower than what assumed in these analyses. However, there is good reason to expect natural mortality to be higher in this northern population of the southern Gulf of St. Lawrence. Douglas et al. (2006) provided information on factors that could contributed to non-fisheries related mortality.

The environment, in particular during the winter, is an important driver of the population dynamics of Striped Bass in the southern Gulf St. Lawrence. As stated in the introduction, the southern Gulf of St. Lawrence Striped Bass population is the only population where avoidance of lethal marine conditions (sub-zero water temperatures) during winter is an obligate element of its life history. The southern Gulf of St. Lawrence is a geographic region in which the coastal and estuary surface waters freeze during the winter. Rainbow Smelt, Atlantic Tomcod, and Atlantic Herring (juveniles) can produce anti-freeze proteins which lowers the freezing point of the blood thus allowing these fish to overwinter in the nearshore areas. Striped Bass do not produce these proteins and hence must overwinter in the upper estuaries near the hide of tide where the water temperatures remain above 0 ºC.

Douglas et al. (2006) identified winter thermal plumes associated with industrial infrastructure in the southern Gulf as potential contributors to winter mortality of Striped Bass. Large numbers of Striped Bass were regularly drawn to the thermal effluents of the power generating station at Trenton (NS), Dalhousie, and Belledune (NB), during late fall and winter and anglers targeted these warm water effluents because of the large concentrations of Striped Bass which seemingly continued to feed at that time of year (Douglas et al. 2006). Well over 1,000 striped bass were estimated to have died at the outflow of the Trenton (NS) station in February 2004. The cause of the fish kill was believed to be the result of an acute reduction in water temperature when the power generating station went off line and the thermal discharge was turned off (Douglas et al. 2006). Buhariwalla et al. (2016) provide details of a similar fish kill that occurred in January 2013 for the same reason; the maximum daily water temperature recorded at the discharge point before the fish kill was 12.8 °C but declined to -2.5 °C during the cold-shock event three days later. The Dalhousie NB generating station which was identified by

Douglas et al. (2006) as another source of thermal effluent utilized by Striped Bass was demolished in 2015. The thermal generating station at Belledune (NB) remains operational. There were other thermal plumes in the Miramichi, associated with pulp and paper mill discharge in the lower portion of the Northwest Miramichi; that mill closed permanently in December 2007.

Striped Bass also fast during the overwintering period and Striped Bass mortalities have been reported in some estuaries and rivers soon after ice-out. Bradford and Chaput (1998) indicated that there had been reports of Striped Bass mortalities in April and May 1997, particularly from the Richibucto River area, shortly after ice-out. The absolute number of losses in the spring of 1997 was not quantified however one mortality was examined by the DFO Fish Health Laboratory (Moncton) and no bacterial pathogens were isolated. Bradford et al. (2001b) reported that dead and moribund striped bass sampled on the Napan River (Miramichi Bay tributary) during early May 1997 were emaciated in appearance, devoid of visceral fat deposits, and exhibited atrophied digestive tracts, suggesting fish had starved.

We have no information on the natural mortality rate of young bass. Natural mortality for young age groups, 0 to 2 years, is expected to be relatively high and a general relationship relating growth parameters from von Bertalanffy relationship to M was used to provide informative priors for population modelling. High M for juvenile Striped Bass is expected because of their small body size which makes them vulnerable to a diversity of predators including Striped Bass in some circumstances (Buhariwalla et al. 2016). Small bodied fish are also more susceptible to overwinter mortality; small bodied fish may have insufficient energy reserves to survive the overwintering fast period that can extend from late October to late April. Harsh environmental conditions can also lead to mortalities, juvenile bass have been observed frozen in the ice (S. Douglas, DFO, pers. comm.).

Reductions in the intensity of a number of anthropogenic stressors likely contributed to improved survival which assisted in the rebuilding of abundance of Striped Bass. The reductions include the elimination of at least two (Dalhousie, Miramichi) thermal effluent discharges. Waste water effluents from industrial and municipal facilities are widespread throughout the southern Gulf, but their effect on striped bass or striped bass habitat is unknown (Douglas et al. 2006). Sites of particular interest in the southern Gulf were reviewed by Robichaud-LeBlanc et al. (2000). Burton et al. (1983) demonstrated significant mortality of striped bass larvae after a 72-h exposure to bleached kraft mill effluent. The number of industrial facilities discharging chemical effluents in the southern Gulf that were identified in the recovery potential assessment of 2006 (Douglas et al. 2006) has been reduced. The facilities which have closed include the paper mill at Dalhousie (NB), two mills in the Miramichi River, and more recently a mill at Pictou (NS).

7.3. ASSUMPTIONS OF STOCK STRUCTURE

There is compelling evidence that the Northwest Miramichi River is the major spawning area of for the Striped Bass population of the southern Gulf of St. Lawrence. Through the years, DFO has reported on the tagging of Striped Bass in various rivers of the southern Gulf and their subsequent recaptures on the spawning grounds of the Northwest Miramichi (DFO 2014). There have been consistent detections in the Northwest Miramichi of bass acoustically tagged from the Gaspe region and from Pictou (NS) illustrating the wide distribution range of Striped Bass in the southern Gulf and the affinity to the Miramichi River spawning area (see Table 3.8). Striped Bass tagged from the eastern boundary of the southern Gulf (Margaree River NS) to Gaspe on the western edge of the southern Gulf and locations in between have subsequently been recaptured in the Northwest Miramichi, strengthening the evidence of broad regional distribution of fish in the southern Gulf. Added to this, the evidence on the outdispersion from the Northwest

Miramich and the distribution of juveniles in other estuaries and rivers, makes the Northwest Miramichi spawning area the most important feature for production of Striped Bass.

Alternative historical spawning areas in the southern Gulf of St. Lawrence have been advocated in literature (Rulifson and Dadswell 1995; Andrews et al. 2019a) although there is no published evidence to date of annual spawning and successful recruitment from these locations. In the past two years, corresponding to a period of high Striped Bass spawner abundance, non-government organisations sampled and reported the presence of Striped Bass eggs and larvae from the Southwest Miramichi River and the Tabusintac River tidal areas, (M. Hambrook, Miramich Salmon Association, pers. comm.; Andrews et al. 2019a). Intense spawning activities were also reported from the Southwest Miramichi near the head of tide at Quarryville in spring 2020 (T. Tunney, DFO personal communication). Expansion of observations of spawning activities would be expected as the overall spawner abundance increases. Striped Bass spawning can be established in new areas, as evidenced by the colonization event of the southern Gulf by Striped Bass with the Holocene glacial retreat and the spawning and recruitment of Striped Bass in new contemporary spawning areas of the St. Lawrence River (DFO 2017). The consequence to population modelling results of the establishment of new spawning areas is that the asymptotic abundance would increase due to a higher carrying capacity although density independent survival rates from eggs to age-0 in summer would be expected to remain as estimated.

7.4. ASSUMPTIONS ON DENSITY DEPENDENT STOCK AND RECRUITMENT RELATIONSHIP

Based on the available observations, the stock and recruitment dynamic between eggs and abundance at age-3 is adequately described by a proportional function or Beverton-Holt stock and recruitment function. The near monotonic increasing trajectory of the population abundance from its low point in the late 1990s to the highest abundance in the late 2010s provides limited information to unequivocally define the asymptotic population size.

We preferentially chose a model that incorporates a limit to the carrying capacity for the southern Gulf population of Striped Bass. Based on literature, life history, and the geographic area where spawning occurs, we chose a model that set the carrying capacity limit at the early juvenile (age-0, summer) phase. The spawning / nursery habitat and food base for the larvae and post-metamorphosis juveniles are constrained to a relatively small tidal area in the Northwest Miramichi.

The model (model 6) that considered the egg to age-3 recruitment directly provides a different perspective on asymptotic abundance at age-3 and total abundance of the population. The difference in model outputs using the same observational data cannot be explained, other than by weak evidence for density dependence from available data. It is possible that the abundance of Striped Bass could continue to increase to levels indicated by model 6 of almost 1 million spawners at age 3 (Table 4.3), 4.8 million spawners and 7.8 million fish (age 3+) at B_{MSY} as the full productive potential for this population has yet to be realized.

7.5. TIME SERIES CONSIDERATIONS

As mentioned previously, the near monotonic increasing trajectory of the population abundance from its low point in the late 1990s to the highest abundance in the late 2010s provides limited information to unequivocally define the population dynamics parameters of the population model. The recruitment from the 2017 to 2019 spawner abundances have not been assessed with 3-year olds from the 2017 spawning first available for assessment in 2020, and the other year-classes in 2021 and 2022. The fork length distributions of Striped Bass in the fall of 2019 suggest a small mode at just under 35 cm FL, which would be 3-year old fish in May 2020, however, such modes at small fork lengths have been noted in previous years but the cohort tracking of these modes is not convincing (see Figure 3.4 but also Figure 3.9 which is the cohort decline analysis).

The assessments of spawners as published in DFO (2020, and previous years) are assumed to be unbiased albeit highly uncertain estimates of the true spawner abundances. The assessment model uses the commercial gaspereau fishery platform to obtain abundance indices by individual trapnet which are then raised using trapnet specific catchability indices estimated from tag and recapture experiments to estimate total abundance. There is a large contrast in catch rates of Striped Bass in these trapnets over the 1994 to 2019 time period (Figure 3.1) that are consistent with the assessed increase in abundance. In recent years, as the commercial gaspereau trapnets began fishing somewhat later to optimize the catch of gaspereau which is the target species, movements of acoustically tagged bass have been used to infer the proportion of the total spawners present in the commercial gaspereau fishing area when the fishery began.

DFO (2020) provides supplementary indices independent of the commercial gaspereau fishery catches that corroborate the trend of increased abundance of Striped Bass over this period. Specifically, index estuary trapnets installed and monitored by DFO Science in the Southwest Miramichi and in the Northwest Miramichi are used to assess the abundance of numerous anadromous species in the Miramichi River (Hayward et al. 2014). Catches of Striped Bass in the months of May and June show an important increase in abundance, however, the data for May should be interpreted with caution as the installation dates of these trapnets for sampling upstream migrating fish have varied among years. The sum of daily catches in the month of June increased over the period of sampling at both locations and with generally higher catches, particularly in the recent decade, recorded at the Northwest Miramichi trapnet located in the Striped Bass spawning area (Figure 7.1). Trapnet catches in the autumn have also greatly increased over the time period with the strongest signal for the month of October in the Northwest Miramichi and for the months of September and October in the Southwest Miramichi. Contrary to the spring, the highest catches in the fall are consistently recorded at the Southwest Miramichi index trapnet as Striped Bass return to the Miramichi River to overwinter (Figure 7.1).

7.6. FISHERIES RELATED LOSSES AND MANAGEMENT OPTIONS

There are no complete fishery catch data for Striped Bass in the southern Gulf of St. Lawrence.

Historically, fisheries statistics included only commercial harvests, exclusive of recreational and Indigenous peoples fisheries harvests.

It was noted previously that Striped Bass is particularly vulnerable to fisheries in estuaries of the southern Gulf of St. Lawrence. Although the fisheries on Striped Bass were essentially closed in 2000, DFO (2011) indicated that large numbers in the tens of thousands of Striped Bass of various life stages were intercepted in a variety of illegal fisheries, commercial fisheries, and aboriginal FSC fisheries. The activity with the greatest contribution to the total loss of Striped Bass was considered to be the illegal fishery followed by the recreational fishery (DFO 2011).

The recreational fishery for Striped Bass in the southern Gulf has a large component of catch and release, in part due to the mandatory slot size restrictions for retention but also associated with the fishing practices of individual anglers that favour a lot of angling activity without intent to retain. In the eastern US, catch and release represented 85% to 90% of the total catch (retained plus released) of Striped Bass during 2015-2017 and annual losses from catch and release . averaged 2.9 million fish during 2015 to 2017, approximately equivalent to the retained catch of 2.9 to 3.5 million for those same years (NEFSC 2019). There are differences in management measures between jurisdictions; notably the use of natural bait is prohibited in the recreational fishery in Quebec but natural bait, usually in the form of chunks of mackerel or other fish placed on hooks, is permitted in DFO Gulf Region. A catch and release mortality rate of 9% is also assumed, as used in the coastwide Striped Bass assessment of the US. Catch and release mortality rate depends upon fishing gear, water temperature, maturity state and angler practices (Millard et al. 2005; NEFSC 2019). The analysis of consequences of these fishing practices on population abundance and reference points cannot be assessed in the absence of such data.

Young of the year (YOY) Striped Bass remain susceptible to capture in the openwater autumn and winter fishing gears (boxnets and gillnets) set for Rainbow Smelt throughout the southern Gulf of St. Lawrence. Prior to the delayed opening of the fall openwater smelt fishery in the Miramichi from Oct. 15 to Nov.1, interceptions of you bass were estimated to have been in the hundreds of thousands annually, in the Miramichi river alone, most of which would be dead given the difficulty to sort and release them alive from the large quantities of fish captured in these fisheries (Bradford et al. 1997). The delayed season opening should have reduced the bycatch but no follow-up assessment has occurred.

There are additional anecdotal reports of unregulated mortality in other sectors, including Striped Bass being kept and used as bait in the lobster fishery. Striped Bass have also increased in abundance in the freshwater portions of larger rivers such as the Miramichi and Restigouche and there are numerous reports of bass being angled and killed via discarding in the woods from these inland areas.

In the absence of any monitoring of recreational catches and harvests, it is not possible to provide fisheries management advice in terms of total allowable catches nor can the status of the population relative to removal rates be assessed. In the absence of catch and harvest data from all the fisheries, the best that could be done is to track the response of the population abundances to variations in fisheries management strategies. Assessments of spawner abundances are usually provided in the fall to early winter of the spawning year and management plans are established based on the past year’s abundance. This approach, used to date for management of Striped Bass of the southern Gulf of St. Lawrence results in low risk to the population if exploitation rates are relatively low. The abundance trajectory of this population indicates that to date, the exploitation rate has been less than the surplus production of the population.

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TABLES

Table 2.1. Management milestones for Striped Bass fisheries from the southern Gulf of St. Lawrence, 1992 to 2013.

Year	Commercial	Recreational	Indigenous FSC
Prior to 1992	Gillnet licences (mesh restriction 127 mm) Bow net fishery open Incidental catches retained and marketed	No retention of bass < 38 cm Total Length (TL), unless in Kent Co. waters	> 68 cm TL
1992	DFO conservation strategy written: - closure of all directed fisheries - incidental catches of bass > 38 cm TL to be released - bycatch tolerance for bass < 38 cm in gaspereau and smelt fisheries - bow net fishery designated as recreational, with recreational bag limit and size restrictions	July 1 to Oct. 31 One bass per day > 68 cm TL	> 68 cm TL
1993	DFO conservation strategy implemented	July 1 to Oct. 31 One bass per day > 68 cm TL	July 1 to Oct. 31 > 68 cm TL
1994	DFO conservation strategy implemented	July 1 to Oct. 31 One bass per day > 68 cm TL	July 1 to Oct. 31 > 68 cm TL
1995	Release of bass > 38 cm not imposed Some voluntary release of spawning fish in Miramichi (May – June) 17 t recorded harvest	July 1 to Oct. 31 One bass per day > 68 cm TL	> 68 cm TL
1996	Commercial fisheries closed Sale of wild caught Striped Bass prohibited Tolerance limit for retention but not sale of bass < 35 cm TL in gaspereau and smelt fisheries 15 t recorded harvest	Hook and release only May 1 to Oct. 31	July 1 to Oct. 31 Size restrictions lifted (impractical because of gillnets)
1997	Commercial fisheries closed Sale of wild caught Striped Bass prohibited Tolerance limit for retention but not sale of bass < 35 cm TL in gaspereau and smelt fisheries	Hook and release only May 1 to Oct. 31	July 1 to Oct. 31
1998	Commercial fisheries closed Sale of wild caught Striped Bass prohibited Tolerance conditions revoked, no retention of bycatch of any size	Hook and release only April 15 to Oct. 31 (opening corresponds to opening date of black salmon and trout fishereries)	July 1 to Oct. 31
1999	Commercial fisheries closed Sale of wild caught Striped Bass prohibited Tolerance conditions revoked, no retention of bycatch of any size	Hook and release only April 15 to Oct. 31	July 1 to Oct. 31

Year	Commercial	Recreational	Indigenous FSC
	Delayed opening to Nov. 1 (from Oct. 15) of fall openwater smelt boxnet fishery in Miramichi		
2000	Continued from 1999	Inland and coastal waters closed to directed fishing for Striped Bass	FSC allocations suspended
2012	Continued from 1999	Inland and coastal waters remain closed to directed fishing for Striped Bass	Re-instatement of Indigenous FSC allocations
2013	Continued from 1999	Re-opening of retention fishery	FSC allocations maintained

Table 2.2. Recreational fisheries management measures for Striped Bass since the re-opening of the fishery in 2013. (see DFO 2016 for management breakdown in 2013 to 2015).

Year	Region	Season for tidal waters	Retention days	Daily bag limit	Retention size limit	Notes
2012	DFO Gulf	Closed	na	na	na	na
2013	DFO Gulf	May 1 to Sept. 30	25	1	55 – 65 cm TL	na
	Prov. of Quebec (Chaleur Bay; Zone 21)	June 15 - Sept. 30	0	0	na	Catch and release only Single hook
2014	DFO Gulf	May 1 to Sept. 30	53	1 (May 1-21) 2 (May 22-25)* 1 (Aug. 1-21) 1 (Sept. 24-30)	50 – 65 cm TL	*Due to cold weather and poor angler success, the retention period in May 2014 was extended for four days to May 25. During this extension, anglers were permitted to retain two Striped Bass per day and possess no more than two at any given time.
	Prov. of Quebec (Chaleur Bay; Zone 21)	June 15 - Sept. 30	30 (July 26 – Aug. 24)	1	< 65 cm TL	Single hook maximum 3 per line Artificial lures only, bait prohibited
2015	DFO Gulf	May 1 to Oct. 31	56 May 11 – 31 Aug. 1 – 23 Sept. 4 – 7 Oct. 24 - 31	1	50 – 65 cm TL	na
	Prov. of Quebec (Chaleur Bay; Zone 21)	June 15 - Sept. 30	56 (July 1 – Aug. 25)	1	50 – 65 cm TL	Single hook maximum 3 per line Artificial lures only, bait prohibited
2016	DFO Gulf	May 1 to Oct. 31	104	1	50 – 65 cm TL	na
	Prov. of Quebec (Chaleur Bay; Zone 21)	June 15 - Oct. 31	109 ((July 1 – Aug. 26; Sept. 9 – Oct. 31)	1	50 – 65 cm TL	Single hook maximum 3 per line Artificial lures only, bait prohibited
2017	DFO Gulf	April 15 to Oct. 31	200 (April 15 to Oct. 31)	1(April 15 – June 14) 2 (June 15 – Aug. 31) 1 (Sept. 1 – Oct. 31)	50 – 65 cm TL	na

Year	Region	Season for tidal waters	Retention days	Daily bag limit	Retention size limit	Notes
	Prov. of Quebec (Chaleur Bay; Zone 21)	June 15 - Oct. 31	139 (June 15 - Oct. 31)	2	50 – 65 cm TL	Single hook maximum 3 per line Artificial lures only, bait prohibited
2018	DFO Gulf	April 15 to Oct. 31	200 (April 15 to Oct. 31)	3	50 – 65 cm TL	na
	Prov. of Quebec (extended Zone 21)	June 15 - Oct. 31	139 (June 15 - Oct. 31)	3	50 – 65 cm TL	Single hook maximum 3 per line Artificial lures only, bait prohibited Extension of Zone 21 upstream in St. Lawrence River to a line approximately joining Rimouski and Forestville and extending to the north shore of the St. Lawrence, including Magdalene Islands
2019	DFO Gulf	April 15 to Oct. 31	200 (April 15 to Oct. 31)	3	50 – 65 cm TL	ns
	Prov. of Quebec (extended Zone 21)	June 15 - Oct. 31	139 (June 15 - Oct. 31)	3	50 – 65 cm TL	Same as 2018 Including in most rivers that flow into Zone 21

Table 2.3. Summary of spawning area closures to all recreational fisheries activities on the spawning grounds of the Northwest Miramichi, 2017 to 2020.

Year	DFO Gulf Region Variation Order	Start Date	End Date	Total days of closure	Length of spawning area closed
2017	GVO-2017-038	1 June	9 June	9	9.8 km
2018	GVO-2018-032	4 June	8 June	5	6.5 km
2019	GVO-2019-035	5 June	9 June	5	6.5 km
2020	GVO-2020-044	28 May	1 June	5	6.5 km

Table 2.4. Recorded landings (t) of Striped Bass from the fisheries statistical districts that are located in the vicinity of the Miramichi River, and overall in the southern Gulf of St. Lawrence. Data for the period 1917 to 1988 are from LeBlanc and Chaput (1991). Data for 1989 to 1994 are from Bradford et al. (1995a). There were no recorded landings for the years 1935 to 1967. Detailed harvests by statistical districts in DFO Gulf NB as well as by season and regions are provided in Bradford et al. (1995a) and Douglas et al. (2003). "ns" means no information specified.

	Miramichi area districts						Southern
Year	68	70	71	72	73	Total	Gulf
1917	8.2	ns	4	0.4	1.5	14.1	61.4
1918	7.2	ns	1.1	4.5	1.5	14.3	54.4
1919	4.1	0.5	1.2	2.3	3.6	11.7	33.7
1920	17.3	ns	2.2	0.5	4.2	24.2	28.3
1921	1.1	ns	1.5	ns	2.7	5.3	15.9
1922	1.4	ns	1.2	ns	ns	2.6	19.1
1923	0.9	ns	0.2	ns	5.4	6.5	25.5
1924	ns	ns	0.9	7.2	ns	8.1	39.8
1925	0.9	ns	0.7	0.4	4.1	6.1	22.1
1926	ns	ns	1.9	0.4	ns	2.3	20.0
1927	ns	ns	ns	ns	6.5	6.5	22.8
1928	ns	ns	0.2	ns	3.7	3.9	10.3
1929	ns	ns	ns	ns	1.7	1.7	5.8
1930	ns	ns	0.5	0.5	0.9	1.9	4.0
1931	ns	ns	ns	0.5	0.9	1.4	3.2
1932	ns	0.8	ns	0.5	1.1	2.4	3.9
1933	ns	0.2	ns	0.1	ns	0.3	0.7
1934	ns	ns	ns	0.3	ns	0.3	0.4
1935	ns	ns	ns	ns	ns	ns	ns
1967	ns	ns	ns	ns	ns	ns	ns
1968	ns	0.4	1.8	1.1	0.1	3.4	8.2
1969	ns	0.1	0.4	1.6	0.1	2.2	9.4
1970	0.1	2.6	0.9	3.4	0.4	7.4	10.6
1971	ns	0.7	1.4	8.5	0.4	11	13.3
1972	ns	0.1	1.8	3.4	0.5	5.8	8.8
1973	ns	0.2	0.1	3.8	ns	4.1	6.1
1974	0.1	ns	0.3	3.6	ns	4	5.4
1975	0.7	3.2	1	ns	ns	4.9	7.2
1976	0.1	1.9	1.6	3.1	ns	6.7	8.6
1977	ns	0.9	1.2	ns	ns	2.1	5.1
1978	ns	1.5	ns	ns	ns	1.5	5.1
1979	0.1	2.2	1.2	ns	ns	3.5	6.8
1980	0.1	9.7	2.9	ns	ns	12.7	15.3
1981	0.9	5.5	4.7	ns	ns	11.1	47.8
1982	1	3.8	2.4	ns	ns	7.2	32.4
1983	2	3	6.9	ns	0.1	12	23.4
1984	0.1	9.9	2.2	ns	ns	12.2	17.3
1985	0.8	2.3	8	ns	ns	11.1	22.0
1986	2.2	3.5	ns	ns	ns	5.7	12.5
1987	ns	0.6	ns	ns	0.1	0.7	2.3
1988	0.1	2	0.9	ns	ns	3	4.1
1989	ns	ns	0.1	ns	ns	0.1	4.0
1990	ns	ns	0.1	ns	ns	0.1	1.0
1991	ns	ns	0.1	ns	ns	0.1	1.3
1992	ns	ns	0.5	ns	ns	0.5	8.9
1993	ns	ns	ns	ns	ns	ns	0.6
1994	ns	ns	ns	ns	ns	ns	1.0
1995	ns	ns	ns	ns	ns	ns	17.3
1996	ns	ns	ns	ns	ns	ns	15.25

Table 2.5. Summary of available estimated recreational fisheries catches since the re-opening of the Striped Bass recreational fisheries in the Gulf of St. Lawrence in 2013 to 2015. Data for 2013 are from DFO (2014) and data for 2014 are summarized in DFO (2015a).

Year	Management authority / daily limit	Survey period	Estimated fish retained Point estimate (95% confidence interval)	Estimated fish released [1]	Estimated total losses due to fishing (assumed 10% mortality from catch and release)
2013	DFO Gulf Region 1 fish per day 55 – 65 cm TL for retention	May 1 – 15 Miramichi River	2,400	29,224	5,322
		Aug. 2 -11 Eight locations in the southern Gulf	244	2,911	535
2014	DFO Gulf Region 1 fish per day 50 – 65 cm TL for retention	17 of 25 days during May 1 to 25 Miramichi River	400	9,637	1,364
		August and September retention periods	na	na	na
	Province of Quebec 1 fish per day < 65 cm TL for retention	July / August	554 (299 to 809)	8,456 (4,865 to 12,047)	1,400 (1,146 to 2,013)
2015	DFO Gulf Region 1 fish per day 50 – 65 cm TL for retention	na	na	na	na
	Province of Quebec 1 fish per day 50 – 65 cm TL for retention	July / August	1,172 (790 to 1,554)	20,797 (14,225 to 27,368)	3,252

[1] for the province of Quebec survey, the value for total catch and release is the value for total catch (retained plus released)

Table 2.6. Characteristics of the recreational fishery in Chaleur Bay, 2014 to 2019. Data for 2014 are presented in DFO (2015a). Data for 2016 to 2019 were provided by Quebec MFFP (unpubl. data).

Year	Management regulation	Catch category	Size group	Percentage of catch category
2014	1 fish per day < 65 cm Total Length for retention	Retained	< 50 cm	27%
			50 – 65 cm	73%
		Released	< 50 cm	33%
			>65 cm	13%
2016	1 fish per day 50 - 65 cm Total Length for retention	Prob. of retaining 1 or more fish		14.2%
		Catch (retained and released)	< 50 cm	69%
			50 – 65 cm	22%
			>65 cm	9%
2017	2 fish per day < 65 cm Total Length for retention	Prob. of retaining 1 or more fish		6.5%
		Catch (retained and released)	< 50 cm	58%
			50 – 65 cm	37%
			>65 cm	5%
2018	3 fish per day 50 - 65 cm Total Length for retention	Prob. of retaining 1 or more fish		22.5%
		Catch (retained and released)	< 50 cm	49%
			50 – 65 cm	44%
			>65 cm	7%
2019	3 fish per day 50 - 65 cm Total Length for retention	Prob. of retaining 1 or more fish		6.5%
		Catch (retained and released)	< 50 cm	55%
			50 – 65 cm	43%
			>65 cm	3%

Table 3.1. Summary of tagging locations, tagging years, as well as overwintering and spawning histories of acoustically tagged Striped Bass with tag identification codes detected at the acoustic receiver line at Port Hope Simpson (Labrador) in 2017. The detections data at the Port Hope line were provided by M. Robertson (DFO Newfoundland and Labrador Region). Striped Bass were tagged in the St. Lawrence and in Gaspe by personnel from the MFFP Quebec.

Location of tagging	Year tagged	Overwinter history	Spawning history	Detected in Labrador	Acoustic detections (n)
St. Lawrence	2015	Never seen in Miramichi	Never seen in Miramichi	28-Sep-17	5
Gaspe	2016	Never seen in Miramichi	Never seen in Miramichi	4-Sep-17	1
Gaspe	2014	Miramichi – 2014/15, 2015/16, 2016/17	Miramichi - 2015, 2016, 2017	5-Sep-2017, 22-Sep-2017	3
Gaspe	2014	Miramichi - 2014/15, 2015/16, 2016/17	Miramichi - 2015, 2016, 2017	30-Aug-2017, 28-Sep-2017	13
Gaspe	2014	Miramichi - 2014/15, 2015/16, 2016/17	Miramichi - 2015, 2016, 2017	29-Aug-17	1
Gaspe	2014	Miramichi - 2014/15, 2015/16, 2016/17	Miramichi - 2015, 2016, 2017	5-Sep-2017, 27-Sep-2017	5
Gaspe	2014	Miramichi - 2014/15, 2015/16, 2016/17, 2017/18, 2018/19	Miramichi - 2015, 2016, 2017, 2019	3-Sep-2017, 22-Sep-2017	6
St. Lawrence	2014	Miramichi - 2016/17, 2017/18, 2018/19	Miramichi - 2017, 2019	29-Aug-17	3
Miramichi	2013	Miramichi – 2013/14, 2014/15, 2015/16, 2016/17, 2017/18, 2018/19	Miramichi - 2015, 2016, 2017, 2019	22-Sep-17	2

Table 3.2. Summary statistics of selected samples of fork length (cm) at scale-interpreted ages of Striped Bass from the Miramichi River used in the von Bertalanffy growth model analysis.

					Posterior summaries of von Bertalanffy predictions		
Age	N retained (available)	Mean (cm)	Std. dev.	CV	Mean (cm)	Std. dev.	Growth increment (cm)
1	71 (71)	17.8	1.5	0.083	17.5	1.5	-
2	200 (562)	28.0	3.2	0.116	29.0	2.6	11.4
3	200 (2606)	40.4	3.6	0.088	38.5	3.4	9.6
4	200 (2542)	46.8	3.9	0.082	46.7	4.2	8.2
5	200 (1485)	52.6	3.9	0.073	53.6	4.8	6.9
6	200 (769)	58.1	4.5	0.077	59.4	5.3	5.8
7	124 (124)	63.6	5.5	0.086	64.4	5.7	5.0
8	94 (94)	69.1	5.3	0.076	68.6	6.1	4.2
9	62 (62)	72.7	5.5	0.076	71.9	6.3	3.3
10	20 (20)	77.1	6.3	0.082	75.0	6.6	3.1
11	21 (21)	78.2	6.3	0.081	77.6	6.8	2.6
12	10 (10)	83.5	5.2	0.062	79.4	6.9	1.9
13	2 (2)	75.5	7.6	0.101	81.4	7.2	2.0
14	5 (5)	78.2	7.2	0.093	82.8	7.4	1.3
15	3 (3)	86.9	16.4	0.189	84.2	7.5	1.4

Table 3.3. Posterior parameter estimates of the von Bertalanffy growth function to fork length (cm) at age (years) data for Striped Bass from the Miramichi River.

			Correlations	
Parameter	Median	5th to 95th percentile	L_∞ to	K to
L_∞ (cm)	90.8	88.5 to 93.3	na	na
K	0.1685	0.1598 to 0.1771	-0.974	-
$a_0 (year)$	-0.2680	-0.3176 to -0.2218	-0.748	0.857
σ (log $scale$)	0.088	0.085 to 0.091	na	na
Pred. length at age 3 (cm)	38.4	33.2 to 44.3	na	na

*Table 3.4. Fork length (cm) to whole weight (kg) relationship for Striped Bass sampled during May and June 2013 to 2105 from the Miramichi River. The equation is: log(WWkg) = intercept + slope * log(FLcm) + ε with ε ~ N(0, sigma^2).*

		Maximum Likelihood	
Sex	Parameter	Mean	Standard error
Combined	Slope	3.0027	0.0094
	Intercept	-11.3428	0.0363
	sigma	0.087	
	N	1,839	
By sex			
Female	Slope	3.0742	0.0156
	Intercept	-11.6014	0.0613
	N	643	
Male	Slope	2.9327	0.0196
	Intercept	-11.0879	0.0760
	N	1,196	
sigma		0.085	

Table 3.5. Number of female and male Striped Bass by age from opportunistic samples collected in May and June in the southern Gulf of St. Lawrence, 1970 to 2018. These could be biased to males because in many cases, the sex was identified by external characteristics (ripe and running) which is more easily detected in males than females.

Age	N - Females	N - Males	Proportion female
2	5	53	0.086
3	32	2053	0.015
4	120	1524	0.073
5	201	487	0.292
6	124	160	0.437
7	41	40	0.506
8	32	18	0.640
9	19	16	0.543
10	8	4	0.667
11	7	7	0.500
12	7	0	1.000
13	0	1	0.000
14	1	2	0.333
15	2	1	0.667

Table 3.6. Summary of assumptions on proportion mature at age and the proportion female at age of spawners for Striped Bass of the southern Gulf of St. Lawrence.

	Age (years)			
Characteristic	3	4	5	6 and older
Proportion mature at age (assumed)				
Male	0.5	0.9	1	1
Female	0.1	0.5	0.9	1
Proportion female at age on spawning grounds assuming similar proportions at age of male and female mature recruits are spawners on the spawning grounds				
Proportion female	0.17	0.36	0.47	0.50

Table 3.7. Predicted M at age of Striped Bass based on the fitted von Bertalanffy growth characteristics and the empirical relationship of M to growth characteristics of Gislason et al. (2010). Mean sizes at age are shown in Table 3.2.

Age	Mid-season mean size (mm) ($L_{a,t}$ to $L_{a+1,\, t+1}$)	Predicted M	Predicted S
0	135 (110 to 160)[1]	1.97	0.14
1	232 (175 to 290)	0.82	0.44
2	337 (290 to 385)	0.45	0.64
3	426 (385 to 467	0.31	0.73
4	501 (467 to 536)	0.24	0.79

[1] Modal length range of young of the year going into their first winter

Table 3.8. Data used in the estimation of survival probabilities from Striped Bass tagged with acoustic tags and detected in the Miramichi River. The data for 2003 to 2009 are from Douglas and Chaput (2011a). N tags is the number of tags from the tagging group detected in the Miramichi that represents the initial number of animals tracked in subsequent years. The size group categories represent the fork length (cm) retention size limits for the recreational fishery, in place since 2014. Fish are assigned to a size group based on their fork length at time of tagging.

Location tagged	Year tagged	Season tagged	Tag type	Size group	N tags	Tags detected in year of inferred survival								
						2003	2004	2008	2009	2014	2015	2016	2017	2018
Miramichi	2003	spring	V16	Total	19	13	na	na	na	na	na	na	na	na
Miramichi	2004	spring	V16	Total	21	na	13	na	na	na	na	na	na	na
Miramichi	2008	spring	V16	Total	20	na	na	14	10	na	na	na	na	na
Miramichi	2009	spring	V16	Total	21	na	na	na	14	na	na	na	na	na
Gaspe	2013	summer	V13	< 46	1	na	na	na	na	1	na	na	na	na
				46 - 61	23	na	na	na	na	22	na	na	na	na
				> 61	15	na	na	na	na	13	na	na	na	na
				Total	39	na	na	na	na	36	na	na	na	na
Miramichi	2013	fall	V16	46 - 61	15	na	na	na	na	12	8	5	5	5
				> 61	21	na	na	na	na	17	15	13	9	9
				Total	36	na	na	na	na	29	23	18	14	14
Gaspe	2014	summer	V13	< 46	3	na	na	na	na	na	3	1	na	na
				46 - 61	12	na	na	na	na	na	10	8	na	na
				Total	15	na	na	na	na	na	13	9	na	na
Gaspe	2014	summer	V16	46 - 61	25	na	na	na	na	na	18	14	6	5
				> 61	18	na	na	na	na	na	16	12	10	9
				Total	43	na	na	na	na	na	34	26	16	14
Pictou	2015	winter	V16	Total	5	na	na	na	na	na	na	5	3	2
Gaspe	2015	summer	V13	Total	1	na	na	na	na	na	na	1	na	na
Gaspe	2016	late fall	V13	Total	8	na	na	na	na	na	na	na	8	3
Gaspe	2016	late fall	V16	Total	4	na	na	na	na	na	na	na	2	1
Miramichi	2016	fall	V16	< 46	4	na	na	na	na	na	na	na	4	4
				46 - 61	14	na	na	na	na	na	na	na	12	11
				> 61	6	na	na	na	na	na	na	na	6	6
				Total	24	na	na	na	na	na	na	na	22	21
Miramichi	2017	fall	V16	< 46	3	na	na	na	na	na	na	na	na	3
				46 - 61	19	na	na	na	na	na	na	na	na	14
				> 61	1	na	na	na	na	na	na	na	na	1
				Total	23	na	na	na	na	na	na	na	na	18

Table 4.1. Model specific parameters and prior assumptions for the life cycle age structured model. In OpenBUGS, the normal distribution is parameterized by the mean and the precision (1/variance) and C(#,) indicates the distribution is constrained to values greater than the first element. The gamma distribution is parameterized on the inverse gamma scale.

Model variant	Parameters with associated priors	Parameter translations
Model 1	δ ~ N(1,0.001)C(0,) K ~ N(1,0.001)C(1,) S.0 ~ Beta(139,861) S[1] ~ Beta(440,560) S[2] ~ Beta(638,362) S[3+] ~ Beta(720,280) p.rec.to.sp[3] ~ Beta(270,730) p.rec.to.sp[4] ~ Beta(630,370) p.rec.to.sp[5] ~ Beta(855,145) p.rec.to.sp[6] ~ Beta(900,100) log(σ) [3:8, Total] ~ U(0,3)	Beverton-Holt; α = exp(-δ) Z(0) = -log(S.0) Z[1] = -log(S[1]) Z[2] = -log(S[2] Z[3+] = -log(S[3+]) p.rec.to.sp[7:15+] = p.rec.to.sp[6]
Model 2	δ ~ N(1,0.001)C(0,) K ~ N(1,0.001)C(1,) S.0 ~ Beta(139,861) S[1] ~ Beta(440,560) S[2] ~ Beta(638,362) S[3] ~ Beta(72,28) S[4] ~ Beta(75,25) S[5] ~ Beta(80,20) S[6] ~ Beta(85,15) S[7] ~ Beta(90,10) S[8] ~ Beta(95,5) p.rec.to.sp[3] ~ Beta(270,730) p.rec.to.sp[4] ~ Beta(630,370) p.rec.to.sp[5] ~ Beta(855,145) p.rec.to.sp[6] ~ Beta(900,100) log(σ) [3:8, Total] ~ U(0,3)	Beverton-Holt; α = exp(-δ) Z(0) = -log(S.0) Z[1] = -log(S[1]) Z[2] = -log(S[2] Z[3:8] = -log(S[3:8]) Z[9:15+] = Z[8] p.rec.to.sp[7:15+] = p.rec.to.sp[6]
Model 3	δ ~ N(1,0.001)C(0,) K ~ N(1,0.001)C(1,) S.0 ~ Beta(139,861) S[1] ~ Beta(440,560) S[2] ~ Beta(638,362) S[3:8] ~ Beta(6,4) p.rec.to.sp[3] ~ Beta(270,730) p.rec.to.sp[4] ~ Beta(630,370) p.rec.to.sp[5] ~ Beta(855,145) p.rec.to.sp[6] ~ Beta(900,100) log(σ) [3:8, Total] ~ U(0,3)	Beverton-Holt; α = exp(-δ) Z(0) = -log(S.0) Z[1] = -log(S[1]) Z[2] = -log(S[2] Z[3:8] = -log(S[3:8]) Z[9:15+] = Z[8] p.rec.to.sp[7:15+] = p.rec.to.sp[6]
Model 4	δ ~ N(1,0.001)C(0,) K ~ N(1,0.001)C(1,) S.0 ~ Beta(14,86) S[1] ~ Beta(44,56) S[2] ~ Beta(64,36) S[3:8] ~ Beta(6,4) p.rec.to.sp[3] ~ Beta(4,12) p.rec.to.sp[4] ~ Beta(3,3) p.rec.to.sp[5] ~ Beta(5,2) p.rec.to.sp[6] ~ Beta(4,1) log(σ) [3:8, Total] ~ U(0,3)	Beverton-Holt; α = exp(-δ) Z(0) = -log(S.0) Z[1] = -log(S[1]) Z[2] = -log(S[2] Z[3:8] = -log(S[3:8]) Z[9:15+] = Z[8] p.rec.to.sp[7:15+] = p.rec.to.sp[6]
Model 5	δ ~ N(1,0.001)C(0,) K ~ N(1,0.001)C(1,) S[0to3] ~ Beta(5,45) S[3:8] ~ Beta(6,4) p.rec.to.sp[3] ~ Beta(4,12)	Beverton-Holt; α = exp(-δ) Z(0to3) = -log(S[0to3]) Z[3:8] = -log(S[3:8]) Z[9:15+] = Z[8] p.rec.to.sp[7:15+] = p.rec.to.sp[6]

Model variant	Parameters with associated priors	Parameter translations
	p.rec.to.sp[4] ~ Beta(3,3) p.rec.to.sp[5] ~ Beta(5,2) p.rec.to.sp[6] ~ Beta(4,1) log(σ) [3:8, Total] ~ U(0,3)	
Model 6	δ ~ N(1,0.001)C(0,) K ~ N(1,0.001)C(1,) S[3:8] ~ Beta(6,4) p.rec.to.sp[3] ~ Beta(4,12) p.rec.to.sp[4] ~ Beta(3,3) p.rec.to.sp[5] ~ Beta(5,2) p.rec.to.sp[6] ~ Beta(4,1) log(σ) [3:8, Total] ~ U(0,3)	Beverton-Holt; α = exp(-δ) Z[3:8] = -log(S[3:8]) Z[9:15+] = Z[8] p.rec.to.sp[7:15+] = p.rec.to.sp[6]
Model 7 Power stock and recruitment function	α ~ Beta(1,1) β ~ Gamma(6,4) S[3:8] ~ Beta(6,4) p.rec.to.sp[3] ~ Beta(4,12) p.rec.to.sp[4] ~ Beta(3,3) p.rec.to.sp[5] ~ Beta(5,2) p.rec.to.sp[6] ~ Beta(4,1) log(σ) [3:8, Total] ~ U(0,3)	Z[3:8] = -log(S[3:8]) Z[9:15+] = Z[8] p.rec.to.sp[7:15+] = p.rec.to.sp[6]

Table 4.2. Description of the models examined for estimating the life history and population dynamics parameters of Striped Bass from the southern Gulf of St. Lawrence. A summary of model fits (deviance, approximate Aikike Information Criterion (AIC'), and the DIC from the OpenBUGS) are also shown. In all models, the weight at age, fecundity, and proportion female at age on the spawning grounds are known or assumed with no uncertainty (Appendix 3).

Model variant	Fit statistics	Comments
Model 1	Deviance: 2440 Parameters: 17 AIC' = Dev+2*p = 2474 DIC = 2448 (pD = 8)	Poor fit to total spawners (residuals are positive generally) Very poor fit to observed abundances at age, dominant residual patterns
Model 2	Deviance: 2442 Parameters: 22 AIC' = Dev+2*p = 2484 DIC = 2450 (pD = 7.6)	Poor fit to total spawners (residuals are positive) Residuals mostly positive for age-3, negative for ages 7 and 8 Temporal trend in residuals for ages 7 and 8
Model 3	Deviance: 2403 Parameters: 22 AIC' = Dev+2*p = 2447 DIC = 2412 (pD = 9.1)	Good fit to spawners at age Temporal trend in residuals for ages 7 and 8 Mostly positive residuals for total spawners No autocorrelation for residual Survival age 3 higher than S for ages 4 to 7 which is not consistent with expectations
Model 4	Deviance: 2396 Parameters: 22 AIC' = Dev+2*p = 2440 DIC = 2401 (pD = 5.0)	Good fit to spawners at ages 3 to 6 A few more positive residuals for total spawners Temporal trend in residuals for ages 7 and 8 No autocorrelation for residuals Survival age 3 higher than for ages 4 to 7 which is not consistent with expectations Negative correlation between α and K, α and S[0]
Model 5	Deviance: 2395 Parameters: 20 AIC' = Dev+2*p = 2435 DIC = 2394 (pD = -1.4)	Good fit to spawners at ages 3 to 6 Almost balanced residual pattern for total spawners Temporal trend in residuals for ages 7 and 8 No autocorrelation for residuals. Survival age 3 higher than for ages 4 to 7 which is not consistent with expectations Negative correlation between α and K, α and S.0to3
Model 6	Deviance: 2391 Parameters: 19 AIC' = Dev+2*p = 2429 DIC = 2392 (pD = 0.3)	Good fit to spawners at age Temporal trend in residuals for ages 7 and 8 No autocorrelation for residuals. Survival age 3 higher than S for ages 4 to 7 which is not consistent with expectations Positive correlation between Bev-Holt alpha and S[3]
Model 7	Deviance: 2385 Parameters: 19 AIC' = Dev+2*p = 2423 DIC = 1330 (pD = -1055)	Equally good fit to spawners at age and total spawners as model with Beverton-holt assumption Beta (power term) is centered on 1, no density dependence (abundance increasing without limit Strong positive correlation between beta and gamma of the power function

Table 4.3. Summary (median; 5th to 95th percentiles range) of posterior estimates of the stock and recruitment parameters and predicted abundances for three models with a Beverton-Holt stock and recruitment function. The asymptotic abundance estimates are based on runs of the equilibrium model with life history parameters from the specific model fits and no fishing.

Feature	Model 4 (BH-eggs to age-0)	Model 5 (BH-eggs to age-0)	Model 6 (BH-eggs to age-3)
Survival eggs to age-0			
α	5.34 E-4 (3.53 E-4 to 8.27 E-4)	2.28 E-4 (1.32 E-4 to 4.02 E-4)	na
Survival age-0 to 3			
assumptions	S[0]*S[1]*S[2]	S[0to3]	na
S	0.0631 (0.0449 to 0.0869)	0.163 (0.103 to 0.249)	na
Survival eggs to age-3 in absence of density dependence			
S	3.34 E-5 (2.45 E-5 to 4.76 E-5)	3.65 E-5 (2.51 E-5 to 5.65 E-5)	4.20 E-5 (2.74 E-5 to 6.92 E-5)
Lifetime reproductive rate (number of recruits at age-3 per lifetime contribution of a spawner in absence of density-dependent compensatory survival)			
Age-3 (number)	5.5 (4.9 to 7.1)	5.0 (3.7 to 7.6)	4.9 (3.7 to 7.4)
Asymptotic abundance (K; Beverton-Holt model)			
Age-0 (millions)	9.10 (6.25 to 12.46)	6.80 (4.06 to 10.27)	na
Age-3 recruitment (thousands)	566 (383 to 834)	1,074 (640 to 1,799)	3,705 (1,622 to 7,373)
Equilibrium modelling abundance			
Age-0 (millions)	7.37 (4.94 to 10.22)	5.23 (2.87 to 8.38)	na
Age-3 recruitment (thousands)	456 (314 to 685)	824 (444 to 1,466)	2,848 (1,251 to 5,686)
Age 3 spawners (thousands)	170 (109 to 265)	288 (159 to 508)	819 (351 to 1,812)
Eggs (millions) [1]	66,175 (37,433 to 182,588)	105,676 (35,939 to 381,738)	286,682 (106,334 to 908,776)

[1] Egg abundances corresponding to the asymptotic abundances of age-0 or age-3 from equilibrium modelling are very high with large uncertainty because the stock and recruitment curve at that point (replacement point) is very flat hence similar levels of recruitment are realized for a very large range of spawners.

Table 6.1. Example management strategies based on size limits that could be considered to define fishery reference points for Striped Bass.

Retention regulations	Minimum size (fork length, cm)	Maximum size (fork length, cm)	Comment
No size limits	na (30)	na (150)	Although no size limits are given, for purposes of modelling, a minimum size of 30 cm was assumed as the smallest fish that would be retained. Although no maximum size limit is given, a maximum size (150 cm) that exceeds the expected size of any fish is assumed
Slot size	47	61	As per recreational fisheries plan of 2016 to 2020
Maximum size only	na (30)	65	Although no minimum size limit is given, for purposes of modelling, a minimum size of 30 cm was assumed as the smallest fish that would be retained.

Table 6.2a. Model 5 - reference levels (median; 5th to 95th percentile range) derived from the equilibrium modelling based on life history parameters and population dynamics parameters for the two scenarios of values of M specific to the management strategy without any size limit for retention and no accounting for catch and release mortality.

References for Model 5	M = Z from modelling	M informed from observations
Equilibrium abundance (ages 3 to 15+) at F = 0		
Total abundance (biomass, t)	4,140 (2,120 to 11,450)	13,980 (8,040 to 24,710)
Total abundance (number, thousands)	2,320 (1,380 to 4,340)	4,700 (2,800 to 8,060)
Spawner abundance (biomass, t)	2,810 (1,430 to 8,100)	10,340 (5,400 to 19,410)
Spawner abundance (number, thousands)	1,360 (800 to 2,620)	3,110 (1,760 to 5,610)
Spawner abundance (eggs, millions)	104,300 (51,300 to 317,300)	413,900 (214,100 to 783,600)
MSY references (ages 3 to 15+)		
Total abundance (biomass; t)	1,620 (890 to 3,600)	4,610 (2,680 to 8,000)
Total abundance (number, thousands)	1,230 (740 to 2,230)	2,430 (1,460 to 4,130)
Spawner abundance (biomass, t)	1,010 (550 to 2,350)	3,200 (1,770 to 5,830)
Spawner abundance (number, thousands)	660 (390 to 1,240)	1,450 (850 to 2,550)
Spawner abundance (eggs, millions)	34,560 (18,190 to 85,230)	121,680 (65,990 to 224,330)
Fishing rate and yield at MSY		
F_{MSY} (fully recruited F)	0.18 (0.12 to 0.23)	0.17 (0.15 to 0.19)
Fcrash (fully recruited F)	0.69 (0.6 to 0.78)	0.87 (0.73 to 1)
Catch at MSY (biomass, t)	210 (130 to 380)	650 (370 to 1140)
Catch at MSY (number, thousands)	160 (100 to 270)	340 (190 to 590)
Equilibrium abundance (age-3)		
Total abundance (number, thousands)	840 (500 to 1420)	1000 (590 to 1690)
Spawner abundance (number, thousands)	290 (170 to 520)	350 (210 to 610)
Lifetime reproductive rate (number of recruits at age-3 per lifetime contribution of a spawner in absence of density-dependent compensatory survival)		
Age-3 (number)	5.01 (3.73 to 7.59)	15.55 (11.01 to 23.29)
Spawner potential per recruit references (ages 3 to 15+) (fully-recruited F)		
F at 50%SPR	0.19 (0.14 to 0.27)	0.12 (0.11 to 0.13)
F at 30%SPR	0.39 (0.28 to 0.53)	0.24 (0.22 to 0.27)

Table 6.2b. Model 4 - reference levels (median; 5th to 95th percentile range) derived from the equilibrium modelling based on life history parameters and population dynamics parameters for the two scenarios of values of M specific to the management strategy without any size limit for retention and no accounting for catch and release mortality.

References for Model 4	M = Z from modelling	M informed from observations
Equilibrium abundance (ages 3 to 15+) at F = 0		
Total abundance (biomass, t)	2,540 (1,470 to 6,620)	8,050 (5,210 to 12,600)
Total abundance (number, thousands)	1,380 (920 to 2,340)	2,670 (1,780 to 3,990)
Spawner abundance (biomass, t)	1,790 (1,040 to 4,730)	6,100 (3,600 to 10,080)
Spawner abundance (number, thousands)	860 (570 to 1,480)	1,850 (1,180 to 2,870)
Spawner abundance (eggs, millions)	66,700 (37,600 to 188,100)	244,000 (142,700 to 405,600)
MSY references (ages 3 to 15+)		
Total abundance (biomass; t)	970 (600 to 1,990)	2,620 (1,730 to 4,000)
Total abundance (number, thousands)	720 (490 to 1,180)	1,360 (920 to 2,020)
Spawner abundance (biomass, t)	650 (400 to 1,340)	1,900 (1,190 to 3,010)
Spawner abundance (number, thousands)	420 (280 to 700)	860 (570 to 1,300)
Spawner abundance (eggs, millions)	22,200 (13,400 to 48,700)	72,100 (44,400 to 115,700)
Fishing rate and yield at MSY		
F_{MSY} (fully recruited F)	0.19 (0.12 to 0.24)	0.17 (0.15 to 0.19)
Fcrash (fully recruited F)	0.73 (0.65 to 0.82)	0.88 (0.76 to 1)
Catch at MSY (biomass, t)	140 (100 to 220)	370 (240 to 580)
Catch at MSY (number, thousands)	100 (70 to 150)	190 (130 to 290)
Equilibrium abundance (age-3)		
Total abundance (number, thousands)	450 (300 to 670)	530 (350 to 780)
Spawner abundance (number, thousands)	170 (110 to 260)	200 (130 to 300)
Lifetime reproductive rate (number of recruits at age-3 per lifetime contribution of a spawner in absence of density-dependent compensatory survival)		
Age-3 (number)	5.45 (4.08 to 7.95)	15.72 (11.63 to 22.05)
Spawner potential per recruit references (ages 3 to 15+) (fully-recruited F)		
F at 50%SPR	0.19 (0.14 to 0.26)	0.12 (0.12 to 0.13)
F at 30%SPR	0.39 (0.28 to 0.52)	0.24 (0.22 to 0.27)

Table 6.3a. Model 5 - reference point summaries (median; 5th to 95th percentile range) from the equilibrium modelling based on life history and population dynamics parameters for the two scenarios of values of M and for the default management strategy of no size limit for retention and no accounting for catch and release mortality.

Reference	Units	M = Z from modelling	M informed from observations
Upper Stock Reference (spawners ages 3 to 15+)			
80%B_{MSY}	Eggs (millions)	25,780 (13,460 to 63,420)	91,320 (49,990 to 168,040)
	Biomass (t)	780 (420 to 1,780)	2,450 (1,360 to 4,450)
	Number (thousands)	530 (310 to 1,020)	1,210 (710 to 2,110)
	Eggs per fish	48,210 (4,0200 to 66,970)	75,670 (64,820 to 86,000)
	Eggs per kg	33,370 (31,370 to 36,070)	37,290 (35,950 to 38,280)
	Mean age of spawners	4.33 (4.05 to 5.04)	5.28 (4.91 to 5.64)
	Mean weight (kg) of spawners	1.45 (1.28 to 1.86)	2.03 (1.8 to 2.25)
50%SPR	Eggs (millions)	32,440 (16,110 to 72,360)	165,250 (82,190 to 315,970)
	Biomass (t)	950 (500 to 2,020)	4,280 (2,190 to 8,120)
	Number (thousands)	620 (360 to 1,150)	1,760 (990 to 3,130)
Limit Reference Point (spawners ages 3 to 15+)			
Brecover	Eggs (millions)	200	
	Biomass (t)	6.5	
	Number (thousands)	4.5	
40%B_{MSY}	Eggs (millions)	11,600 (5,970 to 28,660)	40,580 (22,430 to 74,480)
	Biomass (t)	370 (200 to 850)	1,160 (650 to 2,090)
	Number (thousands)	280 (160 to 580)	700 (410 to 1,220)
	Eggs per fish	41,440 (34,840 to 53,150)	58,030 (50,080 to 65,850)
	Eggs per kg	31,750 (29,660 to 34,220)	35,150 (33,640 to 36,380)
	Mean age of spawners	4.1 (3.88 to 4.52)	4.66 (4.39 to 4.92)
	Mean weight (kg) of spawners	1.31 (1.17 to 1.55)	1.65 (1.49 to 1.81)
30%SPR	Eggs (millions)	7,020 (1,520 to 20,350)	82,420 (38,020 to 161,800)
	Biomass (t)	230 (50 to 620)	2,220 (1,070 to 4,300)
	Number (thousands)	180 (50 to 430)	1,120 (610 to 2,040)
Half K – Bev Holt	Eggs (millions)	29,950 (17,450 to 54,180)	
	Biomass (t)	890 (530 to 1,590)	870 (520 to 1,560)
	Number (thousands)	590 (360 to 1030)	560 (350 to 980)
	Eggs per fish	50,430 (43,480 to 59,350)	53,250 (46,240 to 60,640)

Reference	Units	M = Z from modelling	M informed from observations
	Eggs per kg	33,810 (32,240 to 35,240)	34,360 (32,870 to 35,610)
	Mean age of spawners	4.41 (4.16 to 4.74)	4.49 (4.25 to 4.74)
	Mean weight (kg) of spawners	1.49 (1.35 to 1.69)	1.55 (1.40 to 1.70)
Half equilibrium	Eggs (millions)	19,300 (10,820 to 37,630)	26,160 (15,420 to 47,040)
	Biomass (t)	590 (340 to 1,110)	770 (460 to 1,360)
	Number (thousands)	420 (260 to 750)	510 (310 to 880)
	Eggs per fish	45,350 (38,360 to 55,650)	51,470 (44,590 to 58,450)
	Eggs per kg	32,720 (30,840 to 34,630)	34,020 (32,470 to 35,270)
	Mean age of spawners	4.23 (3.99 to 4.61)	4.43 (4.20 to 4.67)
	Mean weight (kg) of spawners	1.39 (1.24 to 1.61)	1.51 (1.37 to 1.66)
Removal rate reference point (fully recruited F)			
MSY	MSY	0.18 (0.12 to 0.23)	0.17 (0.15 to 0.19)
50%SPR	50%SPR	0.19 (0.14 to 0.27)	0.12 (0.11 to 0.13)
30%SPR	30%SPR	0.39 (0.28 to 0.53)	0.24 (0.22 to 0.27)

Table 6.3b. Model 4 - reference point summaries (median; 5th to 95th percentile range) from the equilibrium modelling based on life history and population dynamics parameters derived for the two scenarios of values of M and for the default management strategy of no size limit for retention and no accounting for catch and release mortality.

Reference	Units	M = Z from modelling	M informed from observations
Upper Stock Reference (spawners ages 3 to 15+)			
80%B_{MSY}	Eggs (millions)	16,700 (10,000 to 36,500)	54,300 (33,700 to 86,400)
	Biomass (t)	500 (310 to 1,030)	1,460 (920 to 2,290)
	Number (thousands)	340 (220 to 580)	720 (480 to 1,090)
	Eggs per fish	49,200 (41,700 to 66,100)	75,400 (65,600 to 85,000)
	Eggs per kg	33,600 (31,800 to 36,000)	37,300 (36,100 to 38,200)
	Mean age of spawners	4.36 (4.11 to 5)	5.28 (4.94 to 5.61)
	Mean weight (kg) of spawners	1.46 (1.31 to 1.83)	2.02 (1.82 to 2.23)
50%SPR	Eggs (millions)	22,500 (12,900 to 44,900)	98,200 (56,000 to 163,600)
	Biomass (t)	650 (390 to 1,240)	2,540 (1,480 to 4,190)
	Number (thousands)	420 (280 to 680)	1,050 (660 to 1,620)
Limit Reference Point (spawners ages 3 to 15+)			
Brecover	Eggs (millions)	200	
	Biomass (t)	6.5	
	Number (thousands)	4.5	
40%B_{MSY}	Eggs (millions)	7,600 (4,500 to 16,700)	24,500 (15,400 to 38,500)
	Biomass (t)	240 (150 to 500)	700 (450 to 1,080)
	Number (thousands)	180 (120 to 330)	420 (280 to 630)
	Eggs per fish	41,900 (35,900 to 52,700)	58,000 (50,700 to 65,200)
	Eggs per kg	31,900 (30,100 to 34,200)	35,200 (33,800 to 36,300)
	Mean age of spawners	4.11 (3.91 to 4.5)	4.65 (4.41 to 4.90)
	Mean weight (kg) of spawners	1.31 (1.2 to 1.54)	1.65 (1.50 to 1.80)
30%SPR	Eggs (millions)	6,400 (2,400 to 14,900)	49,000 (26,400 to 84,200)
	Biomass (t)	200 (80 to 440)	1,320 (730 to 2,230)
	Number (thousands)	160 (70 to 300)	670 (410 to 1,050)
Half K – Bev Holt	Eggs (millions)	17,300 (11,300 to 26,500)	
	Biomass (t)	510 (340 to 770)	510 (340 to 760)
	Number (thousands)	350 (240 to 510)	330 (220 to 490)
	Eggs per fish	49,600 (43,600 to 57,100)	52,400 (46,400 to 59,100)

Reference	Units	M = Z from modelling	M informed from observations
	Eggs per kg	33,700 (32,300 to 35,000)	34,200 (32,900 to 35,400)
	Mean age of spawners	4.38 (4.17 to 4.65)	4.46 (4.26 to 4.69)
	Mean weight (kg) of spawners	1.47 (1.35 to 1.63)	1.53 (1.41 to 1.67)
Half equilibrium	Eggs (millions)	11,600 (7,300 to 19,300)	15,200 (10,000 to 23,000)
	Biomass (t)	350 (230 to 570)	450 (300 to 670)
	Number (thousands)	260 (170 to 390)	300 (210 to 440)
	Eggs per fish	45,300 (39,100 to 53,600)	50,800 (44,900 to 57,200)
	Eggs per kg	32,700 (31,100 to 34,400)	33,900 (32,600 to 35,100)
	Mean age of spawners	4.23 (4.02 to 4.53)	4.41 (4.21 to 4.62)
	Mean weight (kg) of spawners	1.38 (1.26 to 1.56)	1.50 (1.38 to 1.63)
Removal rate reference point (fully recruited F)			
MSY	MSY	0.19 (0.12 to 0.24)	0.17 (0.15 to 0.19)
50%SPR	50%SPR	0.19 (0.14 to 0.26)	0.12 (0.12 to 0.13)
30%SPR	30%SPR	0.39 (0.28 to 0.52)	0.24 (0.22 to 0.27)

Table 6.4a. Model 5 - comparison of calculated reference points for different fishing strategies conditioned by size limits. The equilibrium simulations were run based on life history characteristics from model 5 and assuming M for ages 4 to 15+ based on acoustic tagging observations. There is no accounting for catch and release mortality in these scenarios. Summary statistics shown are the median with the 5th to 95th percentile range.

Reference	Unit	No size restrictions (slot = 30 to 150)	Slot size (47 to 61 cm FL)	Maximum size limit (30 to 65 cm FL)
MSY references (ages 3 to 15+)				
B_{MSY}	Total abundance (biomass, t)	4,610 (2,680 to 8,000)	3,720 (2,210 to 6,450)	3,800 (2,250 to 6,630)
	Total abundance (number, thousands)	2,430 (1,460 to 4,130)	2,060 (1,250 to 3,520)	1,990 (1,200 to 3,390)
	Spawners (biomass, t)	3,200 (1,770 to 5,830)	2,550 (1,460 to 4,540)	2,610 (1,480 to 4,700)
	Spawners (number, thousands)	1,450 (850 to 2,550)	1,180 (720 to 2,040)	1,140 (690 to 1,970)
	Spawners (eggs, millions)	121,680 (65,990 to 224,330)	94,930 (53,650 to 169,950)	98,600 (55,150 to 179,550)
	Catch at MSY (weight, t)	650 (370 to 1,140)	530 (300 to 940)	490 (280 to 850)
	Catch at MSY (number, thousands)	340 (190 to 590)	360 (210 to 640)	400 (230 to 700)
Upper Stock Reference (spawners 3 to 15+)				
80%B_{MSY}	Eggs (millions)	91,320 (49,990 to 168,040)	71,270 (40,530 to 127,900)	74,590 (41,800 to 135,270)
	Biomass (t)	2,450 (1,360 to 4,450)	1,960 (1,130 to 3,490)	2,010 (1,150 to 3,630)
	Number (thousands)	1,210 (710 to 2,110)	990 (600 to 1,710)	940 (570 to 1,630)
	Eggs per spawner	75,670 (64,820 to 86,000)	71,890 (61,140 to 82,490)	79,000 (66,840 to 90,880)
	Eggs per kg of spawner	37,290 (35,950 to 38,280)	36,390 (35,060 to 37,410)	37,080 (35,740 to 38,070)
	Mean age of spawners	5.28 (4.91 to 5.64)	5.26 (4.87 to 5.66)	5.52 (5.06 to 5.96)
	Mean weight (kg) of spawners	2.03 (1.8 to 2.25)	1.97 (1.74 to 2.21)	2.13 (1.87 to 2.39)
50%SPR	Eggs (millions)	165,250 (82,190 to 315,970)	189,420 (94,270 to 362,900)	189,550 (94,260 to 363,200)
	Biomass (t)	4,280 (2,190 to 8,120)	4,880 (2,480 to 9,300)	4,850 (2,480 to 9,240)
	Number (thousands)	1,760 (990 to 3,130)	1,820 (1,030 to 3,250)	1,770 (1,000 to 3,170)
Limit Reference Point (spawners 3 to 15+)				
Brecover	Eggs (millions)		200	
	Biomass (t)		6.5	
	Number (thousands)		4.5	
40%B_{MSY}	Eggs (millions)	40,580 (22,430 to 74,480)	30,960 (17,970 to 55,620)	32,880 (18,660 to 59,550)
	Biomass (t)	1,160 (650 to 2,090)	920 (540 to 1,620)	940 (540 to 1,680)
	Number (thousands)	700 (410 to 1,220)	580 (360 to 1,000)	540 (330 to 930)
	Eggs per spawner	58,000 (50,080 to 65,850)	53,100 (45,640 to 61,190)	61,200 (51,850 to 70,680)
	Eggs per kg of spawner	35,150 (33,640 to 36,380)	33,830 (32,310 to 35,110)	35,040 (33,470 to 36,270)
	Mean age of spawners	4.66 (4.39 to 4.92)	4.57 (4.3 to 4.87)	4.86 (4.52 to 5.21)

Reference	Unit	No size restrictions (slot = 30 to 150)	Slot size (47 to 61 cm FL)	Maximum size limit (30 to 65 cm FL)
	Mean weight (kg) of spawners	1.65 (1.49 to 1.81)	1.57 (1.41 to 1.74)	1.75 (1.55 to 1.95)
30%SPR	Eggs (millions)	82,420 (38,020 to 161,800)	97,590 (44,980 to 192,980)	98,420 (45,770 to 192,480)
	Biomass (t)	2,220 (1,070 to 4,300)	2,620 (1,260 to 5,080)	2,610 (1,260 to 5,030)
	Number (thousands)	1120 (610 to 2,040)	1200 (660 to 2,150)	1,130 (620 to 2,040)
Half K – Bev Holt	Eggs (millions)	29,950 (17,450 to 54,180)	29,840 (17,310 to 53,970)	29,920 (17,400 to 54,370)
	Biomass (t)	870 (520 to 1,560)	890 (520 to 1,580)	860 (510 to 1,540)
	Number (thousands)	560 (350 to 980)	570 (350 to 990)	500 (310 to 870)
	Eggs per spawner	53,250 (46,240 to 60,640)	52,380 (44,720 to 60,950)	59,430 (50,690 to 68,430)
	Eggs per kg of spawner	34,360 (32,870 to 35,610)	33,700 (32,100 to 35,090)	34,780 (33,260 to 36,000)
	Mean age of spawners	4.49 (4.25 to 4.74)	4.54 (4.26 to 4.86)	4.79 (4.47 to 5.13)
	Mean weight (kg) of spawners	1.55 (1.4 to 1.7)	1.55 (1.39 to 1.74)	1.71 (1.52 to 1.9)
Half equilibrium	Eggs (millions)	26,160 (15,420 to 47,040)	25,980 (15,350 to 46,800)	26,160 (15,450 to 47,010)
	Biomass (t)	770 (460 to 1,360)	780 (470 to 1,380)	760 (460 to 1,350)
	Number (thousands)	510 (310 to 880)	520 (320 to 890)	460 (280 to 790)
	Eggs per spawner	51,470 (44,590 to 58,450)	50,240 (42,910 to 58,420)	57,320 (48,860 to 66,070)
	Eggs per kg of spawner	34,020 (32,470 to 35,270)	33,300 (31,680 to 34,710)	34,450 (32,890 to 35,700)
	Mean age of spawners	4.43 (4.2 to 4.67)	4.47 (4.2 to 4.77)	4.72 (4.41 to 5.04)
	Mean weight (kg) of spawners	1.51 (1.37 to 1.66)	1.51 (1.35 to 1.68)	1.66 (1.49 to 1.85)
Fishing rate (fully recruited F)	MSY	0.17 (0.15 to 0.19)	0.66 (0.58 to 0.74)	0.33 (0.29 to 0.38)
	50%SPR	0.12 (0.11 to 0.13)	0.36 (0.34 to 0.38)	0.19 (0.18 to 0.20)
	30%SPR	0.24 (0.22 to 0.27)	0.64 (0.60 to 0.72)	0.34 (0.32 to 0.36)
Exploitation rate (catch number divided by total abundance number at F)	MSY	0.14 (0.12 to 0.16)	0.17 (0.15 to 0.20)	0.20 (0.17 to 0.23)
	50%SPR	0.10 (0.09 to 0.11)	0.09 (0.08 to 0.11)	0.11 (0.10 to 0.12)
	30%SPR	0.19 (0.17 to 0.21)	0.17 (0.15 to 0.2)	0.20 (0.19 to 0.22)

Table 6.4b. Model 4 - comparison of calculated reference points for different fishing strategies conditioned by size limits. The equilibrium simulations were run based on life history characteristics from model 4 and assuming M for ages 4 to 15+ based on acoustic tagging observations. There is no accounting for catch and release mortality in these scenarios. Summary statistics shown are the median with the 5th to 95th percentile range.

Reference	Unit	No size restrictions (slot = 30 to 150)	Slot size (47 to 61 cm FL)	Maximum size limit (30 to 65 cm FL)
MSY references (ages 3 to 15+)				
B_{MSY}	Total abundance (biomass, t)	2,620 (1,730 to 4,000)	2,110 (1,410 to 3,170)	2,180 (1,440 to 3,280)
	Total abundance (number, thousands)	1,360 (920 to 2,020)	1,150 (780 to 1,690)	1,110 (760 to 1,640)
	Spawners (biomass, t)	1,900 (1,190 to 3,010)	1,510 (970 to 2,330)	1,560 (990 to 2,430)
	Spawners (number, thousands)	860 (570 to 1,300)	700 (480 to 1,050)	680 (460 to 1,010)
	Spawners (eggs, millions)	72,100 (44,400 to 115,700)	56,000 (35,500 to 87,500)	58,500 (36,700 to 92,800)
	Catch at MSY (weight, t)	370 (240 to 580)	310 (200 to 470)	280 (180 to 430)
	Catch at MSY (number, thousands)	190 (130 to 290)	210 (140 to 320)	230 (150 to 340)
Upper Stock Reference (spawners 3 to 15+)				
80%B_{MSY}	Eggs (millions)	54,300 (33,700 to 86,400)	42,300 (26,900 to 65,600)	44,500 (27,900 to 70,200)
	Biomass (t)	1,460 (920 to 2,290)	1,170 (750 to 1,790)	1,200 (770 to 1,870)
	Number (thousands)	720 (480 to 1,090)	590 (410 to 880)	570 (380 to 840)
	Eggs per spawner	75,400 (65,600 to 85,000)	71,100 (61,500 to 80,700)	78,800 (67,800 to 89,900)
	Eggs per kg of spawner	37,300 (36,100 to 38,200)	36,300 (35,100 to 37,300)	37,100 (35,900 to 38,000)
	Mean age of spawners	5.28 (4.94 to 5.61)	5.23 (4.87 to 5.6)	5.51 (5.1 to 5.93)
	Mean weight (kg) of spawners	2.02 (1.82 to 2.23)	1.96 (1.75 to 2.17)	2.12 (1.89 to 2.37)
50%SPR	Eggs (millions)	98,200 (56,000 to 163,600)	111,800 (63,300 to 189,000)	111,800 (63,200 to 188,200)
	Biomass (t)	2,540 (1,480 to 4,190)	2,880 (1,660 to 4,790)	2,860 (1,650 to 4,770)
	Number (thousands)	1,050 (660 to 1,620)	1,080 (690 to 1,680)	1,050 (670 to 1,630)
Limit Reference Point (spawners 3 to 15+)				
Brecover	Eggs (millions)		200	
	Biomass (t)		6.5	
	Number (thousands)		4.5	
40%B_{MSY}	Eggs (millions)	24,500 (15,400 to 38,500)	18,600 (12,100 to 28,600)	19,800 (12,700 to 31,100)
	Biomass (t)	700 (450 to 1,080)	550 (370 to 840)	570 (370 to 870)
	Number (thousands)	420 (280 to 630)	350 (240 to 520)	330 (220 to 480)
	Eggs per spawner	58,000 (50,700 to 65,200)	52,600 (46,000 to 60,000)	61,100 (52,700 to 69,900)
	Eggs per kg of spawner	35,200 (33,800 to 36,300)	33,800 (32,400 to 35,000)	35,100 (33,700 to 36,200)
	Mean age of spawners	4.65 (4.41 to 4.90)	4.55 (4.31 to 4.82)	4.86 (4.55 to 5.18)

Reference	Unit	No size restrictions (slot = 30 to 150)	Slot size (47 to 61 cm FL)	Maximum size limit (30 to 65 cm FL)
	Mean weight (kg) of spawners	1.65 (1.50 to 1.80)	1.56 (1.42 to 1.72)	1.74 (1.57 to 1.93)
30%SPR	Eggs (millions)	49,000 (26,400 to 84,200)	57,700 (30,700 to 100,300)	58,100 (31,100 to 100,700)
	Biomass (t)	1,320 (730 to 2,230)	1,550 (850 to 2,630)	1,540 (850 to 2,620)
	Number (thousands)	670 (410 to 1,050)	720 (450 to 1,120)	670 (420 to 1,050)
Half K – Bev Holt	Eggs (millions)	17,300 (11,400 to 26,500)	17,200 (11,200 to 26,400)	17,300 (11,300 to 26,600)
	Biomass (t)	510 (340 to 760)	510 (340 to 770)	500 (330 to 760)
	Number (thousands)	330 (220 to 490)	340 (230 to 490)	290 (200 to 440)
	Eggs per spawner	52,400 (46,400 to 59,100)	51,100 (44,500 to 58,800)	58,600 (51,000 to 66,900)
	Eggs per kg of spawner	34,200 (32,900 to 35,400)	33,500 (32,100 to 34,800)	34,700 (33,400 to 35,800)
	Mean age of spawners	4.46 (4.26 to 4.69)	4.5 (4.26 to 4.78)	4.76 (4.49 to 5.06)
	Mean weight (kg) of spawners	1.53 (1.41 to 1.67)	1.53 (1.39 to 1.69)	1.69 (1.53 to 1.86)
Half equilibrium	Eggs (millions)	15,200 (10,000 to 23,000)	15,100 (10,000 to 22,800)	15,200 (10,000 to 22,900)
	Biomass (t)	450 (300 to 670)	460 310 to 680)	440 (300 to 660)
	Number (thousands)	300 (210 to 440)	310 210 to 450)	270 (180 to 390)
	Eggs per spawner	50,800 (44,900 to 57,200)	49,100 (42,800 to 56,400)	56,600 (49,200 to 64,600)
	Eggs per kg of spawner	33,900 (32,600 to 35,100)	33,100 (31,700 to 34,400)	34,400 (33,000 to 35,600)
	Mean age of spawners	4.41 (4.21 to 4.62)	4.42 (4.19 to 4.69)	4.69 (4.42 to 4.98)
	Mean weight (kg) of spawners	1.50 (1.38 to 1.63)	1.48 (1.35 to 1.64)	1.65 (1.49 to 1.82)
Fishing rate (fully recruited F)	MSY	0.17 (0.15 to 0.19)	0.68 (0.6 to 0.74)	0.34 (0.3 to 0.37)
	50%SPR	0.12 (0.12 to 0.13)	0.36 (0.34 to 0.38)	0.19 (0.18 to 0.2)
	30%SPR	0.24 (0.22 to 0.27)	0.66 (0.62 to 0.72)	0.34 (0.32 to 0.36)
Exploitation rate (catch number divided by total abundance number at F)	MSY	0.14 (0.13 to 0.16)	0.18 (0.16 to 0.21)	0.20 (0.18 to 0.23)
	50%SPR	0.10 (0.10 to 0.11)	0.10 (0.09 to 0.11)	0.11 (0.10 to 0.12)
	30%SPR	0.19 (0.18 to 0.21)	0.18 (0.16 to 0.20)	0.20 (0.19 to 0.22)

Table 6.5. Model 5 - comparison of calculated reference points for different fishing strategies conditioned by size limits and considering whether catch and release mortality is included (A.CR = 0) or excluded (A.CR = 9%) in the equilibrium modelling. The equilibrium simulations were run based on life history characteristics from model 5 and assuming M for ages 4 to 15+ based on informed observations.

Reference values for Model 5	Slot size (47 to 61 cm FL)		Maximum size limit (30 to 65 cm FL)	
	A.CR = 0	A.CR = 9%	A.CR = 0	A.CR = 9%
MSY references (ages 3 to 15+)				
Total abundance (thousands)	2,060 (1,250 to 3,520)	2,020 (1,240 to 3,420)	1,990 (1,200 to 3,390)	1,960 (1,200 to 3,330)
Spawners (thousands)	1,180 (720 to 2,040)	1,160 (700 to 2,020)	1,140 (690 to 1,970)	1,120 (680 to 1,960)
Catch at MSY (number, thousands)	360 (210 to 640)	310 (180 to 550)	400 (230 to 700)	380 (220 to 670)
Losses at MSY (number, thousands)		360 (210 to 640)		390 (230 to 690)
Upper Stock Reference (spawners 3 to 15+)				
80%B_{MSY} (number, thousands)	990 (600 to 1,710)	970 (590 to 1,690)	940 (570 to 1,630)	930 (560 to 1,630)
50%SPR (number, thousands)	1820 (,1030 to 3,250)	,1800 (1,020 to 3,220)	1,770 (1,000 to 3,170)	1,760 (1,000 to 3,150)
Limit Reference Point (spawners 3 to 15+)				
Brecover (number, thousands)	4.5			
40%B_{MSY} (number, thousands)	580 (360 to 1,000)	560 (340 to 980)	540 (330 to 930)	530 (320 to 930)
30%SPR (number, thousands)	1,200 (660 to 2,150)	1,160 (640 to 2,090)	1,130 (620 to 2,040)	1,120 (610 to 2,010)
Half K – Bev Holt (number, thousands)	570 (350 to 990)	580 (350 to 1,000)	500 (310 to 870)	520 (320 to 900)
Half equilibrium (number, thousands)	520 (320 to 890)	520 (320 to 900)	460 (280 to 790)	470 (290 to 810)
Fishing rate (fully recruited F for retained catch)				
MSY	0.66 (0.58 to 0.74)	0.56 (0.48 to 0.62)	0.33 (0.29 to 0.38)	0.32 (0.28 to 0.36)
50%SPR	0.36 (0.34 to 0.38)	0.30 (0.28 to 0.32)	0.19 (0.18 to 0.20)	0.18 (0.17 to 0.19)
30%SPR	0.64 (0.60 to 0.72)	0.56 (0.52 to 0.62)	0.34 (0.32 to 0.36)	0.32 (0.31 to 0.35)

FIGURES

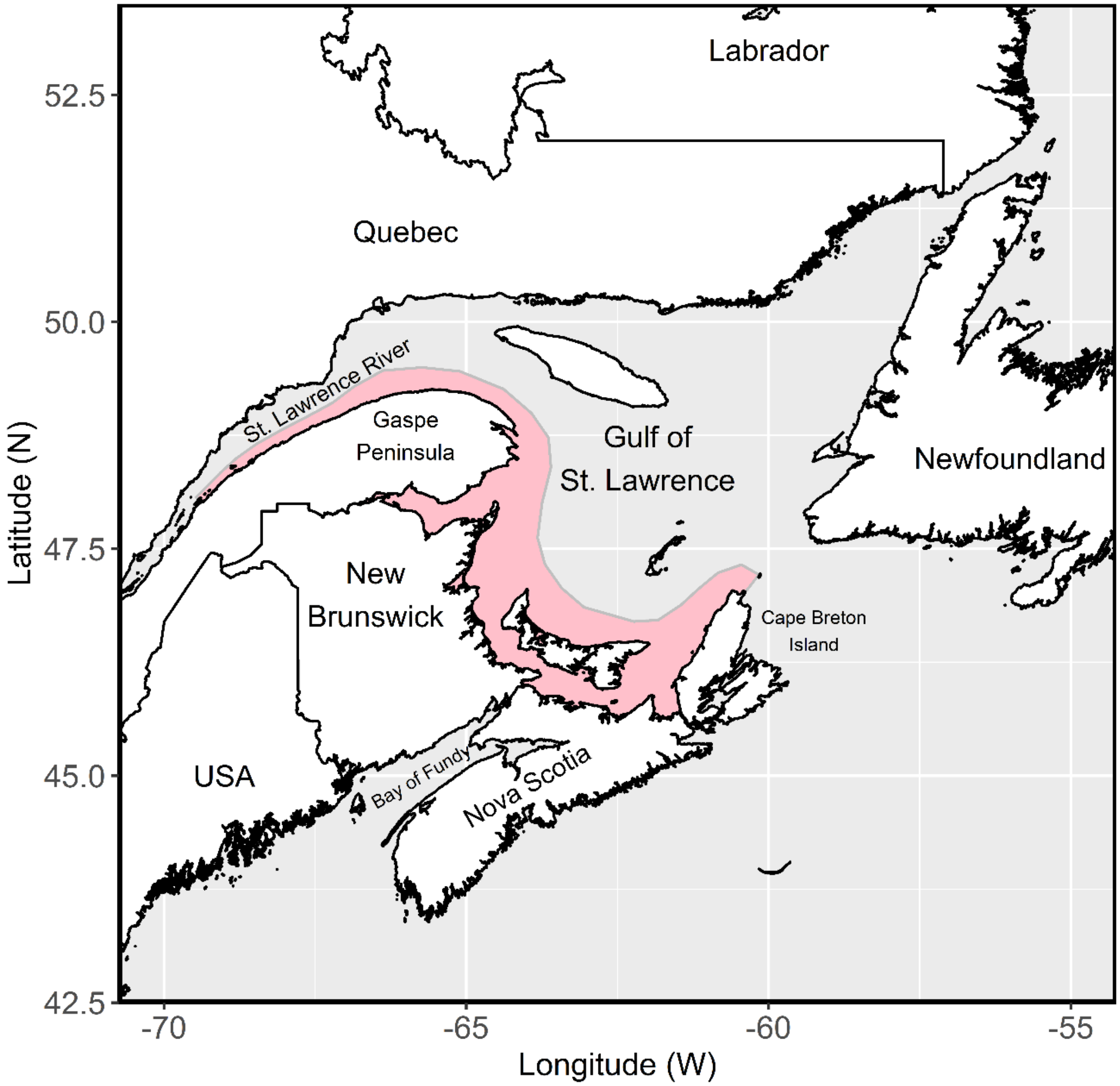


Figure 1.1. Geographic distribution (red shaded area) of the southern Gulf of St. Lawrence Striped Bass population in eastern Canada.

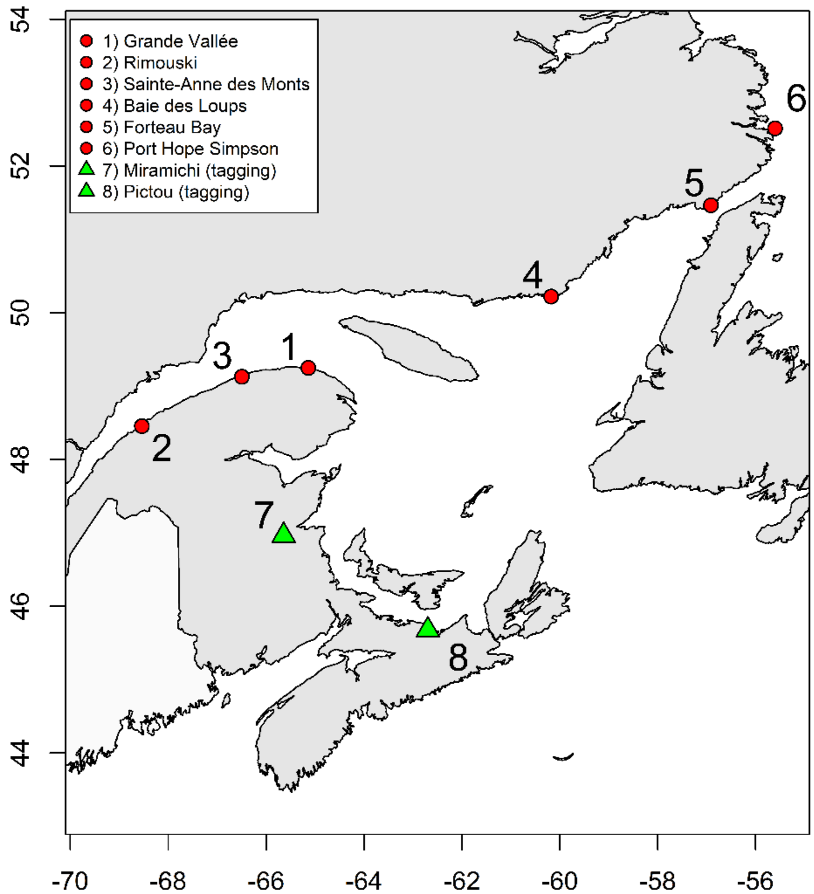


Figure 1.2. Recoveries (circle symbols) in 2017 of Striped Bass tagged in the southern Gulf of St. Lawrence in exceptional areas outside the historic range of the population, including in the estuary of the St. Lawrence River, the north shore of the St. Lawrence, and at the southern Labrador Port Hope Simpson acoustic array deployed by Fisheries and Oceans Canada. Details on external tag recoveries are provided in DFO (2018). The figure is amended from DFO (2018) to show the acoustic array location (Port Hope Simpson) in southern Labrador. Acoustic tag identification codes detected in Labrador were from fish tagged in Miramichi, in the Gaspe region, and in the St. Lawrence River (see Table 3.1 for details). No acoustic tag identification codes for Striped Bass were recorded at the southern Labrador acoustic array in 2018 (M. Robertson, DFO Newfoundland and Labrador Region, pers. comm.).

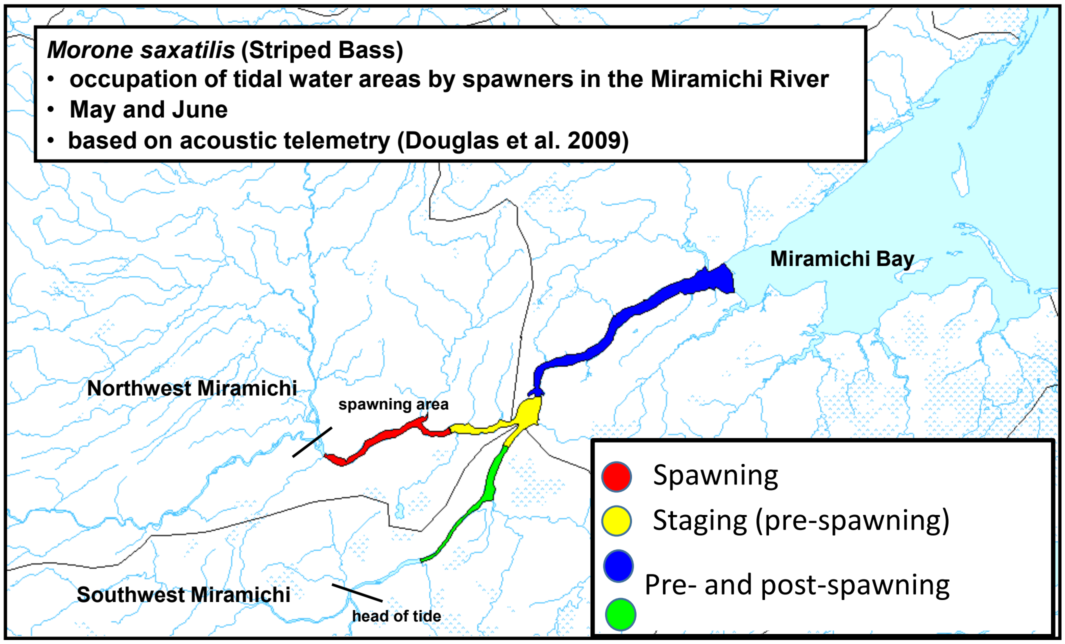


Figure 1.3. Location of the spawning area of the Northwest Miramichi as well as pre- and post-spawning areas of the Miramichi River occupied by Striped Bass, based on the acoustic telemetry study of Douglas et al. (2009).

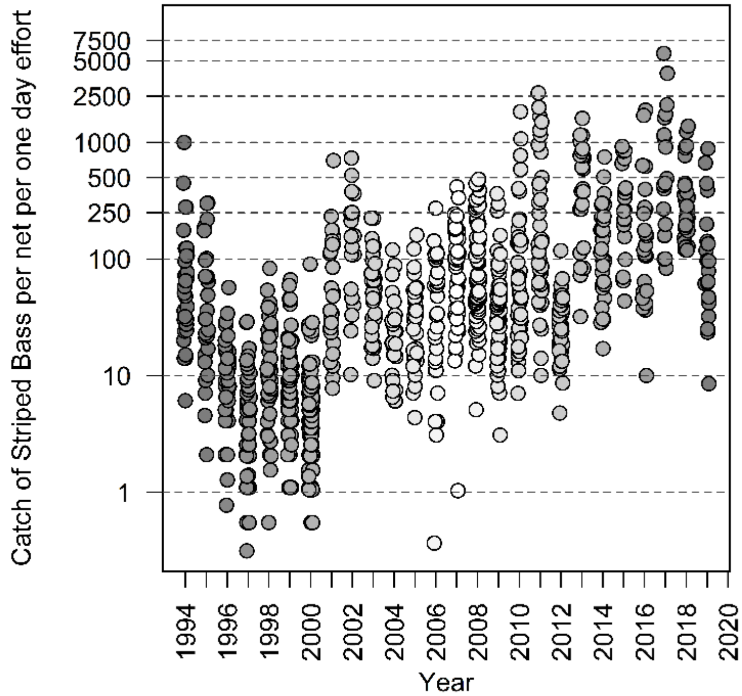


Figure 3.1. The number of Striped Bass captured per net per day of effort from monitoring of the commercial gaspereau fishery in the Northwest Miramichi, 1994 to 2019. The catch rates are not adjusted for the proportion of the spawners available for capture in the fishery. In 2012, the spawning was very early and the majority of the fish was considered to have left the area and were not available to the fishery, hence no estimate was provided for that year. The points within a year are jittered slightly for clarity. The figure is taken from DFO (2020).

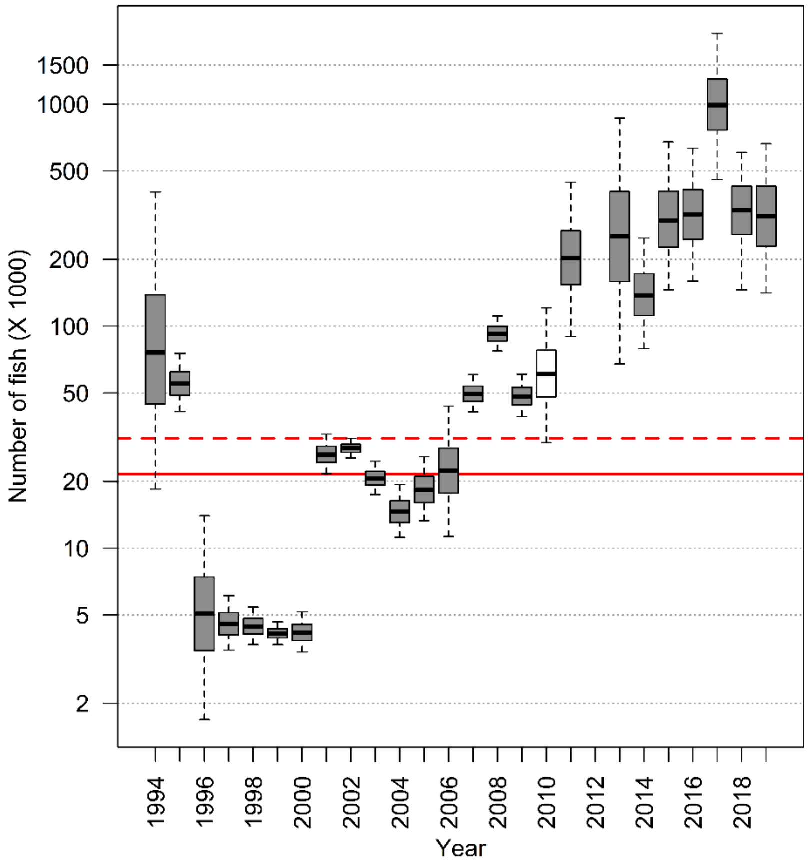


Figure 3.2. Estimated abundance of adult Striped Bass spawners in the Northwest Miramichi estuary between 1994 and 2019. The estimates are shown on a logarithmic scale for visibility of the full range of abundance values over the time series. The estimate for 2010 (unshaded interquartile box) is considered to be an underestimate due to the earlier timing of the spawning events (Douglas and Chaput 2011a). There is no estimate for 2012 because spawning was very early and Striped Bass left the sampling area prior to monitoring activities (DFO 2013). Box plots are interpreted as follows: dash is the median, boxes are the interquartile range, and the vertical dashes are the 5th to 95th percentile ranges. The solid and dashed horizontal lines show the recovery objectives defined in the Recovery Potential Assessment in support of the Species at Risk Act listing decision process (DFO 2006). The figure is taken from DFO (2020).

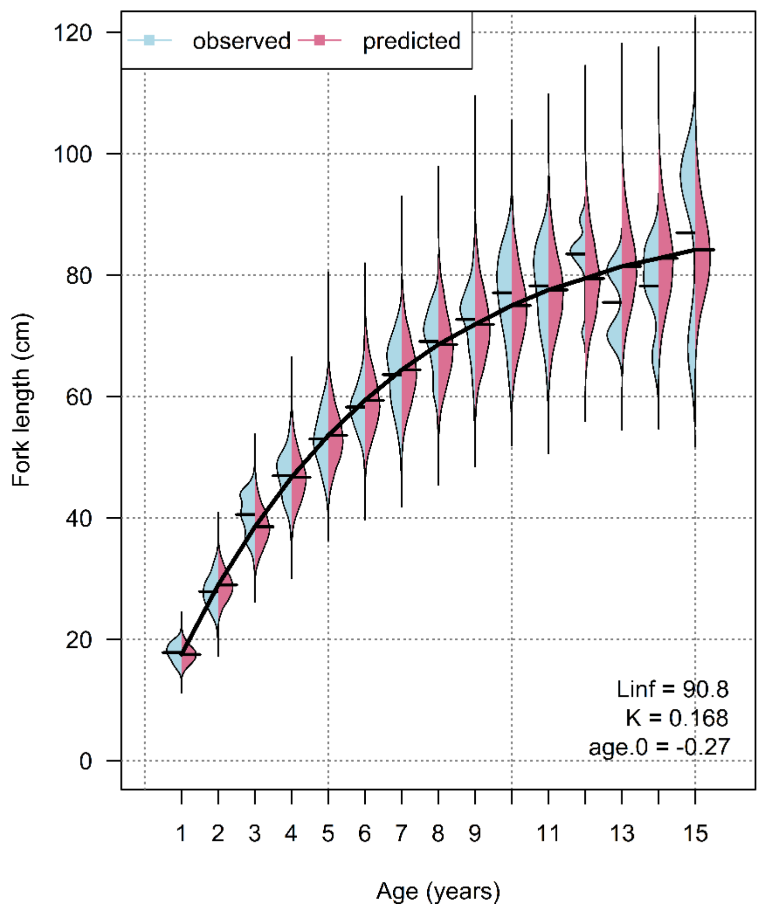


Figure 3.3. Bean plot summaries of the fork length distributions (cm) at age for the observed data used in the von Bertalanffy model fits (light blue) and the posterior distribution of the predicted fork length at age (light red) of Striped Bass from the Miramichi River. The solid black line is the mean predicted fork length at age from the posterior distributions

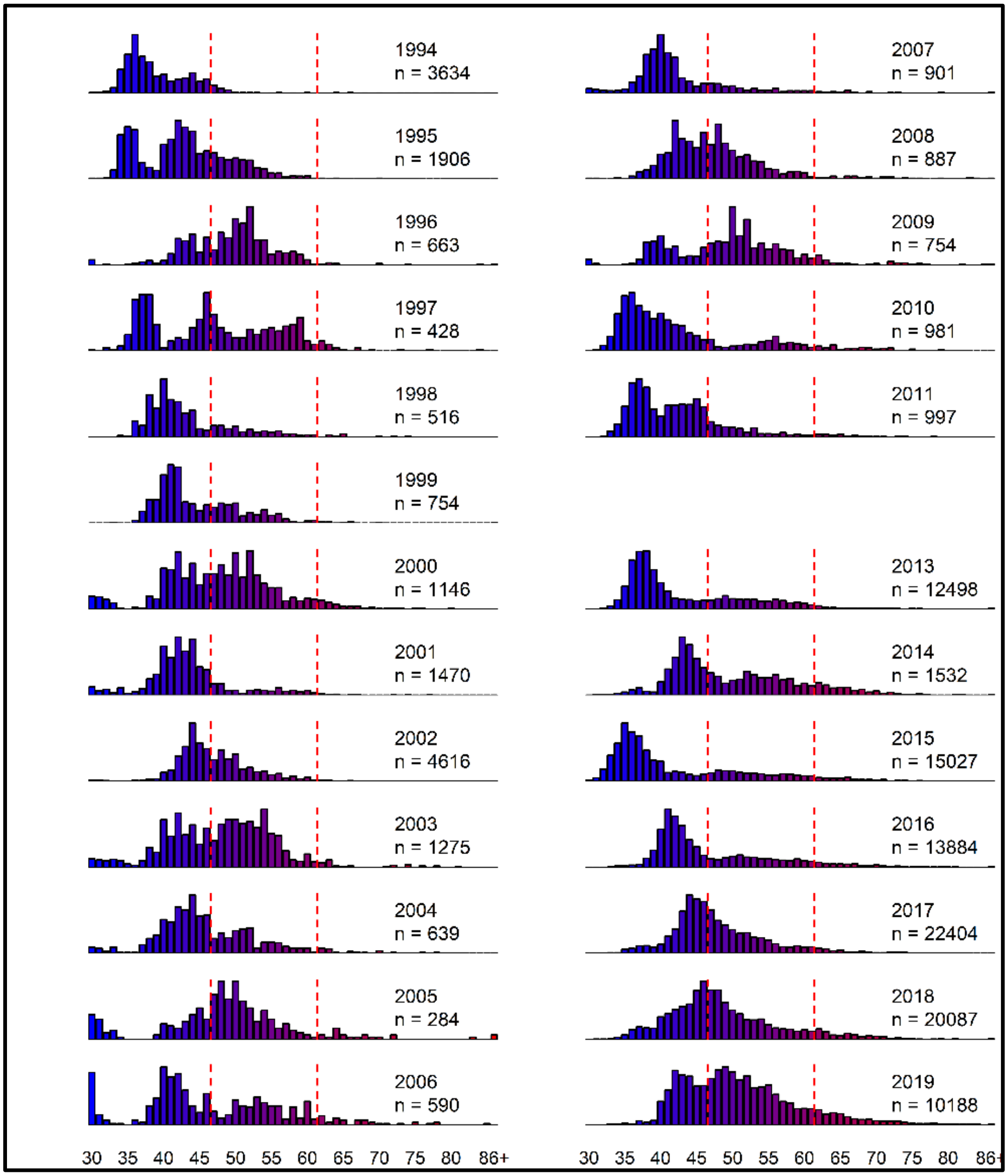


Figure 3.4. Sampled fork length distributions (cm bins) of Striped Bass on the spawning grounds, 1994 to 2019. The dashed vertical lines in each panel correspond to the minimum and maximum length range (47 to 61 cm) of the recreational fishery retention slot limit in effect since 2014.

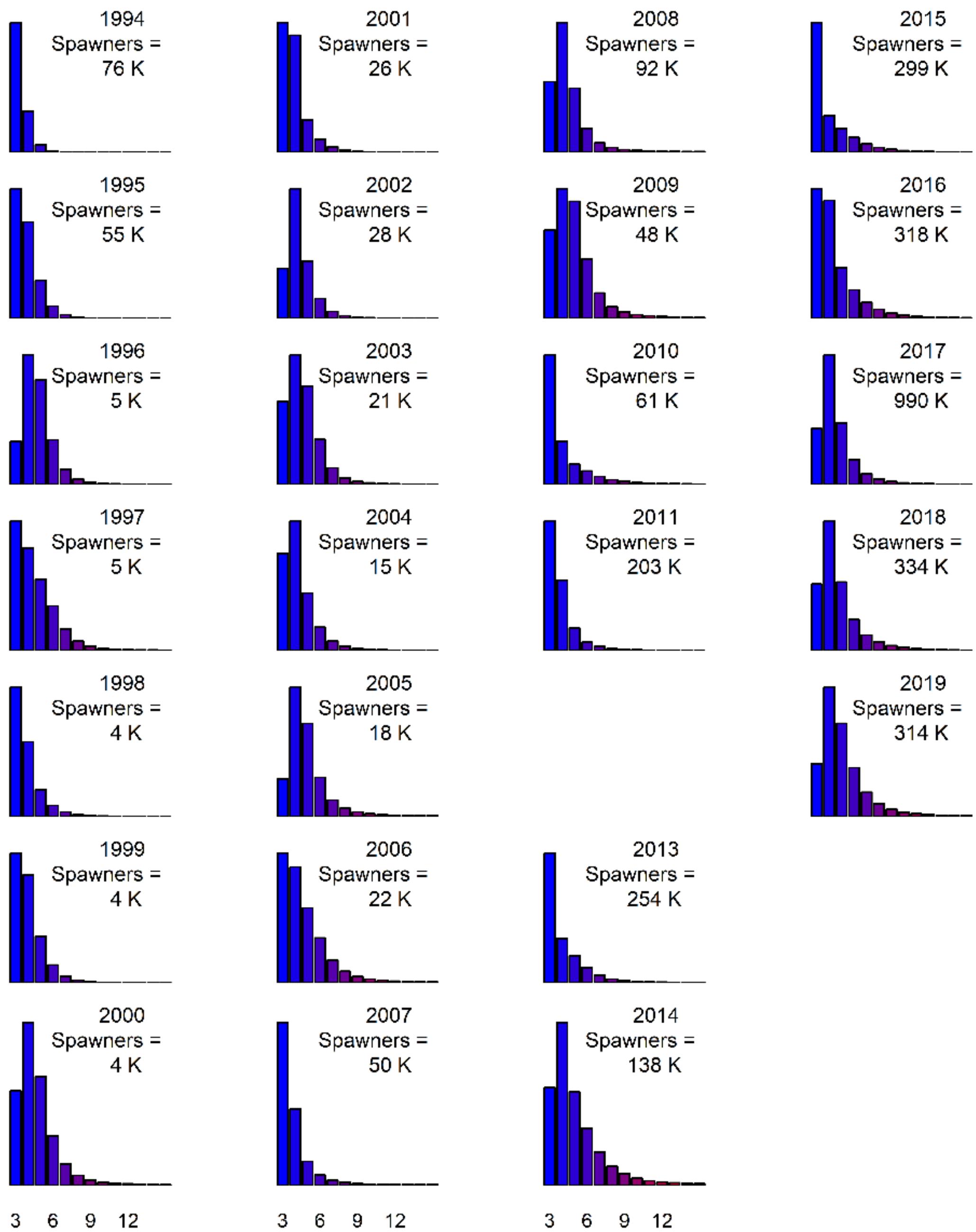


Figure 3.5. The estimated abundances (number, on a relative scale) at age of Striped Bass on the spawning grounds, 1994 to 2019, excluding 2012. The last age group includes fish age 15 and older. In each panel, the median of the estimated spawner abundance (thousands, K) is shown. The estimate for 2010 is considered to be an underestimate due to the earlier timing of the spawning events (Douglas and Chaput 2011a). There is no estimate for 2012 because spawning was very early and Striped Bass left the sampling area prior to monitoring activities (DFO 2013). Estimated spawner abundances at age are provided in Appendix 3.

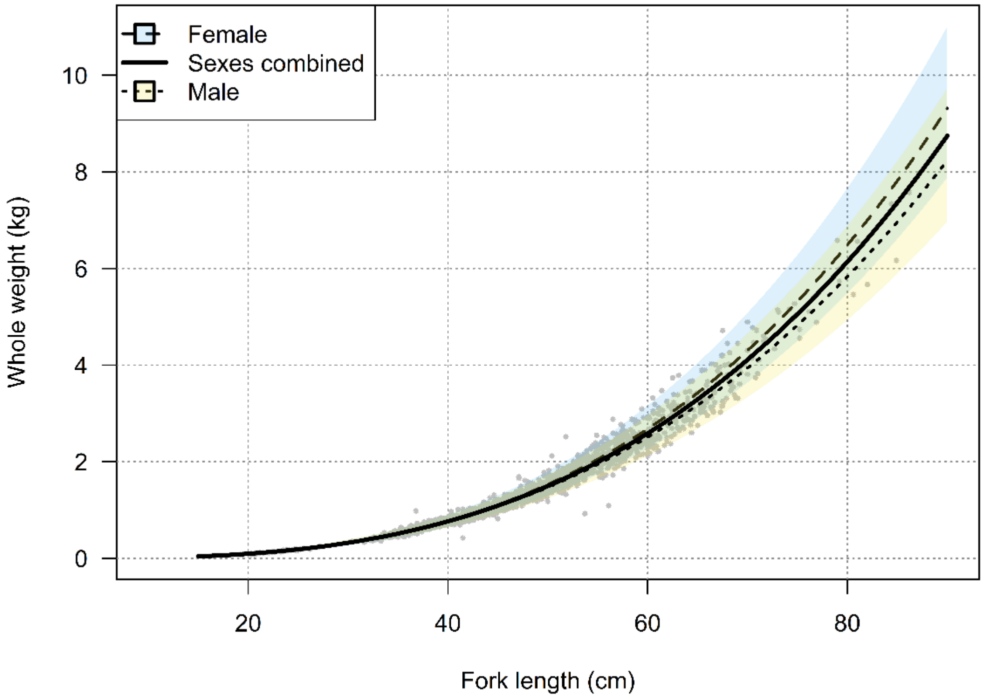


Figure 3.6. Fork length (cm) to whole weight (kg) relationship for Striped Bass from the Miramichi River, obtained from samples collected in May and June 2013 to 2015. The solid line is the mean regression line for sexes combined, the dashed line is for female bass, and the dashed line is for male bass. The coloured polygons represent the approximate 95% confidence interval for the mean line for females (light blue) and males (light yellow), respectively.

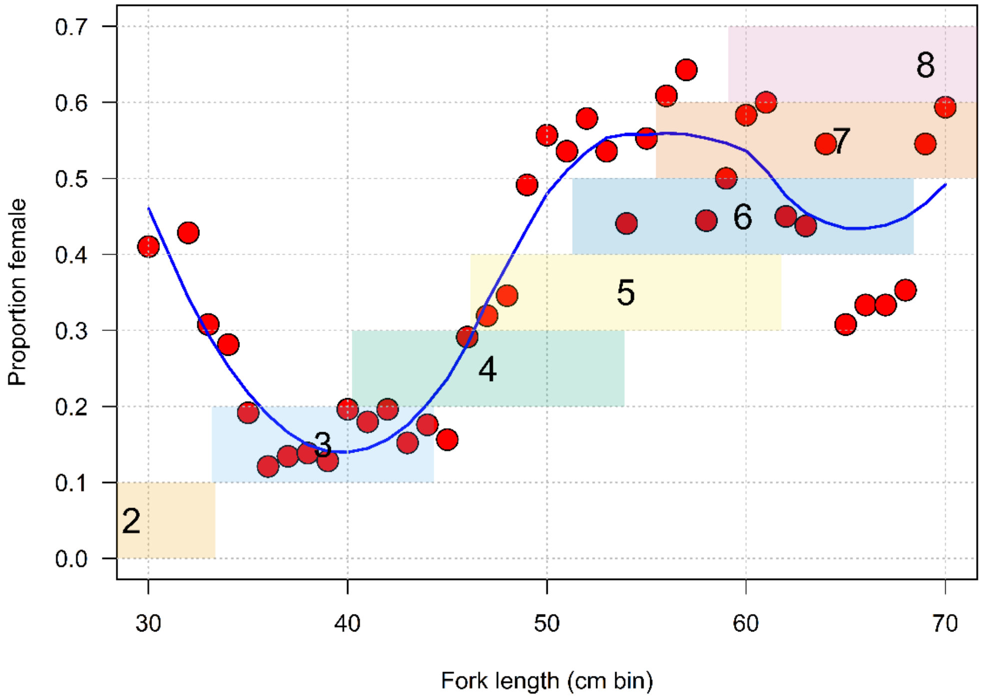


Figure 3.7. Proportion female by fork length (cm bin) of Striped Bass from the Miramichi River, obtained from sacrificed samples collected in May and June, 2013 to 2015. The blue line is a LOESS smoother of the proportion female at age (span = 0.5). The shaded rectangles illustrate the 95% confidence interval range of the predicted fork length for ages 2 to 8; for ages 2, 7 and 8, the confidence range extends beyond the fork length axis range. The size range of samples collected was 19.2 to 86.2 cm fork length. The symbol for the 30 cm fork length bin includes all bass less than or equal to 30 cm (n = 39) and the symbol for the 70 cm fork length bin includes all bass greater than or equal to 70 cm (n = 32). Sample sizes in fork length bins for other symbols range from n = 7 at 32 cm to n = 102 at 42 cm.

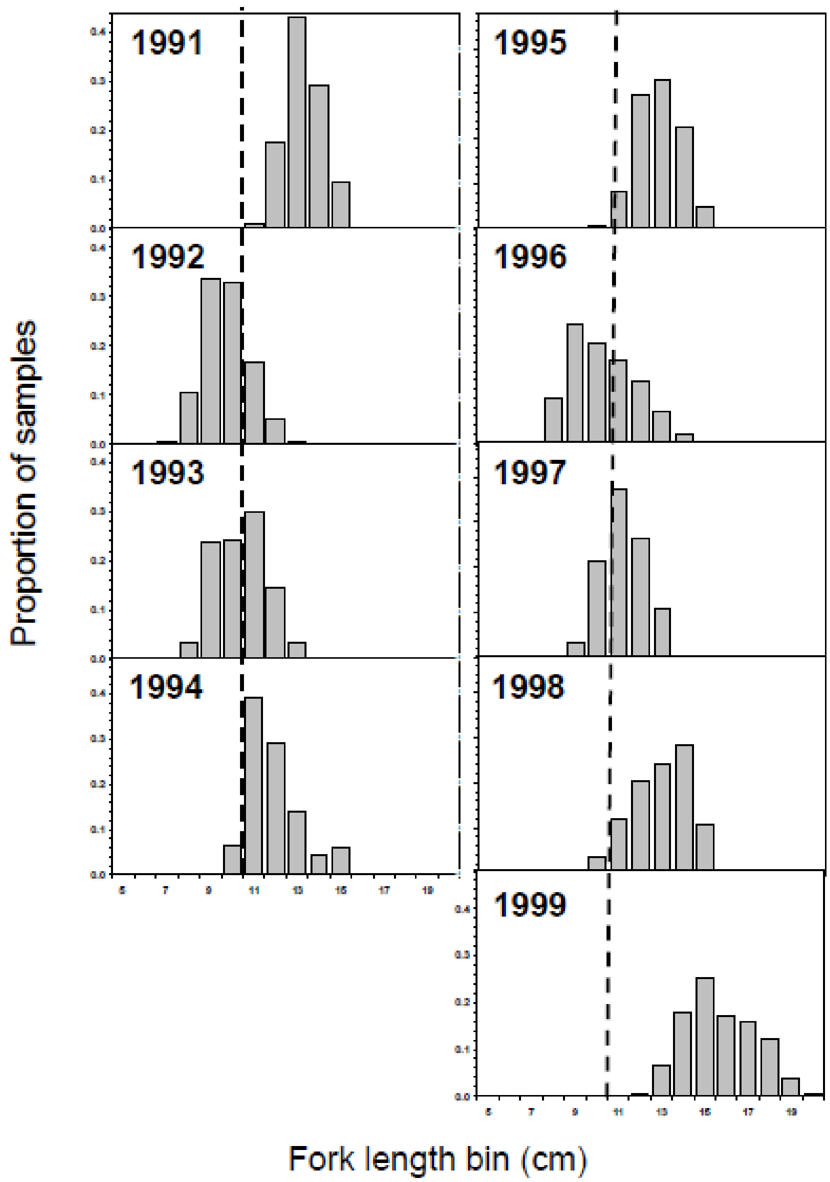


Figure 3.8. Length frequencies of young-of-the-year Striped Bass sampled in the fall open-water smelt fishery of Miramichi Bay (1991 to 1998) and the Tabusintac estuary (1999). The vertical hatched line at the interval between the 10 and 11 cm bins is included to illustrate the size variability among years. The figure is taken from Douglas et al. (2006).

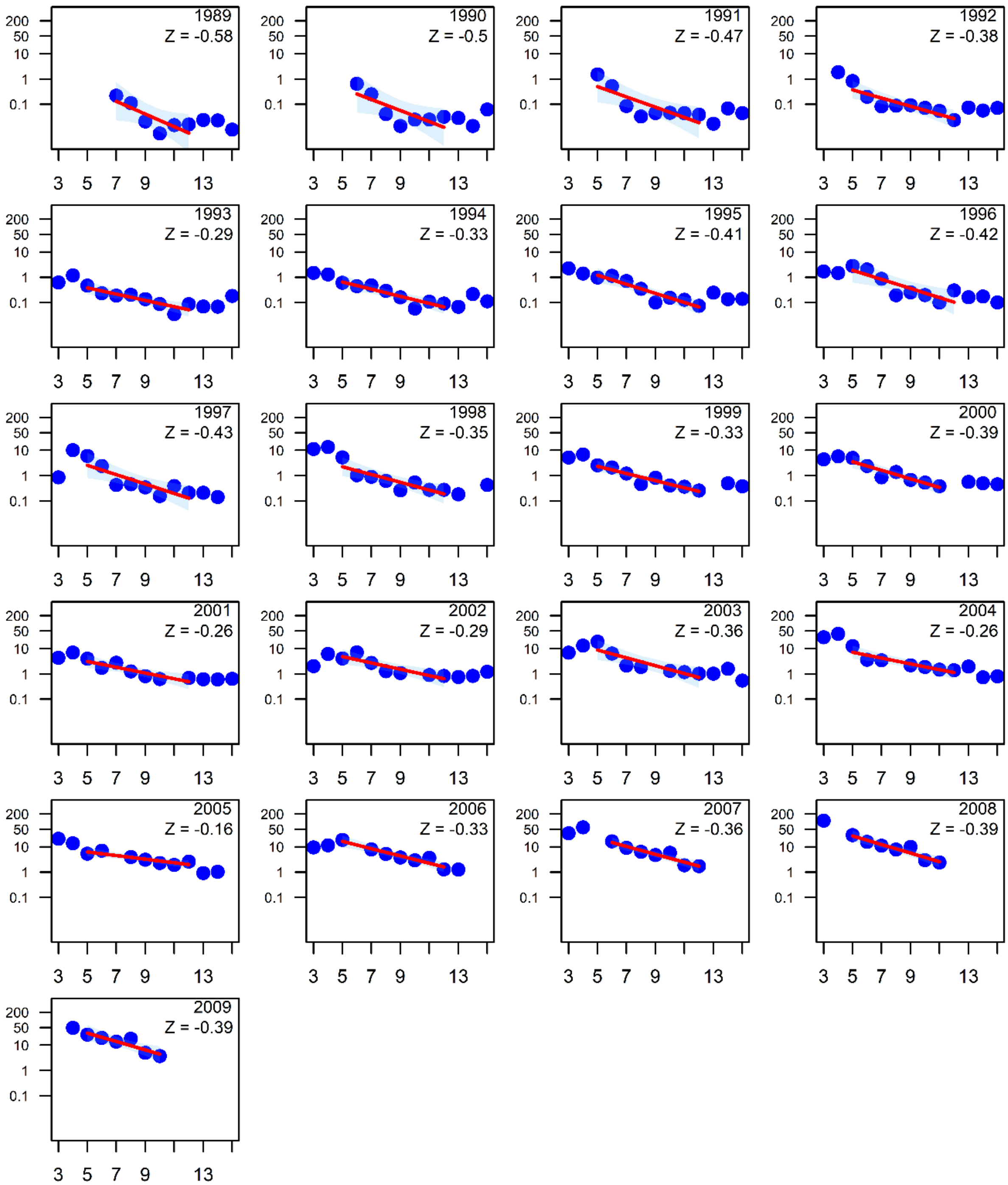


Figure 3.9. Cohort decline analysis based on changes in the natural log of assessed abundances at age by cohort for Striped Bass from the southern Gulf of St. Lawrence. The vertical axis in each plot is on the scale of the natural log of assessed abundance at age (axis labels are in thousands of fish) and the horizontal axis is the age. The red line is the predicted log of abundance over the range of ages 5 to 12 for cohorts with at least six observations within the age range 5 to 12.

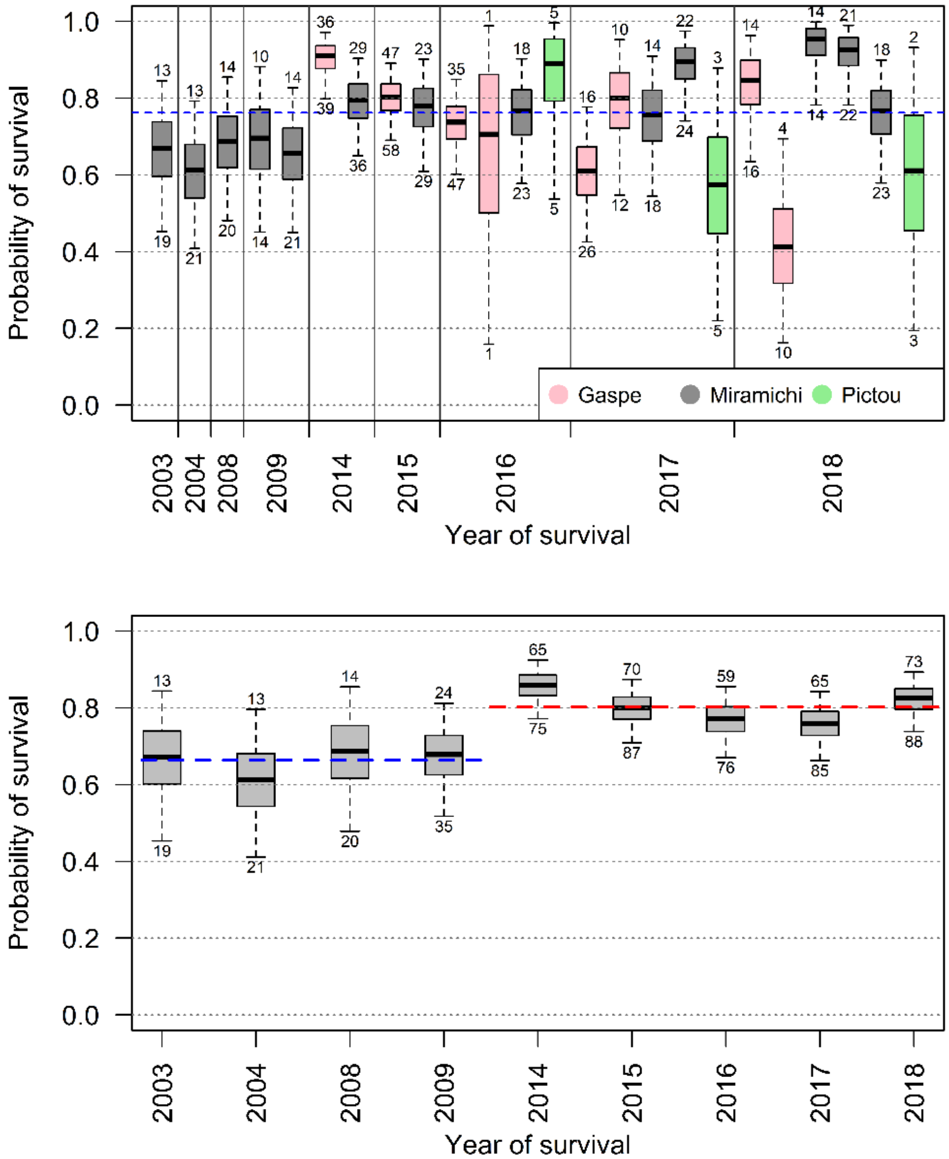


Figure 3.10. Posterior distributions of estimated probabilities of survival of acoustically tagged Striped Bass based on sequential detections in the Miramichi by inferred year of survival for Striped Bass tagged (V13 and V16 tag groups and size groups combined) and released in three locations. The upper panel shows the posterior distributions by year of inferred survival with the horizontal dashed line representing the median across all years and tagging locations. The bottom panel shows the posterior distributions of inferred survival by year, pooled over size groups, tag types and release locations. The horizontal dashed lines represent the median annual survival probabilities for the 2003 to 2009 period and the 2014 to 2018 time period. The inferred year of survival represents the calendar year (eg. 2017 is the survival over the period winter 2016/17 to winter 2017/18). Boxplots show the 2.5 to 97.5 percentile ranges as whiskers, the interquartile range as the rectangle, and the median as the internal dash. The numbers shown in each panel for each boxplot are the numbers of fish detected (above) and the number of tags available (below) used in the estimation of the survival rates.

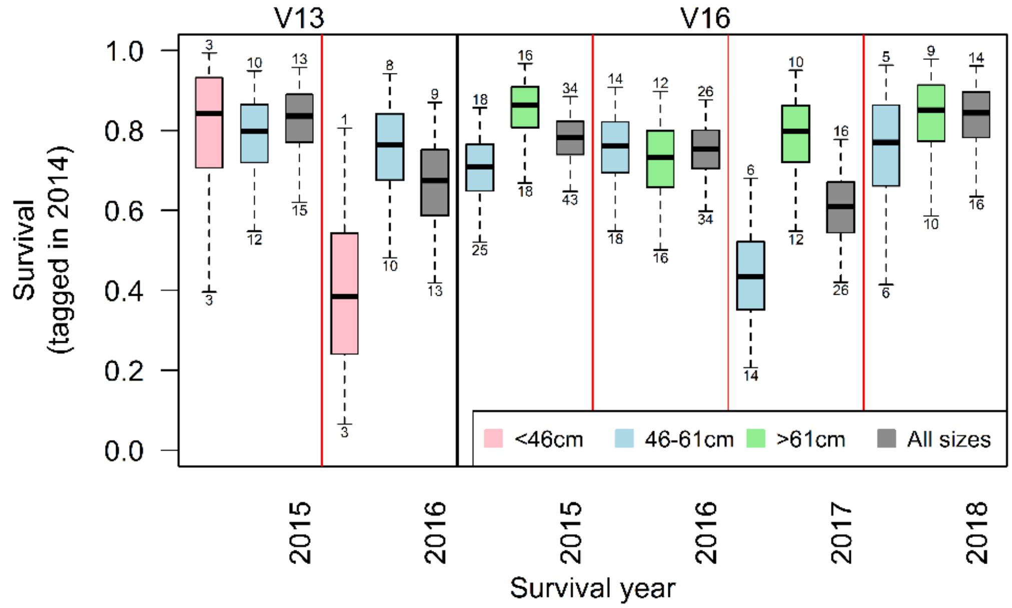
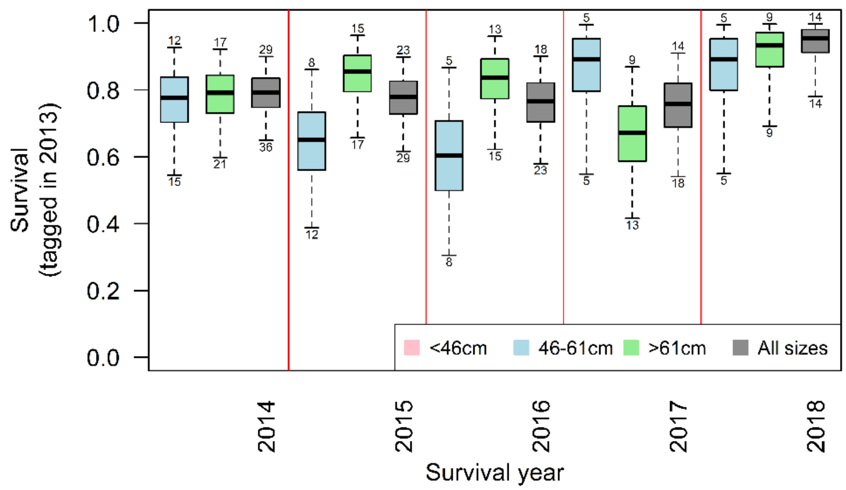


Figure 3.11. Posterior distributions of the sequential survival rate estimates of Striped Bass by size group tagged with V13 or V16 acoustic tags from the Gaspe release location in 2014. Size groups correspond to the fork length size group of the fish at tagging. Box plots are interpreted as in Figure 3.10. The numbers shown in each panel for each boxplot are the numbers of fish detected (above) and the number of tags available (below) used in the estimation of the survival rates.



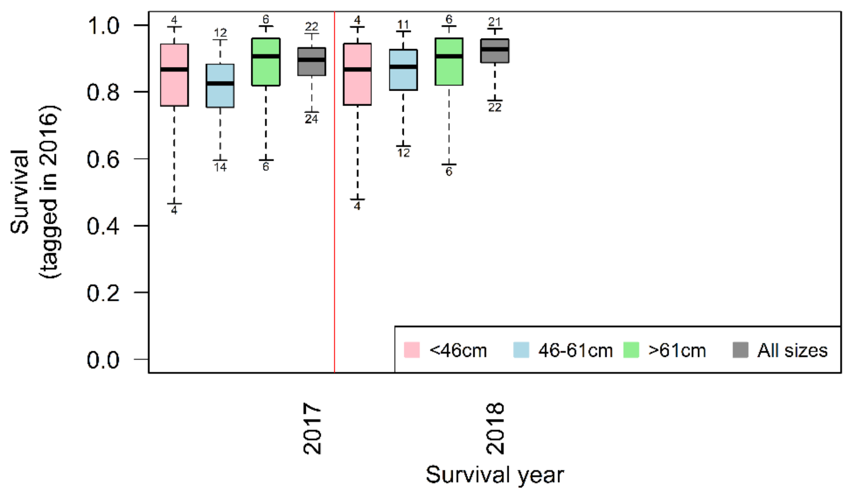


Figure 3.12. Posterior distributions of the sequential survival rate estimates of Striped Bass by size group tagged with V16 acoustic tags from the Miramichi release location in 2013 (upper panel) and 2016 (lower panel). Size groups correspond to the fork length size group of the fish at tagging. Box plot are interpreted as in Figure 3.10. The numbers shown in each panel for each boxplot are the numbers of fish detected (above) and the number of tags available (below) used in the estimation of the survival rates.

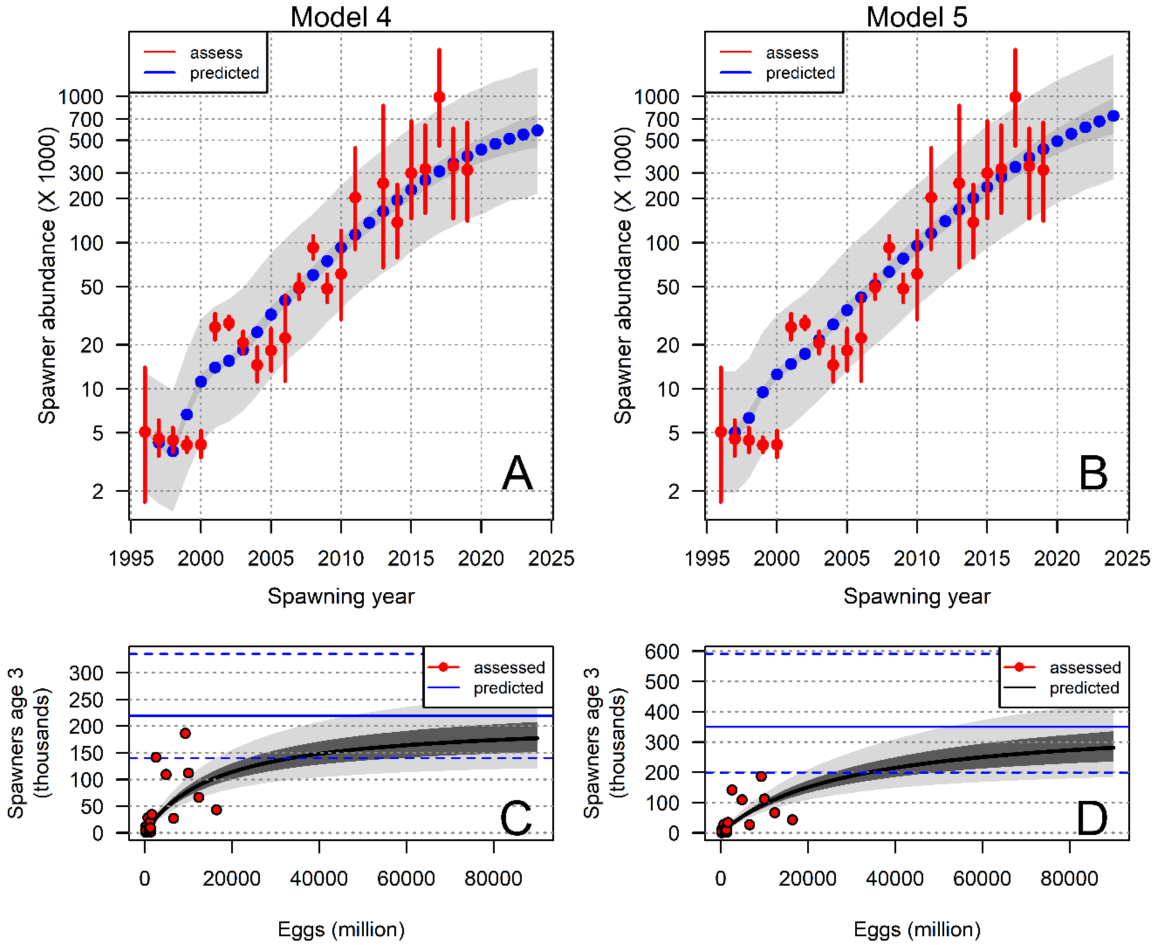


Figure 4.1. Observed and predicted total spawners of Striped Bass from the southern Gulf of St. Lawrence (upper row; A, B) and the stock and recruitment predicted abundance of spawners at age 3 years old (lower row; C, D) based on Model 4 (left panels A and C) and Model 5 (right panels B and D). In the upper row of panels, the assessed abundances are shown as red symbols for the median with 5th to 95th percentiles ranges as red vertical lines. The blue symbols are the predicted abundances, the darker grey shading is the 5th to 95th percentile range of mean predicted abundance and the light grey shading represents the 5th to 95th percentile range of the predicted spawner abundance accounting for the full process uncertainty. Note the y-axis abundance is shown on the log scale. In the lower panel, the assessed abundance of 3-year old spawners is shown as red symbols and the predicted median line with 25th to 75th and 5th to 95th percentile intervals are dark and light grey shading, respectively. The upper (blue) solid horizontal line (median) and the dashed horizontal lines (5th to 9th percentile range) are the Beverton-Holt asymptotic abundance (K) whereas the lower (red) solid horizontal line (median) and the dashed horizontal lines (5th to 9th percentile range) are half saturation values (50 % K) from the Beverton-Holt model.

Figure 4.

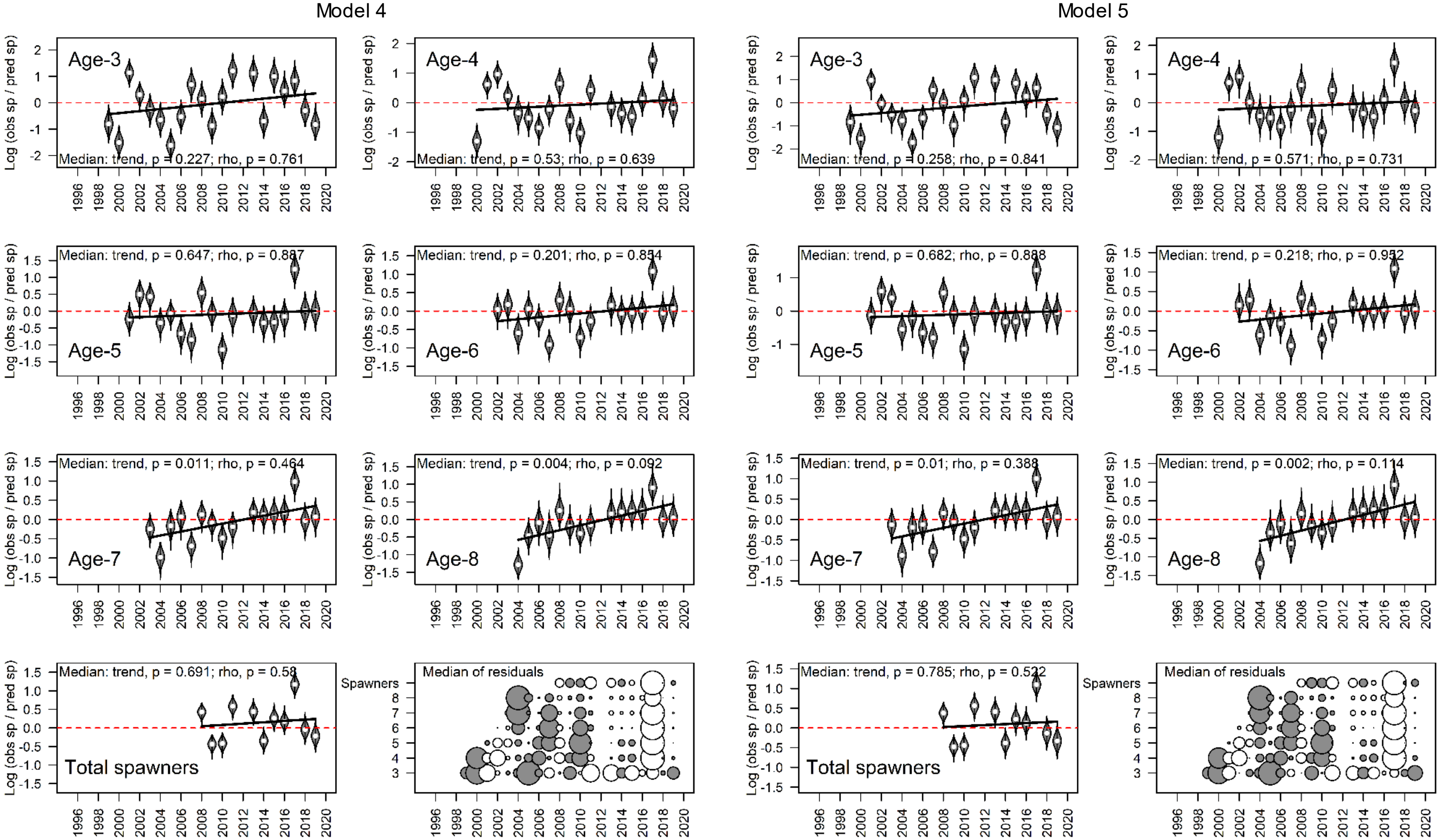


Figure 4.2. Residual plots expressed as log(assessed abundance / predicted abundance) at ages 3 to 8 and total spawners, and relative (by age group) bubble plot of logged residual patterns. Also shown in each panel of residuals are the p-value for the temporal linear trend in residuals and the p-value for the first order autocorrelation of the residuals (from package EnvStats in R).

A)
Model 4

B)
Model 5

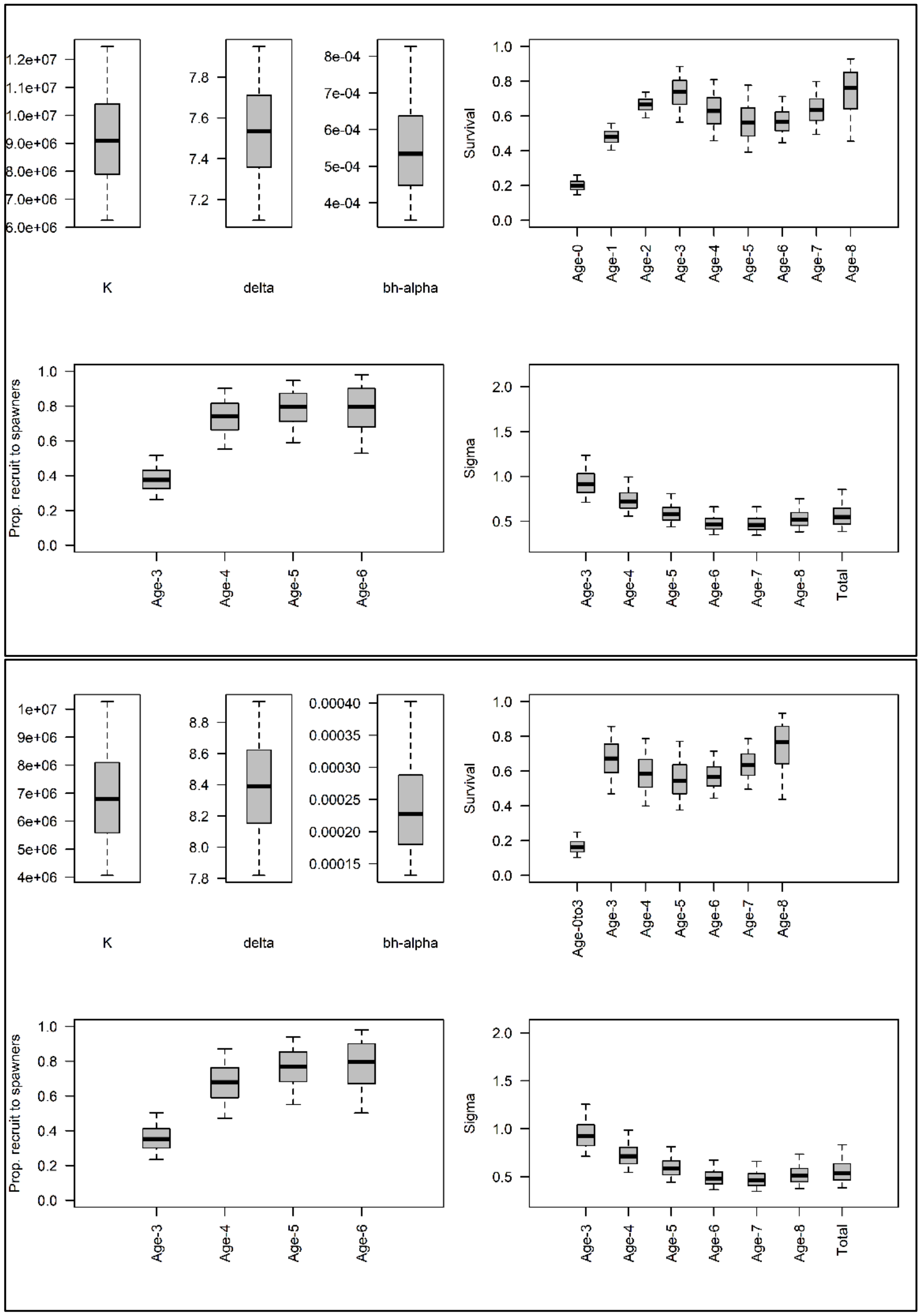


Figure 4.3. Posterior distributions of parameter estimates of the population dynamics for the Striped Bass population of the southern Gulf, from model 4 (A, upper panel) and model 5 (B, lower panel). The boxplot summaries show (from top left to bottom right): K (carrying capacity), delta (-log(bh.alpha)), bh.alpha (survival rate at the origin), survivals at age, proportion recruits that become spawners, and sigma (log of the standard deviation of the likelihood of observed spawner abundance at ages 3 to 8 and for total spawners). Boxplots summarize the following statistics of the posterior distributions: vertical dashed lines are the 5^{th} to 95^{th} percentile range, the box encompasses the interquartile range and the horizontal dash is the median.

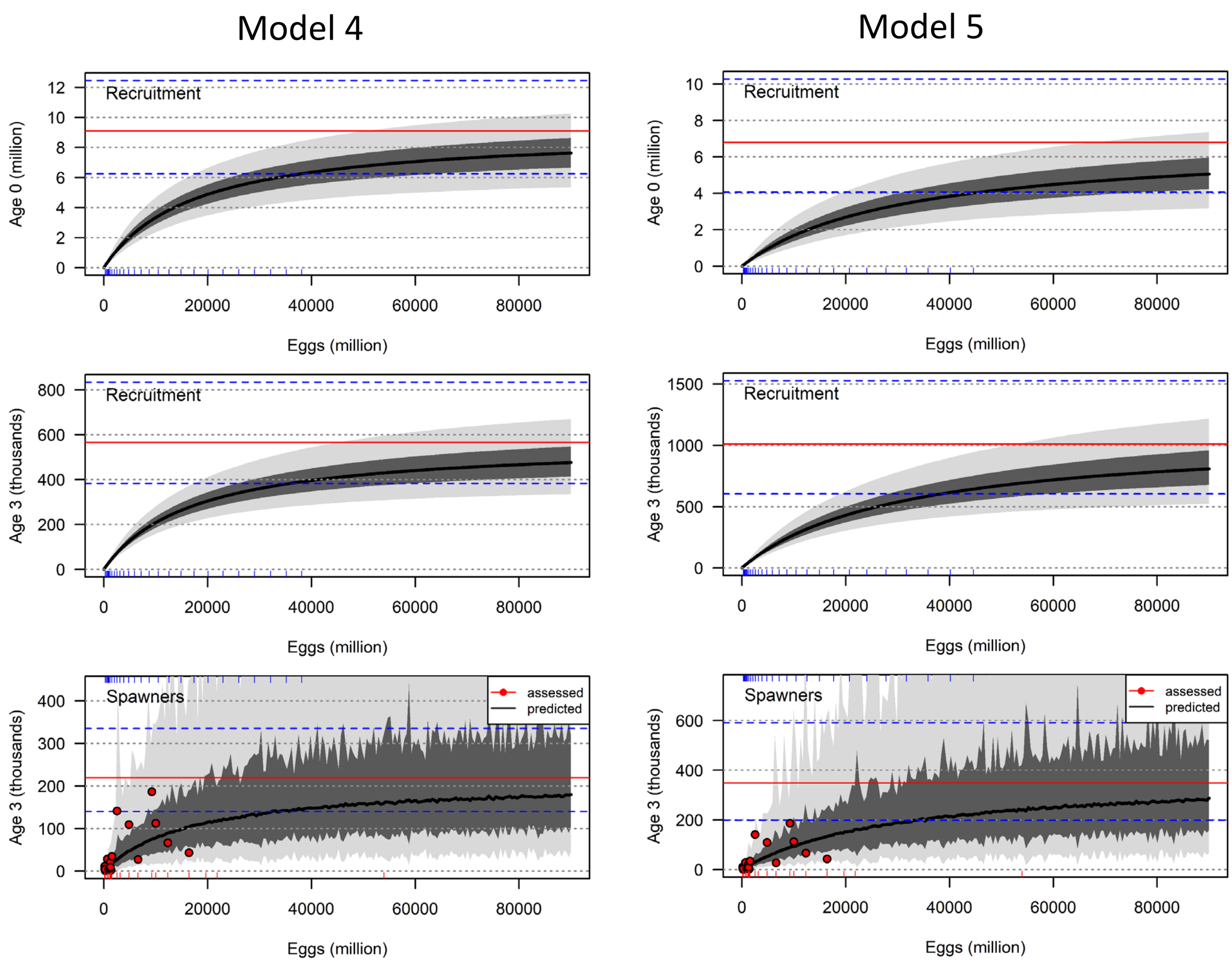


Figure 4.4. Predicted Beverton-Holt stock and recruitment function for abundance of Striped Bass at age-0, (upper panel), adjusted to abundance at age-3 (middle panel) and for predicted spawners at age-3 (bottom panel) based on Model 4 (left column) and Model 5 (right column). The light and dark shading in the upper and middle panels are the interquartile range and the 5th to 95th percentiles range, respectively, of the mean abundance. In the lower panel, the dark and light shading are the interquartile range and the 5th to 95th percentile range accounting for the uncertainty (log sigma-3) in the predicted abundance of spawners at age-3. The assessed abundance of spawners at age-3 corresponding to assessed egg production by cohort is overlain as red symbols in the bottom panel. In all three panels, the solid horizontal line is the median of the predicted carrying capacity scaled to recruitment and spawners at age-3 and the lower and upper dashed lines are the 5th to 95th percentile range.

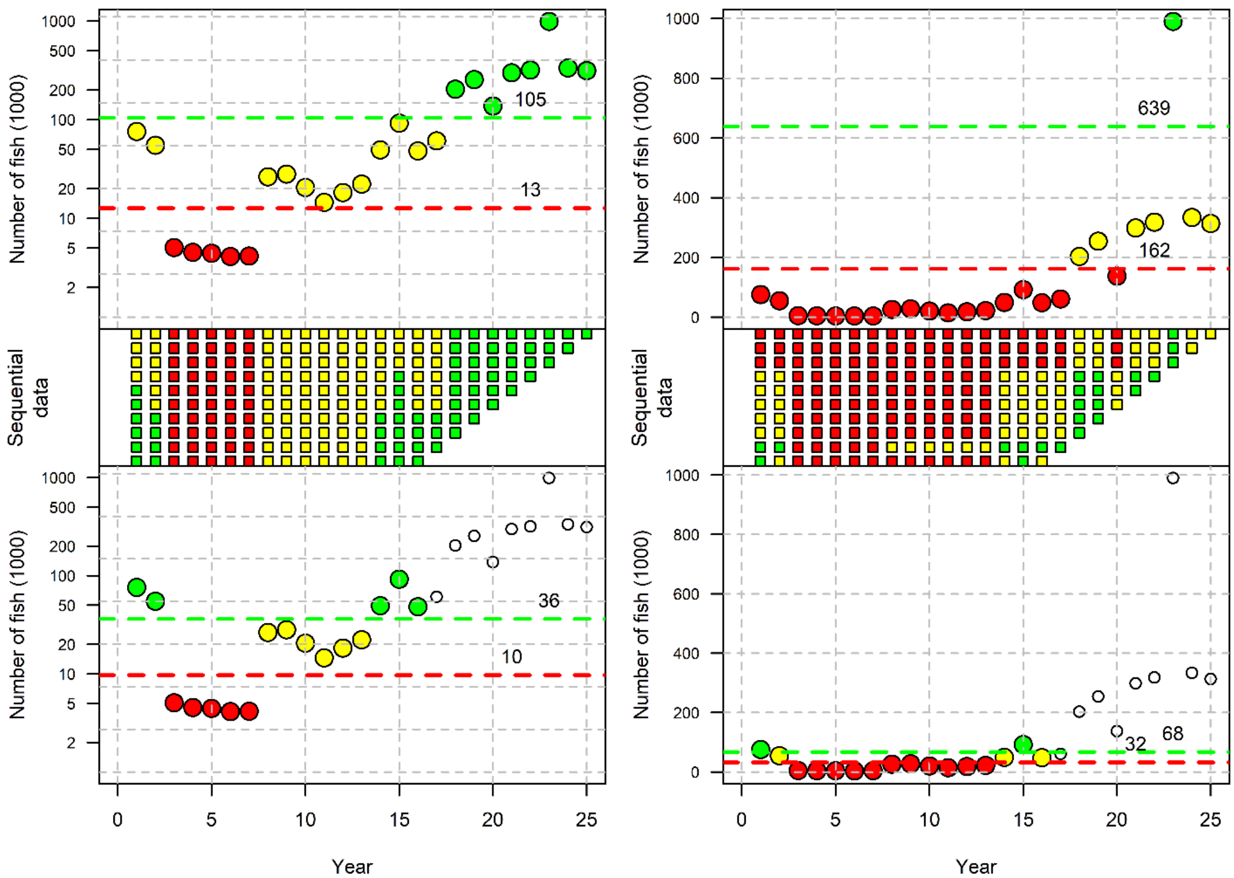


Figure 6.1. The effect of scale of the observations and the effect of the included time series used to assign annual abundance estimates of Striped Bass to one of three zones. The left column presents the results when the log(abundance) is used and the right column presents the results for the natural scale. The upper row of plots shows the status (red equivalent to critical, yellow equivalent to cautious, green equivalent to healthy) of the annual estimated abundances based on groups defined using the entire time series, 1994 to 2019 (excluding 2012). The bottom row shows the status of the annual estimated abundances for 1994 to 2009 based on groups defined using only the 1994 to 2009 time series (symbols in white are not assigned). In both the upper and bottom rows, the lower horizontal dashed line is the proxy LRP based on the average of the lower and middle group centroids and the upper horizontal dashed line is the proxy for the USR based on the average of the middle and upper group centroids; values for each are printed above each corresponding line. The middle row shows the assigned status colour for the corresponding year (on the vertical) relative to the time series included (by increments of one year for each horizontal line) beginning with the 1996 to 2009 time series in the bottom line of symbols to the 1996 to 2019 time series for the upper line of symbols. In this figure the year sequence represents: 1 = 1994, 18 = 2011, 19 = 2013, to 25 = 2019.

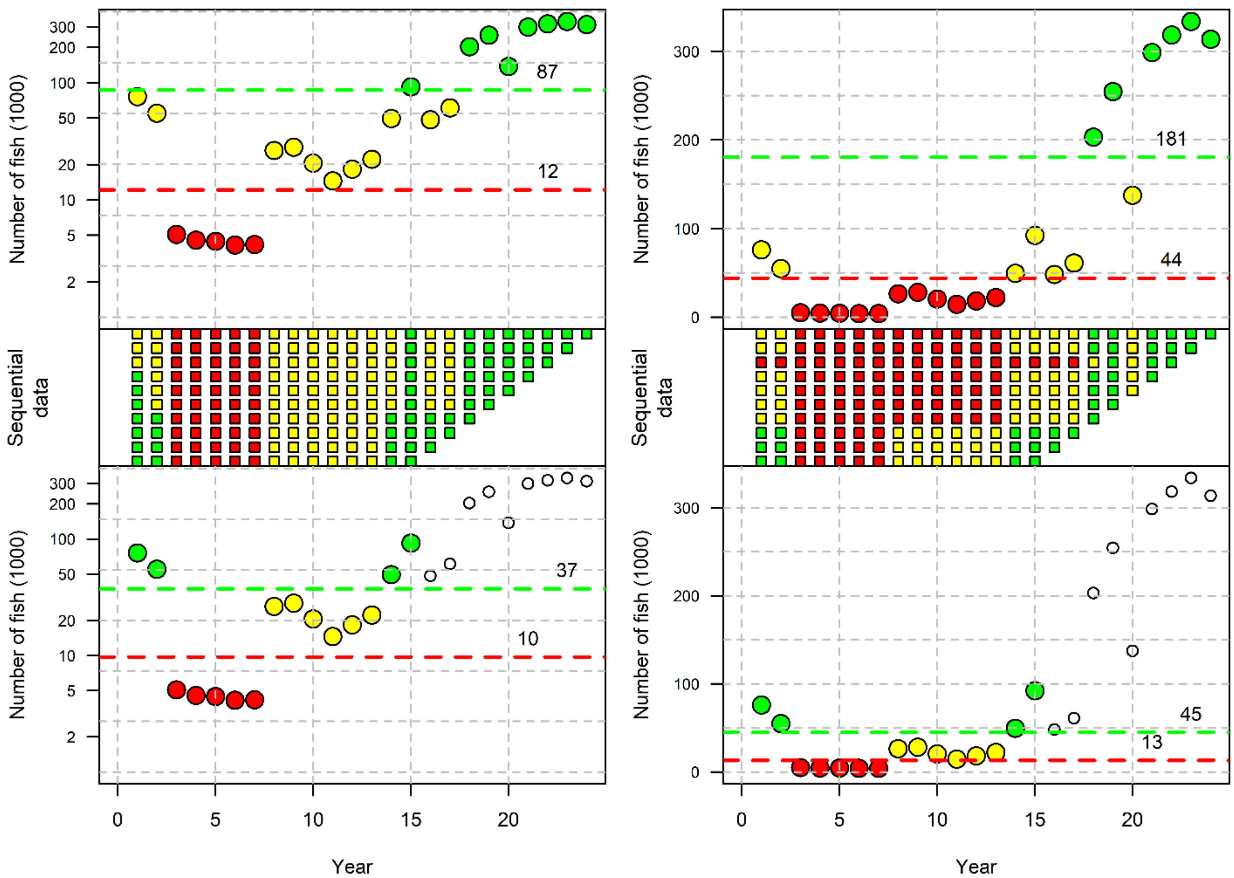


Figure 6.2. The effect of scale of the observations and the effect of the included time series used to assign annual abundance estimates of Striped Bass to one of three zone using the time series of observations that excludes 2017. The plots are interpreted as in Figure 6.1. In this figure the year sequence represents: 1 = 1994, 18 = 2011, 19 = 2013, 22 = 2016, 23 = 2018, 24 = 2019.

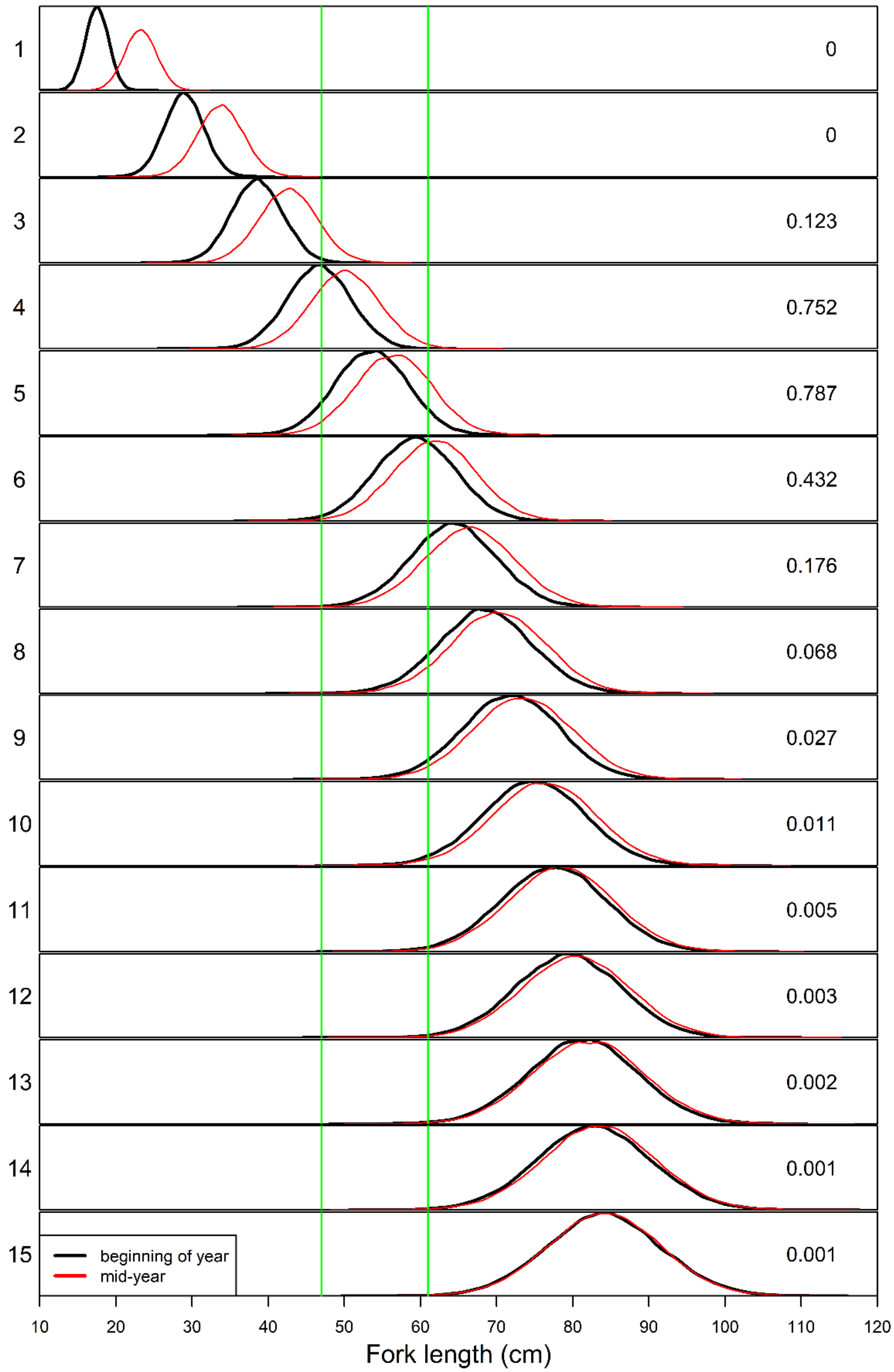


Figure 6.3. Predicted fork length at age distributions (black line start of year, red line mid-year) and the estimate of selectivity at age (s_a) to fully-recruited F (proportion of the age group that is within the fisheries size limits) is shown in the upper right of each age panel. The fisheries management strategy shown (vertical green lines) is a slot size for retention of 47 to 61 cm fork length,.

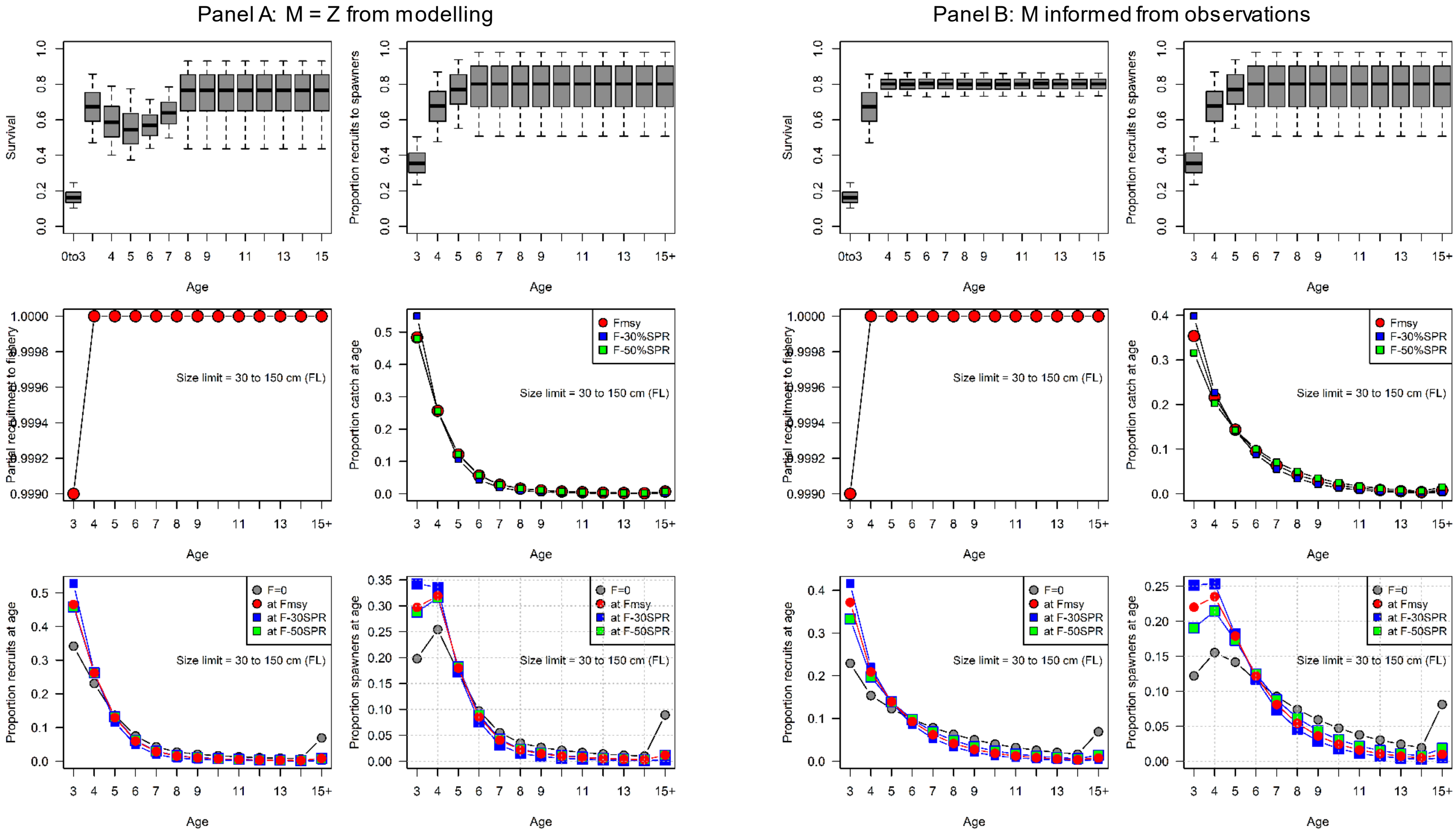


Figure 6.4a. Model 5 - distributions of life history parameters and age structure from equilibrium modelling of Striped Bass, based on parameter estimates and (panel A) modelled estimates of survival rates at ages 4 to 15+ or (panel B) with assumed values for M at ages 4 to 15+ informed from acoustic tag observations. The plots in each panel in reading order from top left to bottom right refer to: survival at age, proportion of recruits that are spawners at age, partial selectivity to the fishery, average proportion catch at age for different fishing rate reference values, average proportion of total abundance at age for different fishing rates, and average proportion spawners at age for fishing rate reference values.

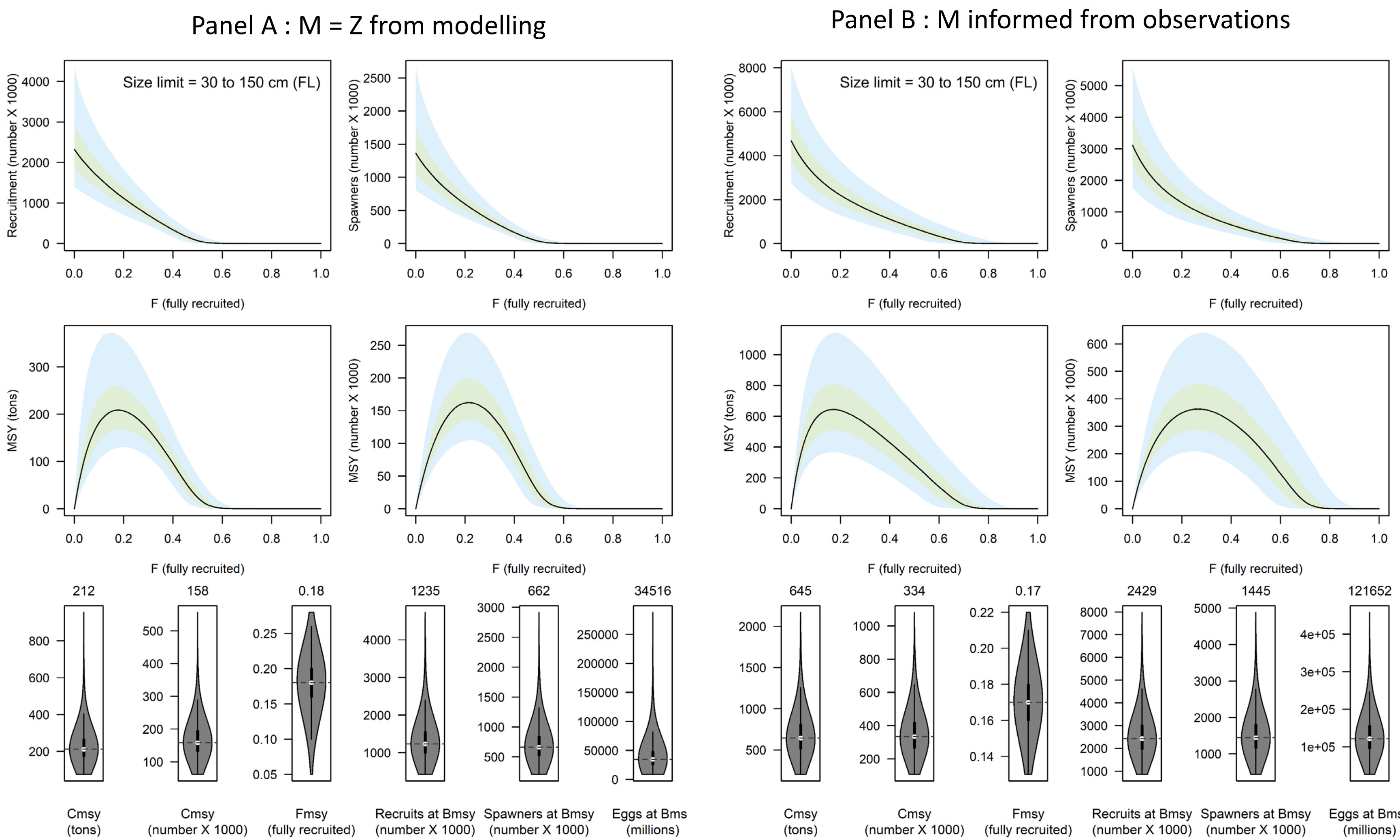


Figure 6.4b. Model 5 - equilibrium modelling abundance, and catch trajectories for increasing levels of F and summary boxplots of reference values associated with MSY, based on parameter estimates from modelling including M=Z (panel A) or with assumed values for M at ages 4 to 15+ (panel B). The plots in each panel refer, in reading order from top left to bottom right to: total abundance for ages 3 to 15+, total spawners aged 3 to 15+, yield in tons, yield in number of fish, and MSY reference values for C_{MSY} (tons), C_{MSY} (number), F_{MSY}, total abundance (number) at B_{MSY}, spawners (number) at B_{MSY}, and total eggs at B_{MSY}.

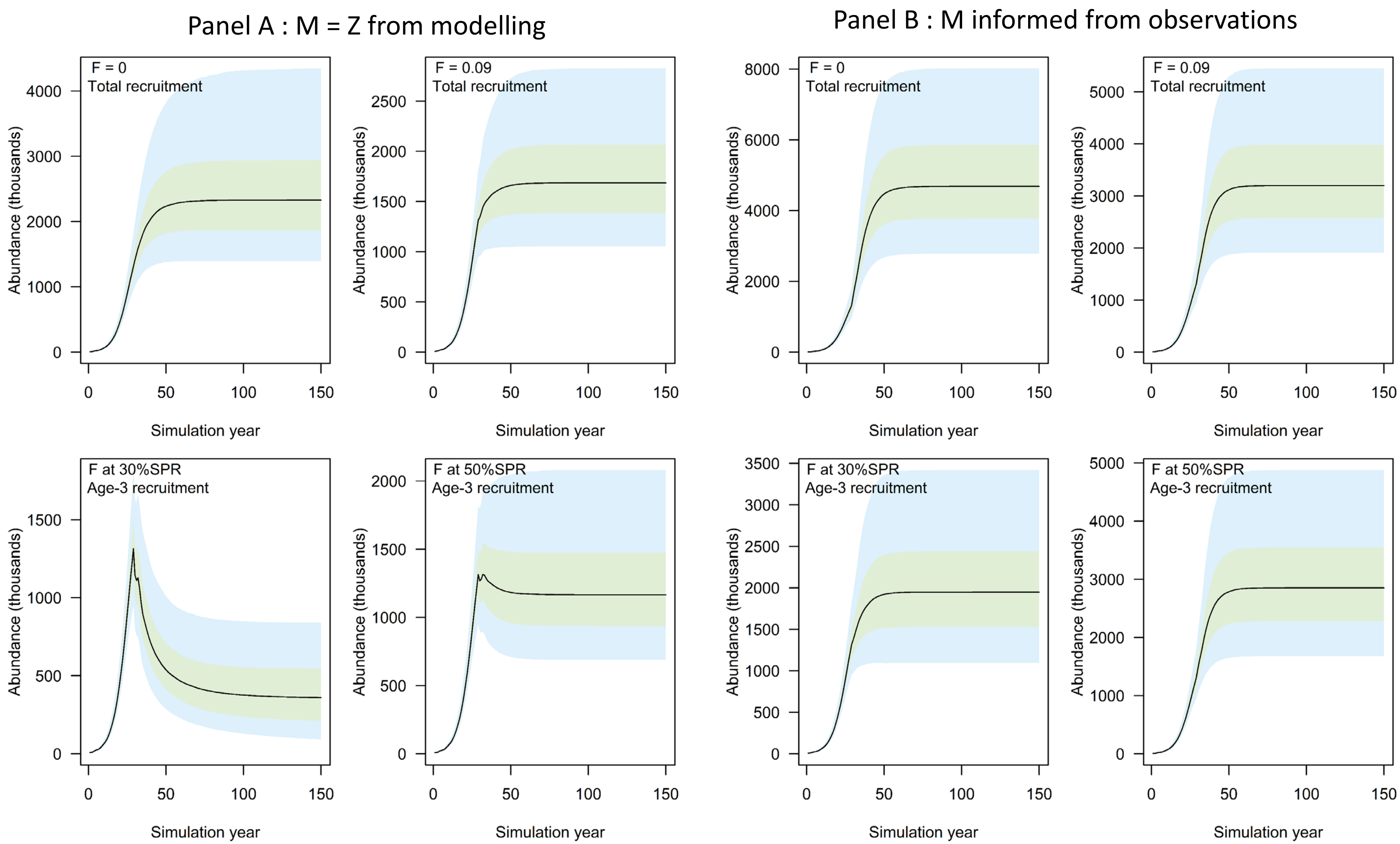


Figure 6.4c. Model 5 - equilibrium modelling of abundance by year of simulation to confirm attainment of equilibrium conditions based on life history parameter estimates from modelling including M=Z (panel A) or with assumed values for M at ages 4 to 15+ (panel B). Estimated abundances for years 1 to 29 are from population modelling, abundances for years 30 to 150 are projected forward.

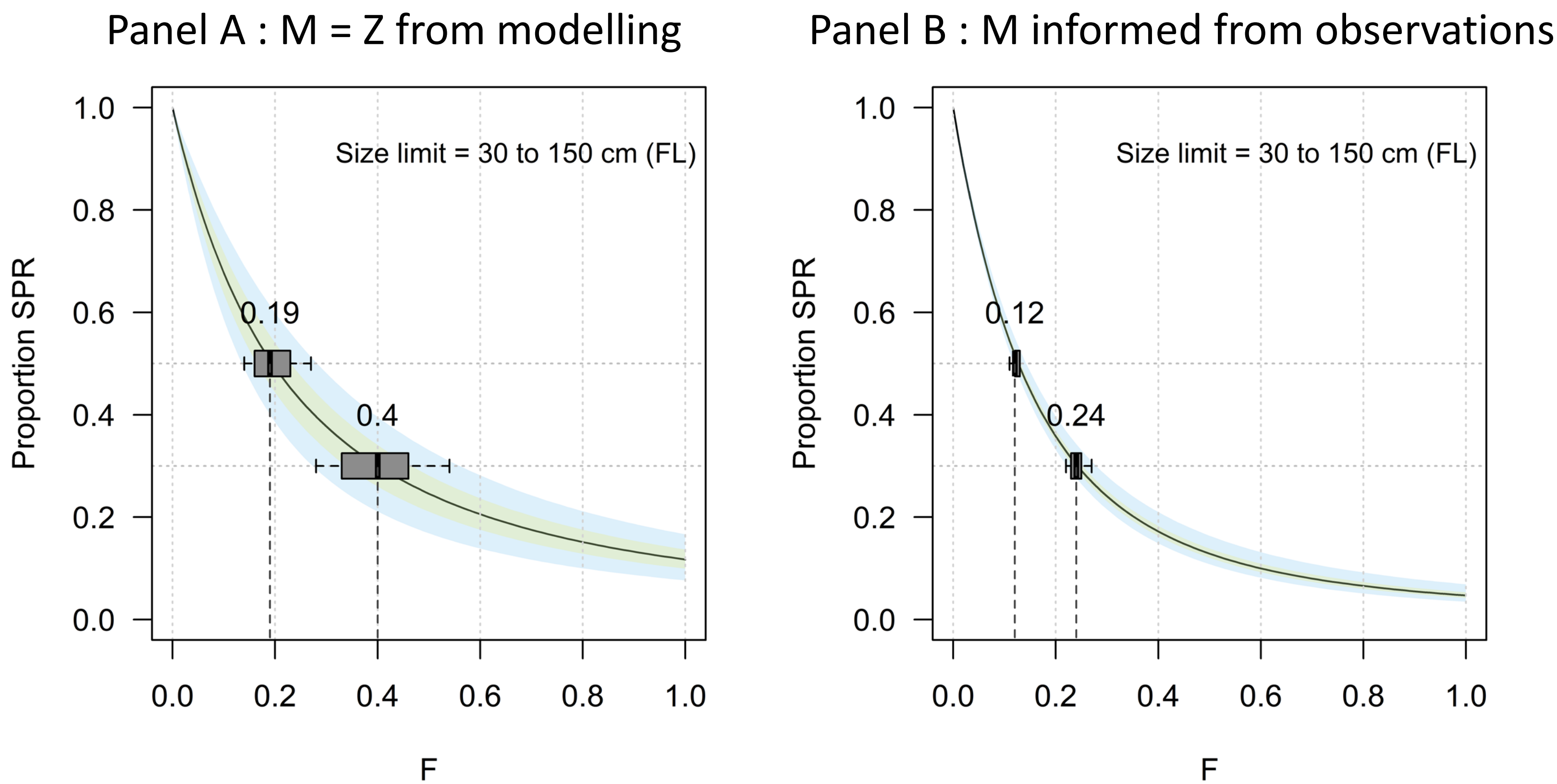


Figure 6.4d. Model 5 - equilibrium modelling of Spawner per Recruit trajectories based on life history parameter estimates from modelling including M=Z (panel A) or with assumed values for M at ages 4 to 15+ (panel B).

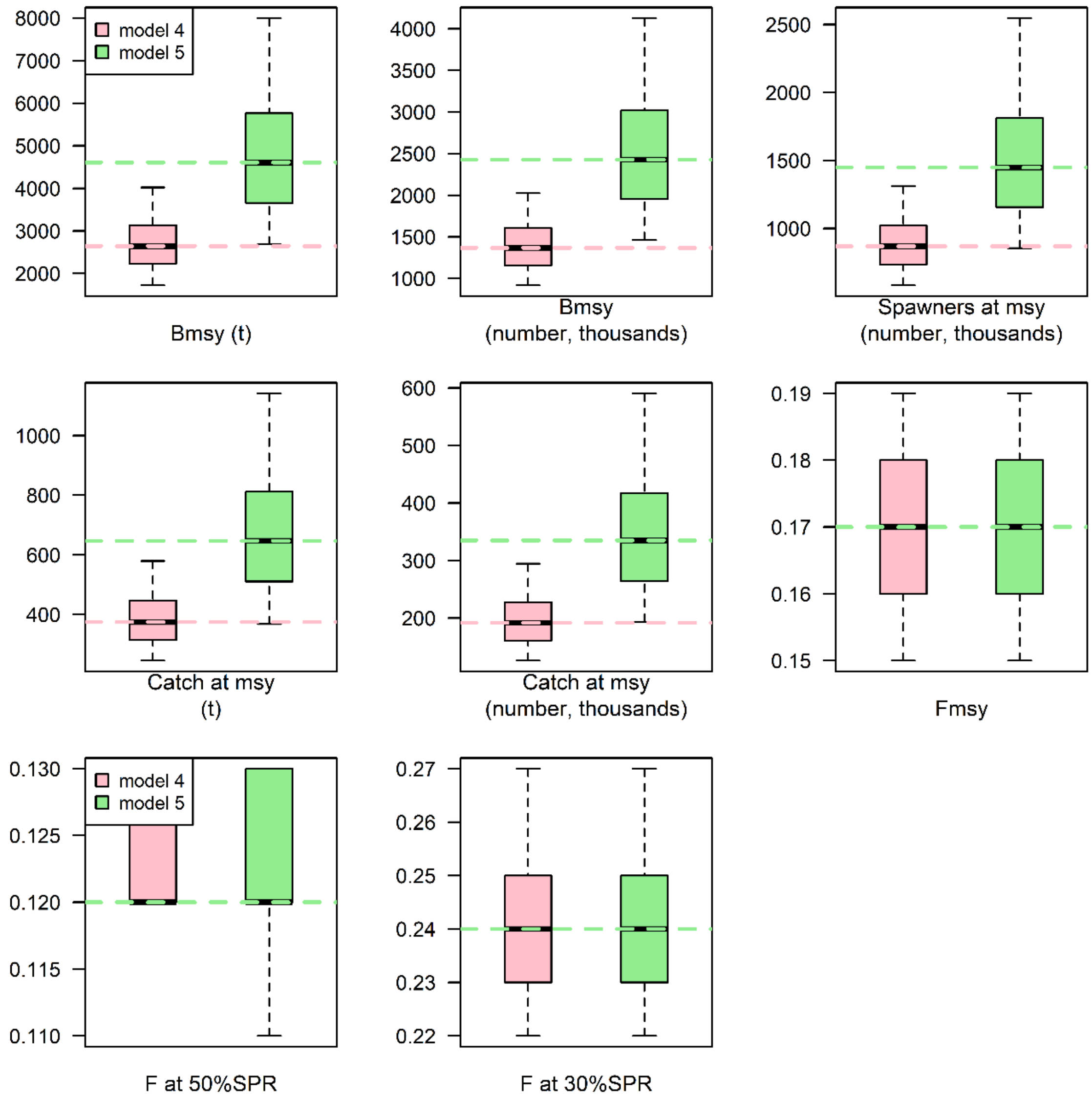


Figure 6.5. Comparison of MSY and SPR reference levels from Model 4 and Model 5 for scenarios with M informed by observations and for the default fishing strategy with no size limit and excluding catch and release mortality. The boxplot summaries are interpreted as follows: vertical dashed lines encompass the 5th to 95th percentile range, the boxes encompass the interquartile range, and the internal dash and dashed horizontal lines are the medians.

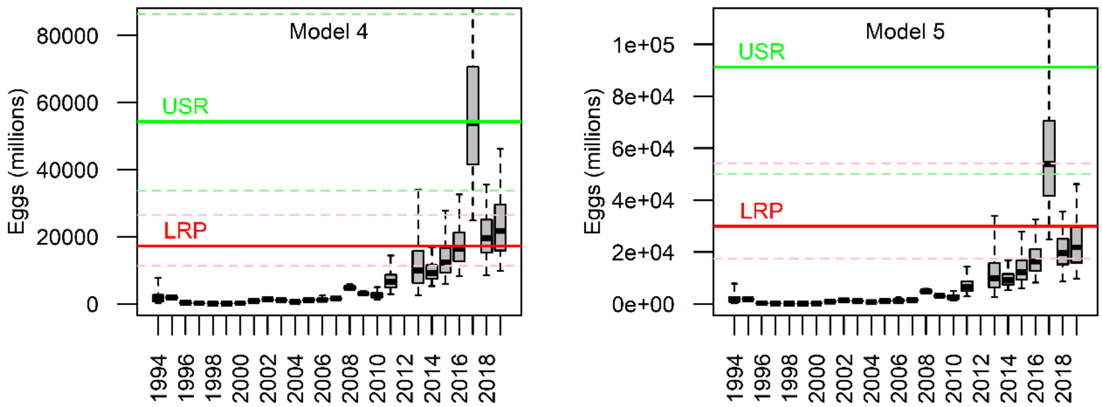


Figure 6.6. Assessed abundance of eggs in spawners (boxplots; eggs in millions) and status relative to the USR (upper green horizontal line) and the LRP (lower red horizontal line) candidate references from Model 4 (left panel) and Model 5 (right panel) for Striped Bass from the southern Gulf of St. Lawrence, 1994 to 2019. For Model 4 and Model 5, the USR corresponds to the median estimate of eggs at 80%B_{MSY} and the LRP corresponds to the median estimate of eggs that result in 50% of Beverton-Holt K (half saturation). The dashed red lines and green lines are the 5th to 95th percentile ranges of the LRP and USR respectively. Note the 95th percentile line of the USR and the 95th percentile point of eggs in 2017 are off scale in both panels.

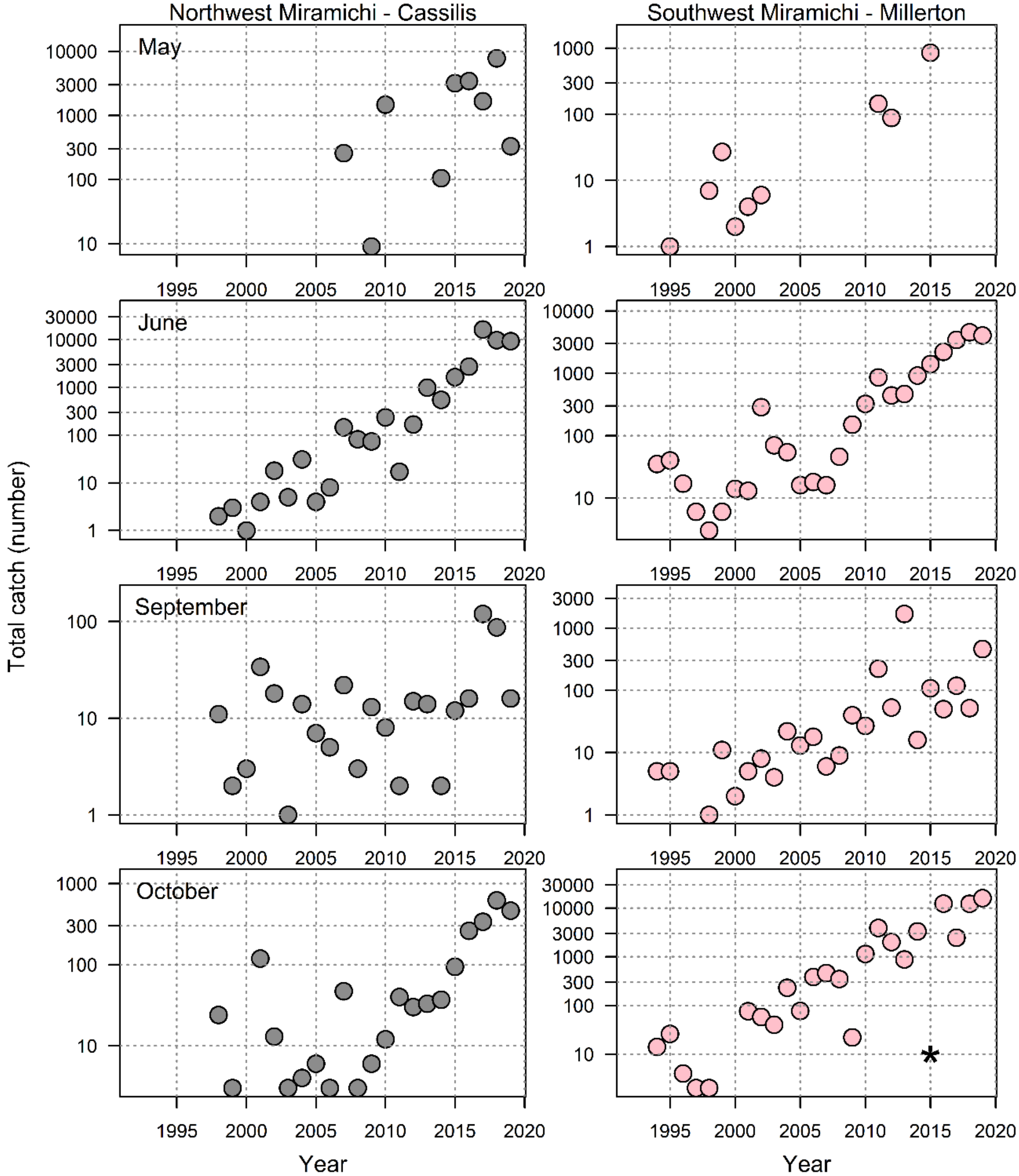


Figure 7.1. The monthly catches of Striped Bass at the DFO index trapnets of Cassilis on the Northwest Miramichi River (left column) and for Millerton on the Southwest Miramichi River (right column) during the months of May (top row), June (second row), September (third row) and October (bottom row), 1998 to 2019 for Cassilis and 1994 to 2019 for Millerton. In the lower right panel (Millerton, October), the asterisk indicates that the trapnet was not operational due to flood conditions which ended the monitoring program on Sept. 30 for the Southwest Miramichi trapnet; the Northwest Miramichi trapnet was not operating for five days during the first week of October in 2015.

APPENDICES

APPENDIX 1. REVIEW OF FISHERIES MANAGEMENT OF STRIPED BASS

Striped Bass have been exploited in numerous fisheries of the southern Gulf of St. Lawrence for over a century of records. The first mention of Striped Bass found in the Canada Gazette is from 1895 referring to fisheries regulations for Bass in New Brunswick; of note it mentions that no bass less than two pounds weight could be retained in any fishery.

In Canada Gazette 1927, the minimum size limit for retention is changed to 12 inches in length, measured from "the tip of the nose to the end of the tail".

There is an absence of reported landings from the southern Gulf of St. Lawrence during the period 1933 to 1968. This is not interpreted to be a period without fisheries. In Canada Gazette Part II (1949; SOR/49-223), an amendment is made to the Special Fishery Regulations for the province of New Brunswick (Council P.C. 5357 of 31st December 1947) that changed the retention conditions for Striped Bass, effectively closing the commercial fishery by authorizing the retention of Striped Bass from angling only and detailing precise restrictions to a number of rivers:

> "By deleting therefrom subsection one of section one and substituting the following new subsection one:
>
> 1. (a) No one shall fish for or kill any striped bass, otherwise than by angling, from the first day of April to the thirtieth day of November, both dates inclusive; nor otherwise than by angling at any time in the waters of the Miramichi, Kouchigouguac, Tabusintac, Tracadie, or Richibucto Rivers or any of the tributaries of these rivers.
>
>   (b) No one shall buy, sell, or have in his possession any striped bass unless, the proof whereof shall be on him, the same has been legally caught or killed."

The Nova Scotia fisheries regulations for Striped Bass combined them with other bass species (smallmouth bass, largemouth bass or occasionally referred to as black bass). The 1954 Canada Gazette Part II Amendment to the Nova Scotia Fishery Regulations (SOR/54-728) included the following:

- Definition of sport fish that includes salmon, trout and bass;
- No fishing for bass except by angling;
- No fishing for smallmouth and largemouth bass during Nov. 1 to 30 June;
- Total daily limit of bass (all species) defined as: "No person shall fish for, catch or kill, in any one day by angling or shall carry away a greater number of bass than, in the aggregate, shall weigh more than twenty pounds plus one such fish and no greater number than thirty, although the said number weigh less than twenty pounds."; and
- Size limit for striped bass as: "No person shall retain any striped bass less than twelve inches in length nor any black bass less than nine inches in length, measured from the tip of the nose to the end of the tail; any one who catches any such bass shall immediately return it to the water."

In the province of Quebec (14 July 1965, volume 99 number 13; Canada Gazette Part II):

- No person shall fish for, catch or kill any striped bass from the first day of December in any year to the thirty-first day of May next following, both days inclusive;

- Every person that catches a striped bass that is less than sixteen inches in length, measured from the tip of the snout to the posterior edge of the tail, shall return it to the water immediately.

In January 1960 (Canada Gazette Part II Volume 94 Number 1, 13 January 1960), the New Brunswick Fishery Regulations were amended and authorized the sale of incidentally captured Striped Bass captured in nets , traps, or weirs set for catching fish other than striped bass:

> "1. Paragraph(t) of section 2 of the New Brunswick Fishery Regulations is revoked and the following substituted therefor:
>
> (t) "sport fish" includes salmon, trout, and black bass
>
> 2. (1) Subsection (2) of section 3 of the said Regulations is revoked and the following substituted therefor:
>
> (2) Striped bass may be retained and marketed when unintentionally caught in nets, traps or weirs set for the catching of fish other than striped bass.

In 1965, a complete revision to the New Brunswick Fishery Regulations was published in Canada Gazette Part II (SOR/65-111, April 14, 1965) that included the following definitions and regulations related to striped bass:

- Sport fish includes salmon, trout and black bass
- No person shall fish for, catch or kill striped bass except with gill nets or by angling ("directed fishing")
- No person shall fish for striped bass with a net except under a licence
- No person shall fish for, catch or kill striped bass by means of a gill net, the mesh of which is less than five inches, extension measure, when in use
- Striped bass that are unintentionally caught in nets, traps or weirs set for other fish may be retained and marketed.
- No person shall make a hole in the ice for the purpose of fishing for striped bass unless he marks the hole with four evergreen trees, each tree being six feet in height (was in regs since1895).

Bow net specific, SOR/80-434: defined what a bow net, season for Kent County (NB) and size limit minimum of 38 cm.

In 1993, the Nova Scotia Fishery Regulations C.R.C. c848, the New Brunswick Fishery Regulations C.R.C. c844, and the Prince Edward Island Fishery Regulations C.R.C., c850 were revoked and replaced with the Maritime Provinces Fishery Regulations (SOR/95-55, 4 Feb. 1993) that specified regulations specific to fishing in the three Maritime provinces and in adjacent tidal waters. For Gulf Region waters:

- For striped bass, length referred to a straight line from the tip of the nose to the tip of the tail;
- Sport fish were defined as smallmouth bass, landlocked salmon, salmon and trout;
- Retention of striped bass incidentally caught with any fishing gear operated under the authority of a licence;
- No person shall use as bait or possess for use as bait in a province any: live or dead, bass, bullhead, sunfish, white perch, yellow perch, or other spiny fin-rayed fish;
- No person shall fish for striped bass except by angling or with a bow net;

- Bow net fishing is only allowed in tidal waters of Kent County (NB) during the period 1 December to 31 March, with a bow net with a mesh not less than 127 mm;
- Angling is open year round (excluding Dec. 30 and 31) in tidal waters but closed in inland waters during April 15 to Sept. 30 in NS, May 1 to Sept. 15 in NB, and April 15 to Sept. 30 in PEI;
- Daily quota and size restrictions of:
  - Nova Scotia: angling inland and tidal waters, 1 per day, 68 cm minimum length
  - New Brunswick: angling inland and tidal waters, 1 per day, 68 cm minimum length
  - New Brunswick: bow net fishing in tidal waters, no quota ,minimum length 38 cm
  - Prince Edward Island: angling inland and tidal waters, 10 fish per day, minimum length 30 cm.

A major amendment to Maritime Fisheries Regulations was introduced in 1996 to prohibit the retention and sale of bycatch of Striped Bass (Canada Gazette 1996 SOR/96-125):

- In 1996, Paragraph 4(2)b of the Maritime Provinces Fisheries Regulations which permitted the retention of unlimited bycatch of Striped Bass in commercial fishing gears for gaspereau, Rainbow Smelt, American Shad, and American Eel was repealed (Canada Gazette Part II, Vol. 130, No. 5; SOR/96-125). The regulatory impact analysis statement stated:

  "Striped bass are currently being caught in large numbers as a by-catch in other fisheries, notably those for gaspereau, shad, smelt and eel. Although there is no fishery specifically directed at striped bass, the species is being taken in sufficient quantities through by-catches to threaten its survival. Because paragraph 4(2)b of the Maritime Provinces Fishery Regulations allows an unlimited by-catch of striped bass, it is necessary to remove this provision from the regulations. If striped bass stocks return to healthy numbers, by-catches in the commercial fishery can be regulated through licence conditions. This amendment applies to fishers in Nova Scotia, New Brunswick and Prince Edward Island.

- Alternatives Considered:

  The Department asked fishers to release striped bass voluntarily, but few compiled with this request during the trial period. Fisheries manages found that a large number of striped bass were still being retained in other fisheries and sold commercially. The only acceptable solution is to prohibit by-catches of this species outright.

- Benefits and Costs:

  The primary benefit of this amendment is the conservation and protection of striped bass. Recreational fishers will benefit in the short-term and commercial fishers could benefit in the long-term.

  Commercial fishers will lose the opportunity to catch and sell striped bass unless they are allowed to do so through licence conditions. However, since no directed fishery of this species currently occurs, the impact of this measure on them should be minor. The amendment is necessary to ensure the conservation of striped bass."

Subsequent modifications to the Striped Bass fisheries management of the southern Gulf were made via licence conditions (for commercial fisheries) and variation orders for recreational fisheries. Additional restrictions to various fisheries interacting with Striped Bass were introduced from 1996 to 2000 which culminated in the closure of all legal Striped Bass fisheries (Table 2.1).

The commercial fisheries for Striped Bass were closed in March 1996 and commercial fishers were required to release all Striped Bass that are incidentally caught in commercial gear while fishing for other species. An exception to this in 1996 was made through condition of licence for gaspereau and smelt fisheries where a bycatch tolerance for fish <35 cm total length was in effect recognizing the difficulty of sorting bass less than 35 cm TL from large quantities of similar-sized fish, however these fish could not be sold. Bradford and Chaput (1998) provide a breakdown of the reported harvests of Striped Bass from 1996: harvests were reported from three statistical districts in DFO Gulf Region New Brunswick including:

- 14.5 t during January and February 1996 from district 76 (Richibucto district)
- 0.25 t in June 1996 from district 66 (Acadian peninsula, Miscou area)
- 0.25 t in October to December 1996 from district 77 (Bouctouche area).

Subsequent modifications to the Striped Bass fisheries management of the southern Gulf were made via licence conditions (for commercial fisheries) and variation orders for recreational fisheries. Additional restrictions to various fisheries interacting with Striped Bass were introduced from 1996 to 2000 which culminated in the closure of all legal Striped Bass fisheries (Table 2.1).

Although the fisheries on Striped Bass were essentially closed in 2000, mortality of Striped Bass from fishing activities continued (Chiasson et al. 2002; Douglas et al. 2006; DFO 2011). DFO (2011) indicated that Striped Bass of various life stages continued to be intercepted in a variety of illegal fisheries, commercial fisheries, and aboriginal FSC fisheries, with a total estimated loss of medium and large sized Striped Bass in all southern Gulf of St. Lawrence fisheries in the range of 60,000 fish per year. The total number of bass handled in the fisheries was estimated to be 152,000 fish, of which 41% were estimated to have died or been killed (DFO 2011). The activity with the greatest contribution to the total loss of Striped Bass is considered to be the illegal fishery, accounting for over 50% of the estimated adult losses, followed by the recreational fishery (illegal retention and bycatch) at about 15% (DFO 2011).

Following indications of sustained increases in abundance, re-initiation of Indigenous FSC allocations began in 2012 and the recreational fisheries were re-opened in 2013, followed by a pilot commercial fishery licence to an Indigenous community in 2018 and 2019 (Table 2.1).

Striped Bass originating from the southern Gulf are also exploited in fisheries along the coast of Chaleur Bay in Quebec. Fisheries management measures for the recreational Striped Bass fishery in Quebec that paralleled the fisheries management measures in DFO Gulf Region were introduced in 2013. Based on elemental composition analyses of otoliths and different characterizations of these signatures in Striped Bass originating from the Miramichi River and from the St. Lawrence River spawning areas, Valiquette et al. (2018) indicated that the southern Gulf of St. Lawrence Striped Bass distribution extended around Chaleur Bay and upstream along the Gaspe peninsula to Rivière du Loup. Occasionally, as noted in the samples of Striped Bass from 2017, southern Gulf bass were also distributed along the lower north shore of the St. Lawrence River (Valiquette et al. 2018). Tag returns of bass marked in the southern Gulf and reports of the presence of Striped Bass in southern Labrador in late summer and into the winter (DFO 2018) as well as detections of acoustically tagged Striped Bass on the receiver line at Port Hope (Labrador) confirmed the broader excursion of southern Gulf Striped Bass outside its historic range in 2017 and its exploitation in various fisheries in the Gulf of St. Lawrence.

Indigenous Peoples have allocations for Striped Bass within Food, Social, and Ceremonial fisheries agreements. In 1997, FSC agreements included 290 Striped Bass for three groups in the Miramichi River area, 500 bass from the Richibucto River and 172 bass from the Buctouche River (Bradford and Chaput 1998).

There are no complete fishery catch data for Striped Bass. Historically, fisheries statistics reported commercial harvests exclusive of recreational and Indigenous peoples fisheries harvests (LeBlanc and Chaput 1991; Bradford et al. 1995a; Douglas et al. 2003). Since the re-opening of the recreational fisheries in 2013, partial catch data for some sectors of the recreational fishery have been collated but they are incomplete.

In addition to the directed fishery management measures, short-term closures to directed recreational fisheries in the spawning area of the Northwest Miramichi to preclude harm to spawning fish were instituted since 2017. The temporary closure to all recreational fisheries of the spawning area in the Northwest Miramichi during the peak spawning period was previously identified as one of several management measures that would enhance the protection of Striped Bass and promote its recovery and justify the decision not to list the add the population to the schedule under the *Species at Risk Act* (List of Wildlife Species at Risk (Decisions Not to Add Certain Species) Order; Canada Gazette Part II Vol. 147 No. 7 (2013), SI/2013-27 March 27, 2013).

APPENDIX 2. DERIVATION OF AGE LENGTH KEY AND SPAWNERS AT AGE

A2.1. Interpretation of Ages

Ages of Striped Bass are interpreted from scales. Size-at-age has been reported previously by Chaput and Robichaud (1995) and in Douglas et al. (2006). Sampling and age determination has occurred opportunistically. There has not been any age validation nor is a reference scale set available for doing reader tests.

Striped Bass grow during the open-water season in the southern Gulf (May to October). No growth occurs through the winter when bass are overwintering under the ice in the upper areas of estuaries and they do not feed; this is evident from an examination of size distributions of bass sampled in the fall in the Miramichi at DFO index trapnets which are identical to those of bass sampled the following spring in the Miramichi (for example, see DFO 2020).

A total of 8,497 age and length data combinations are available from sampling in the southern Gulf of St. Lawrence; from the samples available, maximum age interpreted is 15 years and maximum fork length recorded is 97.0 cm (Table 3.2). There is a broad size distribution at age (Table A2.1; Figure A2.1). Samples were restricted to those collected in May and June (n = 8,376), corresponding to the spawning period.

Length distributions at age from sampling show annual variations, although there is no statistically significant trend over time (Figure A2.2).

A2.2. Von Bertalanffy Growth Model

A von Bertalanffy growth function was adjusted to the selected age and length data over all years:

$$L_a = L_\infty \left(1 - e^{-K(a - a_0)}\right) e^{\varepsilon}$$

with L_a = fork length (cm) at age a, L_∞ = predicted asymptotic fork length (cm), K = predicted metabolic parameter, a_0 = predicted apparent age at time of hatching, and $\varepsilon \sim N(0, \sigma^2)$.

The von Bertalanffy model parameters were estimated with OpenBugs using non-informative priors for the parameters $(L_\infty, K, a_0, \ \sigma)$ to be estimated (Section 3.1.1). The posterior distributions of the parameters are summarized in Table 3.3 and a visualization of the data, model fits and predicted length distributions at age are presented in Figure 3.3.

A2.3. Spawner Abundance at Age

Sampling for and age interpretations are not available for all assessment years, nor are there sufficient samples of older and larger fish in any year to adequately estimate their relative abundances. Consequently, the von Bertalanffy model predicted length at age distributions were used to derive an age length key which was then used to estimate the annual abundance at age of spawners based on the assessed annual length distributions of the spawners.

The posterior predicted fork length at age distributions show a large size overlap at age, particularly for ages 6 and older (Figure A2.3). Fork length distributions at age for the purpose of developing the age–length key were derived assuming a normal distribution defined by the posterior median and standard deviation of the predicted fork length at age (Table 3.2; Figure A2.3).

The age-length key proportions at age by cm fork length bins (Figure A2.4) were estimated from the length bin standardized proportions at age as:

$p.Age_{a,fl} = \left. DN_{a,fl} \middle/ \sum_a^A DN_{a,fl} \right.$

with $p.Age_{a,fl}$ = proportion of fish age *a* within the fork length bin *fl* (cm) and

$DN_{a,fl}$ = density at fork length *fl* for age *a* assuming a normal distribution of fork length at age (Table A2.2; Figure A2.5; $N(\mu_a, \sigma_a)\ in\ cm$).

$DN_{a,fl}$ is calculated as the difference in the left-tailed cumulative distributions between two fork length bins (fl-0.5 to fl+0.5) for each value of fl (cm, 10 to 100) over ages a = 1 to 15+:

$DN_{a,fl} = pNorm(fl + 0.5, \mu_a, \sigma_a) - pNorm(fl - 0.5, \mu_a, \sigma_a)\ \ (R\ code).$

This age-length key (Figure A2.4) was applied to the sampled fork length distributions of spawners (Figure 3.4) to derive the number of sampled spawners at age by year, as:

$n_{y,a,fl} = p.Age_{a,fl} * n.fl_{y,fl}$

with $n_{y,a,fl}$ = number of fish in year y, of age a, in fork length bin fl from the sampled length distribution in year y,

$p.Age_{a,fl}$ as above, age-length key proportion of fish of age a in fork length bin fl, and

$n.fl_{y,fl}$ = number of fish in fork length bin *fl* from the sampled length distribution in year y.

The number of sampled spawners at age by year is:

$n.Sp_{y,a} = \sum_{fl} n_{y,a,fl}$ for fl = 10 to 100 cm.

and the proportion of sampled spawners at age, assuming spawners are age 3 and older is:

$p.Sp_{y,a} = \left. n.Sp_{y,a} \middle/ \sum_a^A n.Sp_{y,a} \right.$ for a = 3 to A = 15.

Finally the number of spawners at age by year y is calculated using:

$Sp.at.age_{y,a} = p.Sp_{y,a} * med.Sp_y$ for a = 3 to 15

with $med.Sp_y$ = median of the estimated spawner abundance in year y (from the assessment).

A2.4. OpenBugs Code for Von Bertalanffy Modelling

```
# bugs model for von Bertalanffy length age data for striped bass
# data are fork length in cm (FLcm[y]), age in years (Age[y]), total observations Y
model {
  # priors for von B parameters
Linf ~ dlnorm(0,0.001)
K ~ dlnorm(0, 0.001)
age.0 ~ dunif(-5, 0)
sig.eps ~ dunif(0,5)
prec.eps <- pow(sig.eps, -2)

for (y in 1:Y){
    Flcm[y] ~ dlnorm(u.logfl[y], prec.eps)
    u.logfl[y] <- log(Linf * (1 - exp(-K * (Age[y] - age.0))))
    }   # end likelihood loop
# predicting length distributions at ages 1 to 15
for (a in 1:15){
    pred.FL[a] ~ dlnorm(u.pred.fl[a], prec.eps)
    u.pred.fl[a] <-log(Linf * (1 - exp(-K * (a - age.0))))
  } # end predicted length at age loop
} # end model
```

Table A2.1. Summary statistics of fork length (mm) at scale-interpreted ages of Striped Bass from the Miramichi River.

Age (years)	mean	Std. dev.	n	min	max	median	p0.025	p0.975	CV
1	178	15	71	146	210	179	152	200	0.083
2	282	31	562	140	414	278	232	345	0.109
3	406	35	2606	244	512	410	338	463	0.085
4	473	38	2542	290	592	475	399	542	0.080
5	528	41	1485	348	658	527	455	606	0.077
6	580	40	769	445	726	580	495	659	0.069
7	636	55	124	480	740	645	524	724	0.086
8	691	53	94	515	780	702	588	764	0.076
9	727	55	62	572	848	738	609	822	0.076
10	771	63	20	644	858	781	644	851	0.082
11	782	63	21	640	861	801	671	861	0.081
12	835	52	10	705	897	841	730	894	0.062
13	755	76	2	701	809	755	704	806	0.101
14	782	72	5	665	847	784	676	846	0.093
15	869	164	3	680	970	958	694	969	0.189

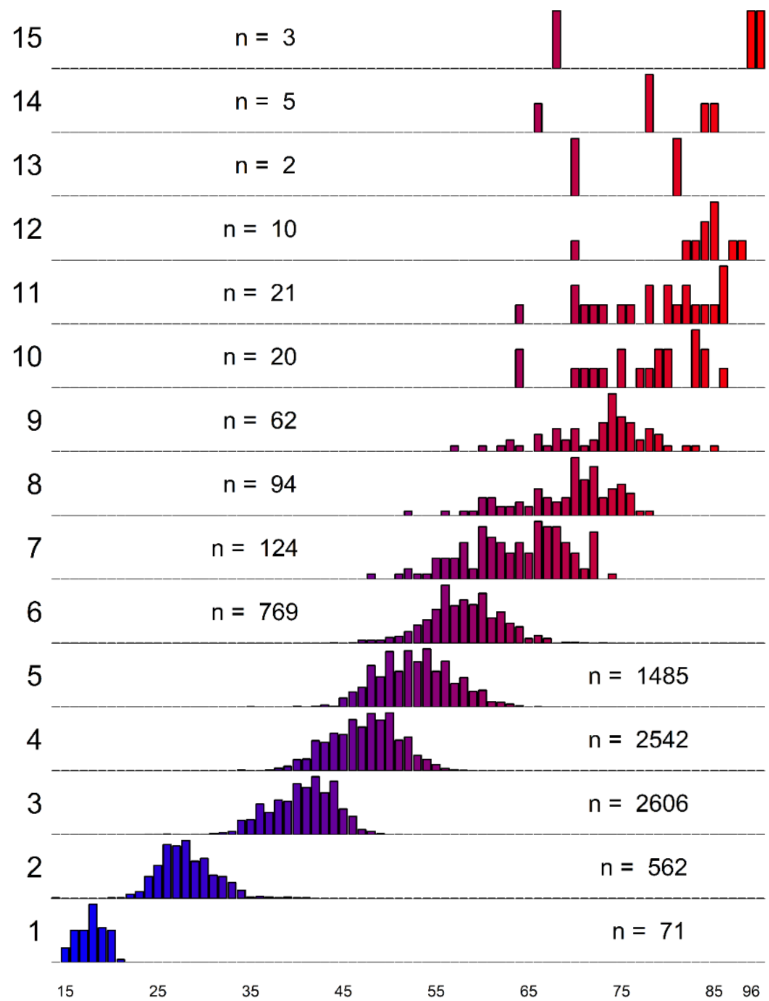


Figure A2.1. Length (cm) frequency distributions at age (year; rows) of Striped Bass from the southern Gulf of St. Lawrence, based on available samples with scale age interpretations.

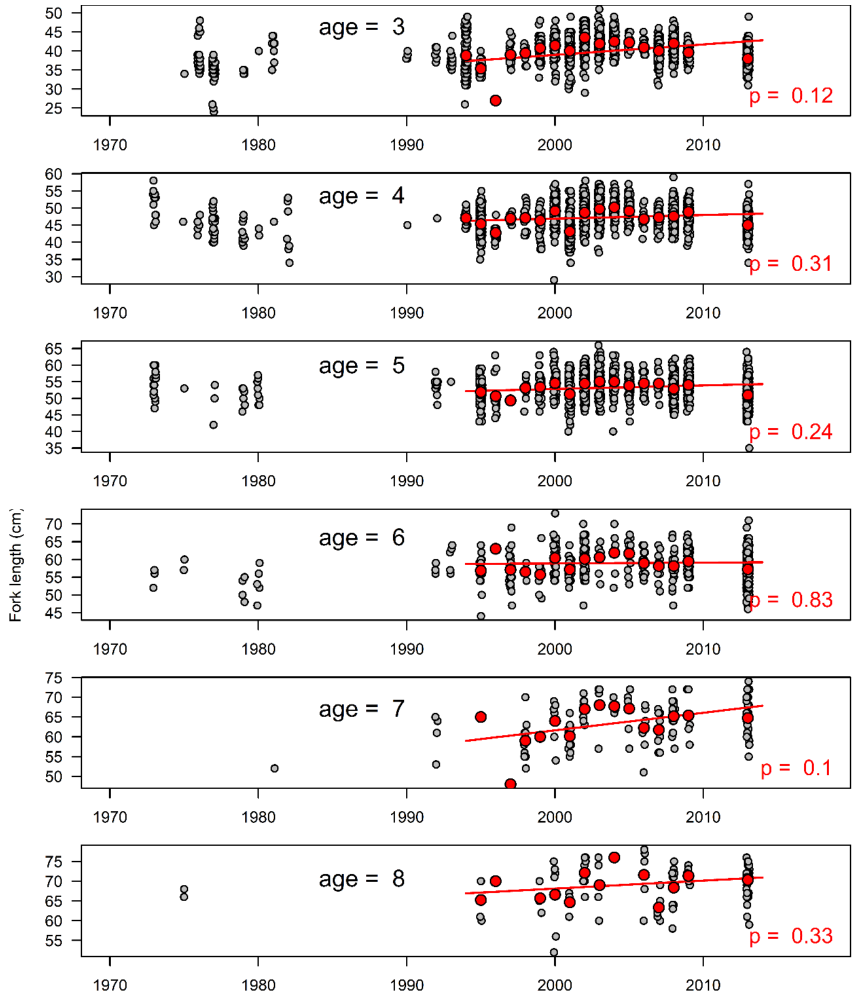


Figure A2.2. Fork length (cm) at interpreted age of Striped Bass, by year of sampling from the southern Gulf of St. Lawrence, based on scale interpretations. Shown are individual (jittered slightly for clarity) lengths at ages 3 to 8 (successive rows) by year of sampling. The linear regression of median annual size at age (red symbols) versus year is shown in each age plot with the corresponding p-value of the slope of the regression of median values over years.

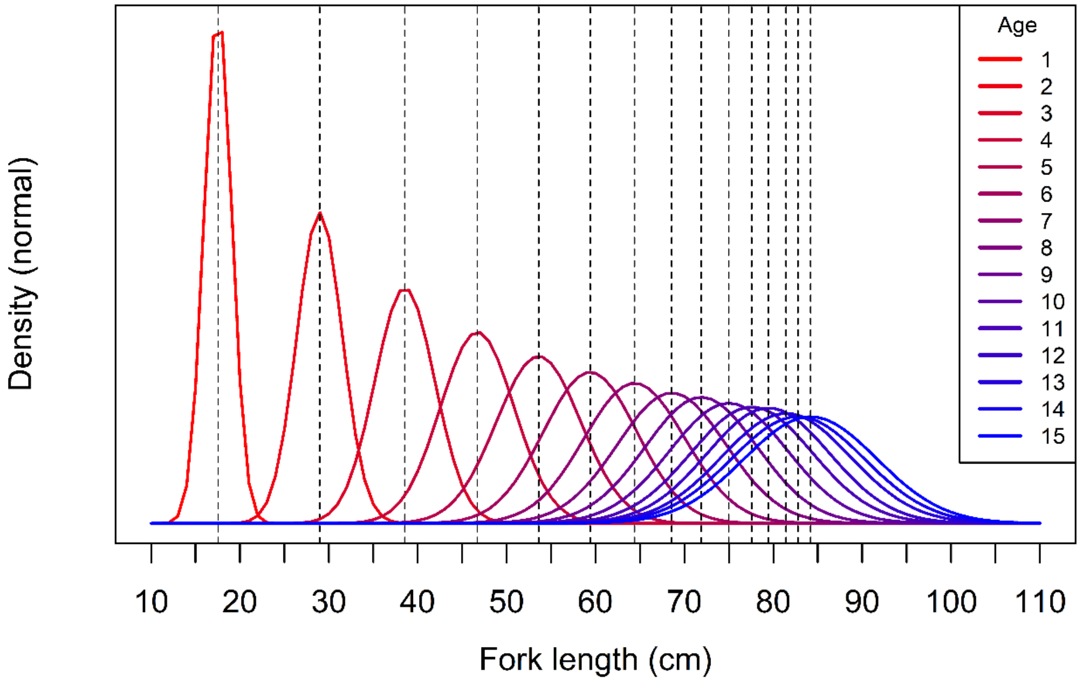


Figure A2.3. Fork length distributions (cm) at age (1 to 15) assuming a normal distribution with parameters mean and standard deviation of the posterior predicted distributions of the von Bertalanffy growth model (Table 3.2).

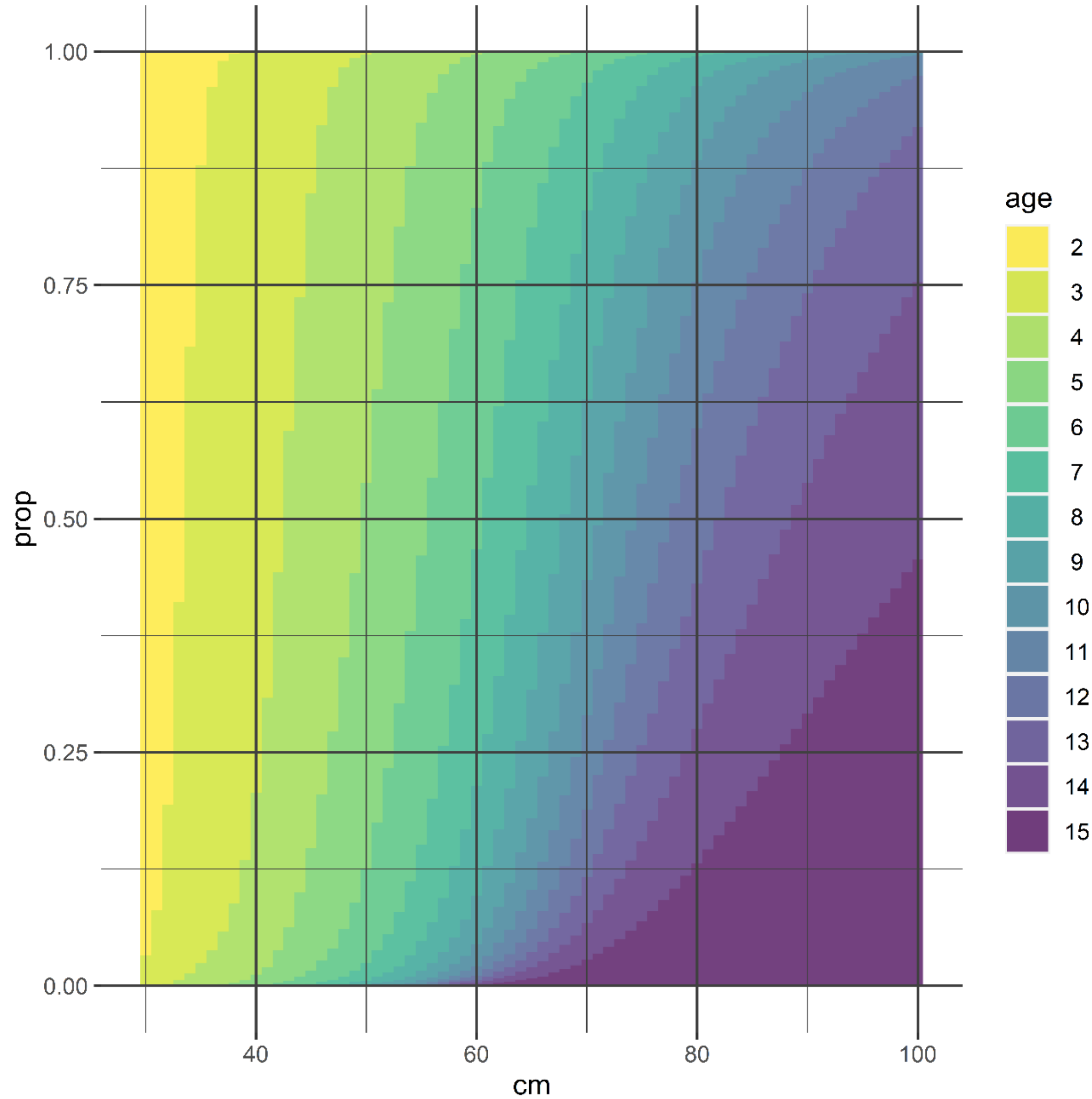


Figure A2.4. The proportions at age by cm fork length bin (30 to 100) ($p.Age_{a,fl}$) used to estimate the abundance at age of spawners on the spawning grounds in the Miramichi. For illustration, the fork length bin range shown is 30 to 100 cm and the age range shown is 2 to 15+ years.

APPENDIX 3. INPUT DATA USED IN THE POPULATION MODELLING

Table A3.1. Posterior summaries of the estimated abundance (number of fish) of Striped Bass spawners in the Miramichi River, 1994 to 2019. There are no estimates for 2012.

Year	mean	sd	2.5pc	5.0pc	25.0pc	median	75.0pc	95.0pc	val97.5pc
1994	130600	217300	12560	18440	44450	76020	138400	402000	594500
1995	56220	10560	39070	41230	48740	55020	62320	75420	80160
1996	6104	4390	1219	1687	3449	5072	7408	13980	17600
1997	4634	818	3294	3465	4057	4545	5112	6108	6489
1998	4484	534	3546	3677	4107	4447	4820	5421	5636
1999	4141	300	3591	3672	3933	4128	4335	4655	4766
2000	4208	539	3280	3403	3827	4163	4540	5164	5385
2001	26670	3378	20900	21660	24280	26400	28750	32640	34030
2002	28210	1738	24990	25470	27010	28150	29340	31180	31800
2003	20760	2219	16850	17400	19200	20600	22150	24630	25540
2004	14820	2510	10640	11170	13040	14570	16330	19330	20460
2005	18770	3912	12520	13270	16010	18310	21000	25820	27720
2006	24210	10870	9161	11300	17670	22260	28190	43620	51580
2007	49980	5933	39700	41080	45800	49530	53670	60440	62860
2008	93000	10380	74690	77180	85660	92320	99610	111200	115300
2009	48930	6677	37610	39120	44230	48320	52970	60730	63670
2010	66450	30560	23860	29840	48000	61090	77830	120800	143500
2011	227100	121700	69860	89790	153800	203200	268700	444400	537200
2012	na	na	na	na	na	na	na	na	na
2013	333900	304500	46420	67460	158800	254500	403400	864600	1131000
2014	147400	55990	66260	79090	111600	137600	172100	249500	288400
2015	339800	179200	118600	145800	226400	298600	405300	675300	807200
2016	346900	155700	132800	159600	245700	318400	411700	633000	750700
2017	1093000	553400	275800	456500	763400	990200	1296000	2083000	2507000
2018	348900	142300	55170	145800	258500	333800	425800	605100	674500
2019	346100	168800	116500	140900	229100	313600	426000	663200	773600

Table A3.2. Estimated abundance (number of fish) at age (3 to 15+ years) of Striped Bass spawners in the Miramichi River, 1994 to 2019. Abundance at age is derived using an age-length key applied to length distribution of spawners and raised to total abundance based on the median of the assessed total abundance of spawners (Table A3.1). There are no estimates for 2012.

	Age (years)												
Year	3	4	5	6	7	8	9	10	11	12	13	14	15+
1994	54669	17302	3135	490	124	67	48	41	36	32	28	25	22
1995	25182	18710	7387	2398	738	267	114	62	43	35	31	27	25
1996	627	1888	1526	649	221	81	33	16	9	7	6	6	5
1997	1512	1194	832	522	250	111	52	26	15	11	8	7	5
1998	2279	1317	474	199	86	41	21	12	7	5	3	2	2
1999	1711	1421	613	235	83	33	14	7	4	3	2	2	2
2000	858	1480	989	448	190	88	45	25	15	10	7	5	4
2001	11311	10209	2837	1149	483	205	93	46	25	16	11	8	6
2002	5211	13539	5979	2063	718	292	137	73	45	32	24	20	16
2003	4409	6906	5244	2397	880	350	162	88	55	39	29	23	18
2004	4321	5769	2558	1039	425	196	102	58	35	24	17	14	10
2005	2026	6976	5019	2121	901	454	255	156	108	87	75	69	62
2006	6923	6180	3999	2395	1212	617	340	200	129	92	70	57	45
2007	28335	13253	4097	1732	851	459	263	155	100	75	68	69	72
2008	20928	38426	19008	7087	2780	1388	822	539	387	305	249	217	184
2009	9504	13918	12576	6364	2725	1257	674	408	274	208	163	137	112
2010	34618	11537	5411	3615	2127	1272	813	532	366	274	210	175	140
2011	109574	59488	18928	7102	3451	1880	1078	627	386	259	181	143	102
2012	na	na	na	na	na	na	na	na	na	na	na	na	na
2013	141492	48472	29316	16641	8006	3954	2189	1333	905	697	568	498	428
2014	27270	45493	26051	15897	9164	5248	3116	1867	1184	828	609	494	378
2015	171327	48442	31348	19425	11187	6422	3834	2312	1470	1029	747	602	453
2016	112323	102255	43883	24683	13819	7899	4774	2952	1932	1389	1023	833	636
2017	186751	433056	205540	83570	36494	18002	9879	5815	3710	2637	1946	1582	1218
2018	66676	129860	68724	31012	15572	8592	5026	2987	1871	1285	919	733	543
2019	43325	106070	76332	40063	19945	10657	6182	3742	2422	1736	1283	1042	801

Table A3.3. Predicted mean fork length (cm) at age, predicted mean weight (kg) at age, assumed proportion mature at age, and derived proportion female at age of spawners of Striped Bass from the Miramichi River.

Age (years)	Fork length (predicted mean; cm)	Whole weight (predicted mean; kg) [1]	Proportion mature		Prop. female spawners
			male	female	
3	38.5	0.677	0.5	0.1	0.167
4	46.7	1.204	0.9	0.5	0.357
5	53.6	1.818	1.0	0.9	0.474
6	59.4	2.474	1.0	1.0	0.50
7	64.4	3.166	1.0	1.0	0.50
8	68.6	3.814	1.0	1.0	0.50
9	71.9	4.400	1.0	1.0	0.50
10	75.0	4.999	1.0	1.0	0.50
11	77.6	5.544	1.0	1.0	0.50
12	79.4	5.946	1.0	1.0	0.50
13	81.4	6.399	1.0	1.0	0.50
14	82.8	6.746	1.0	1.0	0.50
15+	84.2	7.058	1.0	1.0	0.50

[1] Predicted mean whole weight is based on a weight to length relationship parametrized as
$\ln(WW_{kg}) = -11.3428 + 3.0027 * \ln(FL_{cm})$

APPENDIX 4. CODES FOR MODELS

Appendix 4a. Model 4-Bayesian life cycle model code in OpenBugs.

```
model {
# Y is total years of matrix, 1996 to 2019
# priors for Bev Holt parameters
bh.alpha <- exp(-delta)  # survival rate as e(-Z)
delta ~ dnorm(1,0.001)C(0,)
K.prime ~ dnorm(1,0.001)C(1,)
K <- K.prime*100000
# priors for mortality rates
z.0 <- -log(S.0)
S.0 ~ dbeta(s.0.a, s.0.b)
for (a in 1:8){
  S[a] ~ dbeta(s.age.a[a], s.age.b[a])
  z.at.age[a] <- -log(S[a])
  }
for (a in 9:15){
  z.at.age[a] <- z.at.age[8]
  }
# priors for proportion recruits to spawners at age assumed similar for male and female
# spawners are for ages 3 to 15 so index runs from 1 to 13
for (a in 1:4){  # spawner ages 3 to 6, strongly informative prior
  p.rec.sp.at.age[a] ~ dbeta(p.rec.sp.a[a], p.rec.sp.b[a])
  }
for (a in 5:13){ # ages 7 to 15
  p.rec.sp.at.age[a] <- p.rec.sp.at.age[4]
  }
# initial year 1996
for (y in 1:1){
   # for ages 1 and 2, use age 3 spawners to estimate recruits
   pred.R[y,1] <- obs.sp.at.age[y,1] / p.rec.sp.at.age[1] / exp(-(z.at.age[1] + z.at.age[2]))
   pred.R[y,2] <- obs.sp.at.age[y,1] / p.rec.sp.at.age[1] / exp(-z.at.age[2])
   for (a in 3:15){
     pred.R[y,a] <- obs.sp.at.age[y,(a-2)] / p.rec.sp.at.age[a-2]
     pred.S[y,a-2] <- pred.R[y,a]*p.rec.sp.at.age[a-2]
     u.log.S.a[y,a-2] <- log(pred.S[y,a-2])
     eggs[y,a-2] <-pred.S[y,a-2]*wt.at.age[a-2]*p.fem.sp.at.age[a-2]*eggs.kg
     }
  tot.eggs[y] <- sum(eggs[y,])
  pred.R0[y] <- bh.alpha*tot.eggs[y]/(1 + tot.eggs[y] * bh.alpha/K)
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds, fill in first year
  }  # end first year
for (y in 2:Y){  # year loop 1997 to 2019
  pred.R[y,1] <- pred.R0[y-1] * exp(-z.0)
  pred.R[y,2] <- pred.R[y-1,1]*exp(-z.at.age[1])
  for (a in 3:14){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1])
    pred.S[y,a-2] <- pred.R[y,a]*p.rec.sp.at.age[a-2]
    u.log.S.a[y,a-2] <- log(pred.S[y,a-2])
    eggs[y,a-2] <-pred.S[y,a-2]*wt.at.age[a-2]*p.fem.sp.at.age[a-2]*eggs.kg
    }  # end age 3 to 14 loop
  for (a in 15:15){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1]) + pred.R[y-1,a]*exp(-z.at.age[a])
    pred.S[y,a-2] <- pred.R[y,a]*p.rec.sp.at.age[a-2]
    u.log.S.a[y,a-2] <- log(pred.S[y,a-2])
    eggs[y,a-2] <-pred.S[y,a-2]*wt.at.age[a-2]*p.fem.sp.at.age[a-2]*eggs.kg
    }  # end age 12+ loop
  tot.eggs[y] <- sum(eggs[y,])
  pred.R0[y] <- bh.alpha*tot.eggs[y]/(1 + tot.eggs[y] * bh.alpha/K)
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds
```

```
  } # end year loop
# likelihoods
# age 3 likelihood
for (y in 4:Y){
   obs.sp.at.age[y,1] ~ dlnorm(u.log.S.a[y,1], tau.sp[1])   # likelihood of spawner abundance
   res.S.3[y] <- log(obs.sp.at.age[y,1]/pred.S[y,1]) # residual for spawners age 3
   }
# age 4 likelihood
for (y in 5:Y){
   obs.sp.at.age[y,2] ~ dlnorm(u.log.S.a[y,2], tau.sp[2])   # likelihood of spawner abundance
   res.S.4[y] <- log(obs.sp.at.age[y,2]/pred.S[y,2]) # residual for spawners age 4
   }
# age 5 likelihood
for (y in 6:Y){
   obs.sp.at.age[y,3] ~ dlnorm(u.log.S.a[y,3], tau.sp[3])   # likelihood of spawner abundance
   res.S.5[y] <- log(obs.sp.at.age[y,3]/pred.S[y,3]) # residual for spawners age 5
   }
# age 6 likelihood
for (y in 7:Y){
   obs.sp.at.age[y,4] ~ dlnorm(u.log.S.a[y,4], tau.sp[4])   # likelihood of spawner abundance
   res.S.6[y] <- log(obs.sp.at.age[y,4]/pred.S[y,4]) # residual for spawners age 6
   }
# age 7 likelihood
for (y in 8:Y){
   obs.sp.at.age[y,5] ~ dlnorm(u.log.S.a[y,5], tau.sp[5])   # likelihood of spawner abundance
   res.S.7[y] <- log(obs.sp.at.age[y,5]/pred.S[y,5]) # residual for spawners age 7
   }
# age 8 likelihood
for (y in 9:Y){
   obs.sp.at.age[y,6] ~ dlnorm(u.log.S.a[y,6], tau.sp[6])   # likelihood of spawner abundance
   res.S.8[y] <- log(obs.sp.at.age[y,6]/pred.S[y,6]) # residual for spawners age 8
   }
# total spawner likelihood beginning in year 2008
for (y in 13:Y){
   u.log.S[y] <- log(sum.S[y])
   obs.med.sp[y] ~ dlnorm(u.log.S[y], tau.sp[7])   # likelihood of spawner abundance
   res.S[y] <- log(obs.med.sp[y]/sum.S[y])  # residual for total spawners
   }
for (s in 1:7){
 logsigmaS[s] ~ dunif(0,3)
 tau.sp[s] <- pow(logsigmaS[s],-2)}
# predictions
for (y in Y2:Y3){  # predictions Y+1 to Y+more
  pred.R[y,1] <- pred.R0[y-1] * exp(-z.0)
  pred.R[y,2] <- pred.R[y-1,1]*exp(-z.at.age[1])
 for (a in 3:14){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1])
    pred.S[y,a-2] <- pred.R[y,a]*p.rec.sp.at.age[a-2]
    eggs[y,a-2] <- pred.S[y,a-2]*wt.at.age[a-2]*p.fem.sp.at.age[a-2]*eggs.kg
    }  # end age 3 to 11 loop
  for (a in 15:15){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1]) + pred.R[y-1,a]*exp(-z.at.age[a])
    pred.S[y,a-2] <- pred.R[y,a]*p.rec.sp.at.age[a-2]
    u.log.S.a[y,a-2] <- log(pred.S[y,a-2])
    eggs[y,a-2] <-pred.S[y,a-2]*wt.at.age[a-2]*p.fem.sp.at.age[a-2]*eggs.kg
    }  # end age 15+ loop
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds
  u.log.S[y] <- log(sum.S[y])  # log mean of total spawners, for likelihood
  tot.eggs[y] <- sum(eggs[y,])
  pred.R0[y] <- bh.alpha*tot.eggs[y]/(1 + tot.eggs[y] * bh.alpha/K)
   } # end year loop
} # end model
```

Appendix 4b. Model 5-Bayesian life cycle model code in OpenBugs.

```
model {
# Y is total years of matrix, 1996 to 2019
# priors for Bev Holt parameters
bh.alpha <- exp(-delta)  # survival rate as e(-Z)
delta ~ dnorm(1,0.001)C(0,)
K.prime ~ dnorm(1,0.001)C(1,)
K <- K.prime*100000
# priors for mortality rates
# cumulative mortality age 0 to 3
S.0to3 ~ dbeta(s.0to3.a,s.0to3.b)  # survival from summer age 0 to age 3
z.0to3 <- -log(S.0to3)/3  # annual instantaneous rate for age 0, age 1, age 2 non-cohort
for (a in 1:6){  # ages 3 to 8
  S[a] ~ dbeta(s.age.a[a], s.age.b[a])
  z.at.age[a] <- -log(S[a])
  }
for (a in 7:13){
  z.at.age[a] <- z.at.age[6]
  }
# priors for proportion recruits to spawners at age assumed similar for male and female
# spawners are for ages 3 to 15 so index runs from 1 to 13
for (a in 1:4){  # spawner ages 3 to 6, strongly informative prior
  p.rec.sp.at.age[a] ~ dbeta(p.rec.sp.a[a], p.rec.sp.b[a])
  }
for (a in 5:13){ # ages 7 to 15
  p.rec.sp.at.age[a] <- p.rec.sp.at.age[4]
  }
# initial year 1996
for (y in 1:1){
   for (a in 1:13){
     pred.R[y,a] <- obs.sp.at.age[y,a] / p.rec.sp.at.age[a]
     pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
     u.log.S.a[y,a] <- log(pred.S[y,a])
     eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
     }
  tot.eggs[y] <- sum(eggs[y,])
  pred.R0[y] <- bh.alpha*tot.eggs[y]/(1 + tot.eggs[y] * bh.alpha/K)
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds, fill in first year
  }  # end first year
for (y in 2:3){  # year loop 1997 and 1998
  for (a in 1:1){  # age 3
    pred.R[y,a] <- obs.sp.at.age[y,a] / p.rec.sp.at.age[a]
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end age 3 loop
  for (a in 2:12){ }  # ages 4 to 14 loop
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1])
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end ages 4 to 14 loop
  for (a in 13:13){  # 15 plus group
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1]) + pred.R[y-1,a]*exp(-z.at.age[a])
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end 15 plus group
  tot.eggs[y] <- sum(eggs[y,])
  pred.R0[y] <- bh.alpha*tot.eggs[y]/(1 + tot.eggs[y] * bh.alpha/K)
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds
```

```
  } # end year loop
for (y in 4:Y){  # year loop 1999 to 2019
   for (a in 1:1){
    pred.R[y,a] <- pred.R0[y-3]* S.0to3
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end age 3 loop
  for (a in 2:12){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1])
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end ages 4 to 14 loop
  for (a in 13:13){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1]) + pred.R[y-1,a]*exp(-z.at.age[a])
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end 15 plus group

  tot.eggs[y] <- sum(eggs[y,])
  pred.R0[y] <- bh.alpha*tot.eggs[y]/(1 + tot.eggs[y] * bh.alpha/K)
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds
  } # end year loop
# likelihood
# age 3 likelihood
for (y in 4:Y){
   obs.sp.at.age[y,1] ~ dlnorm(u.log.S.a[y,1], tau.sp[1])   # likelihood of spawner abundance
   res.S.3[y] <- log(obs.sp.at.age[y,1]/pred.S[y,1]) # residual for spawners age 3
   }
# age 4 likelihood
for (y in 5:Y){
   obs.sp.at.age[y,2] ~ dlnorm(u.log.S.a[y,2], tau.sp[2])   # likelihood of spawner abundance
   res.S.4[y] <- log(obs.sp.at.age[y,2]/pred.S[y,2]) # residual for spawners age 4
   }
# age 5 likelihood
for (y in 6:Y){
   obs.sp.at.age[y,3] ~ dlnorm(u.log.S.a[y,3], tau.sp[3])   # likelihood of spawner abundance
   res.S.5[y] <- log(obs.sp.at.age[y,3]/pred.S[y,3]) # residual for spawners age 5
   }
# age 6 likelihood
for (y in 7:Y){
   obs.sp.at.age[y,4] ~ dlnorm(u.log.S.a[y,4], tau.sp[4])   # likelihood of spawner abundance
   res.S.6[y] <- log(obs.sp.at.age[y,4]/pred.S[y,4]) # residual for spawners age 6
   }
# age 7 likelihood
for (y in 8:Y){
   obs.sp.at.age[y,5] ~ dlnorm(u.log.S.a[y,5], tau.sp[5])   # likelihood of spawner abundance
   res.S.7[y] <- log(obs.sp.at.age[y,5]/pred.S[y,5]) # residual for spawners age 7
   }
# age 8 likelihood
for (y in 9:Y){
   obs.sp.at.age[y,6] ~ dlnorm(u.log.S.a[y,6], tau.sp[6])   # likelihood of spawner abundance
   res.S.8[y] <- log(obs.sp.at.age[y,6]/pred.S[y,6]) # residual for spawners age 8
   }
# total spawner likelihood beginning in year 2008
for (y in 13:Y){
   u.log.S[y] <- log(sum.S[y])
   obs.med.sp[y] ~ dlnorm(u.log.S[y], tau.sp[7])   # likelihood of spawner abundance
   res.S[y] <- log(obs.med.sp[y]/sum.S[y])  # residual for total spawners
   }
```

```
for (s in 1:7){
 logsigmaS[s] ~ dunif(0,3)
 tau.sp[s] <- pow(logsigmaS[s],-2)
  }
# predictions
for (y in Y2:Y3){  # predictions Y+1 to Y+more
  for (a in 1:1){
    pred.R[y,a] <- pred.R0[y-3]* S.0to3
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end age 3 loop
  for (a in 2:12){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1])
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    eggs[y,a] <- pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end age loop
  for (a in 13:13){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1])+ pred.R[y-1,a]*exp(-z.at.age[a])
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    eggs[y,a] <- pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end age loop
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds
  u.log.S[y] <- log(sum.S[y])  # log mean of total spawners, for likelihood
  tot.eggs[y] <- sum(eggs[y,])
  pred.R0[y] <- bh.alpha*tot.eggs[y]/(1 + tot.eggs[y] * bh.alpha/K)
   } # end year loop
} # end model
```

Appendix 4c. Model 6-Bayesian life cycle model code in OpenBugs.

```
model {
# Y is total years of matrix, 1996 to 2019
# priors for Bev Holt parameters
bh.alpha <- exp(-delta)  # survival rate as e(-Z)
delta ~ dnorm(1,0.001)C(0,)
K.prime ~ dnorm(1,0.001)C(1,)
K <- K.prime*100000
# priors for mortality rates
for (a in 1:6){  # ages 3 to 8
  S[a] ~ dbeta(s.age.a[a], s.age.b[a])
  z.at.age[a] <- -log(S[a])
  }
for (a in 7:13){
  z.at.age[a] <- z.at.age[6]
  }
# priors for proportion recruits to spawners at age assumed similar for male and female
# spawners are for ages 3 to 15 so index runs from 1 to 13
for (a in 1:4){  # spawner ages 3 to 6, weakly informative prior
  p.rec.sp.at.age[a] ~ dbeta(p.rec.sp.a[a], p.rec.sp.b[a])
  }
for (a in 5:13){ # ages 7 to 15
  p.rec.sp.at.age[a] <- p.rec.sp.at.age[4]
  }
# initial year 1996
for (y in 1:1){
   for (a in 1:13){  # spawners at age 3 to 15
     pred.R[y,a] <- obs.sp.at.age[y,a] / p.rec.sp.at.age[a]
     pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
     u.log.S.a[y,a] <- log(pred.S[y,a])
     eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
     }
  tot.eggs[y] <- sum(eggs[y,])
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds, fill in first year
  }  # end first year
for (y in 2:3){  # year loop 1997 and 1998
  for (a in 1:1){
    pred.R[y,a] <- obs.sp.at.age[y,a] / p.rec.sp.at.age[a]
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end age 3 loop
  for (a in 2:12){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1])
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end ages 4 to 14 loop
  for (a in 13:13){  # age 15 loop
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1]) + pred.R[y-1,a]*exp(-z.at.age[a])
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end 15 plus group
  tot.eggs[y] <- sum(eggs[y,])
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds
  } # end year loop
for (y in 4:Y){  # year loop 1999 to 2019
  for (a in 1:1){
    pred.R[y,a] <- bh.alpha*tot.eggs[y-3]/(1 + tot.eggs[y-3] * bh.alpha/K)
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
```

```
   u.log.S.a[y,a] <- log(pred.S[y,a])
   eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
   }  # end age 3 loop
  for (a in 2:12){
   pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1])
   pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
   u.log.S.a[y,a] <- log(pred.S[y,a])
   eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
   }  # end ages 4 to 14 loop
  for (a in 13:13){
   pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1]) + pred.R[y-1,a]*exp(-z.at.age[a])
   pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
   u.log.S.a[y,a] <- log(pred.S[y,a])
   eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
   }  # end 15 plus group
  tot.eggs[y] <- sum(eggs[y,])
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds
  } # end year loop
# likelihoods
# age 3 likelihood
for (y in 4:Y){
  obs.sp.at.age[y,1] ~ dlnorm(u.log.S.a[y,1], tau.sp[1])   # likelihood of spawner abundance
  res.S.3[y] <- log(obs.sp.at.age[y,1]/pred.S[y,1]) # residual for spawners age 3
  }
# age 4 likelihood
for (y in 5:Y){
  obs.sp.at.age[y,2] ~ dlnorm(u.log.S.a[y,2], tau.sp[2])   # likelihood of spawner abundance
  res.S.4[y] <- log(obs.sp.at.age[y,2]/pred.S[y,2]) # residual for spawners age 4
  }
# age 5 likelihood
for (y in 6:Y){
  obs.sp.at.age[y,3] ~ dlnorm(u.log.S.a[y,3], tau.sp[3])   # likelihood of spawner abundance
  res.S.5[y] <- log(obs.sp.at.age[y,3]/pred.S[y,3]) # residual for spawners age 5
  }
# age 6 likelihood
for (y in 7:Y){
  obs.sp.at.age[y,4] ~ dlnorm(u.log.S.a[y,4], tau.sp[4])   # likelihood of spawner abundance
  res.S.6[y] <- log(obs.sp.at.age[y,4]/pred.S[y,4]) # residual for spawners age 6
  }
# age 7 likelihood
for (y in 8:Y){
  obs.sp.at.age[y,5] ~ dlnorm(u.log.S.a[y,5], tau.sp[5])   # likelihood of spawner abundance
  res.S.7[y] <- log(obs.sp.at.age[y,5]/pred.S[y,5]) # residual for spawners age 7
  }
# age 8 likelihood
for (y in 9:Y){
  obs.sp.at.age[y,6] ~ dlnorm(u.log.S.a[y,6], tau.sp[6])   # likelihood of spawner abundance
  res.S.8[y] <- log(obs.sp.at.age[y,6]/pred.S[y,6]) # residual for spawners age 8
  }
# total spawner likelihood beginning in year 2008
for (y in 13:Y){
  u.log.S[y] <- log(sum.S[y])
  obs.med.sp[y] ~ dlnorm(u.log.S[y], tau.sp[7])   # likelihood of spawner abundance
  res.S[y] <- log(obs.med.sp[y]/sum.S[y])  # residual for total spawners
  }
for (s in 1:7){
 logsigmaS[s] ~ dunif(0,3)
 tau.sp[s] <- pow(logsigmaS[s],-2)
  }
# predictions
for (y in Y2:Y3){  # predictions Y+1 to Y+more
  for (a in 1:1){
```

```
    pred.R[y,a] <- bh.alpha*tot.eggs[y-3]/(1 + tot.eggs[y-3] * bh.alpha/K)
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    u.log.S.a[y,a] <- log(pred.S[y,a])
    eggs[y,a] <-pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end age 3 loop
  for (a in 2:12){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1])
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    eggs[y,a] <- pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end age loop
  for (a in 13:13){
    pred.R[y,a] <- pred.R[y-1,a-1]*exp(-z.at.age[a-1])+ pred.R[y-1,a]*exp(-z.at.age[a])
    pred.S[y,a] <- pred.R[y,a]*p.rec.sp.at.age[a]
    eggs[y,a] <- pred.S[y,a]*wt.at.age[a]*p.fem.sp.at.age[a]*eggs.kg
    }  # end age loop
  sum.S[y] <- sum(pred.S[y,]) # total spawners on the spawning grounds
  u.log.S[y] <- log(sum.S[y])  # log mean of total spawners, for likelihood
  tot.eggs[y] <- sum(eggs[y,])
   } # end year loop
} # end model
```

APPENDIX 5. DIAGNOSTICS OF MODEL FITS

The following outputs from models 4, 5, and 6 are provided.

- Table summarizing the model structure, parameters, priors, fitting diagnostic (deviance, AIC') and comments on fits;
- Density plots of prior versus posteriors for model parameters;
- Boxplots of posterior distributions of parameters;
- Correlation plots of parameters;
- Residuals plot;
- Observed vs predicted total spawners;
- Observed versus predicted proportions at age of spawners.

Table A5.1. Parameters, priors and diagnostics of model 4.

Feature	Specifics
Parameters and prior assumptions	Non-informative: Bev-Holt (α, K) σ (3:8, Total) Weakly Informative: S[0:2] S[3:8] p.rec.to.spawner[3:6]
Parameter	Beverton-Holt α = exp(-δ) Z(0) = -log(S.0) Z[1] = -log(S[1]) Z[2] = -log(S[2] Z[3:8] = -log(S[3:8]) Z[9:15+] = Z[8] p.rec.to.sp[7:15+] = p.rec.to.sp[6]
Prior	δ ~ N(1,0.001)C(0,) K ~ N(1,0.001)C(1,) S.0 ~ Beta(14,86) S[1] ~ Beta(44,56) S[2] ~ Beta(64,36) S[3:8] ~ Beta(6,4) p.rec.to.sp[3] ~ Beta(4,12) p.rec.to.sp[4] ~ Beta(3,3) p.rec.to.sp[5] ~ Beta(5,2) p.rec.to.sp[6] ~ Beta(4,1) log(σ) [3:8, Total] ~ U(0,3)
Fit statistics	Deviance: 2396 Parameters: 22 AIC' = Dev+2*p = 2440 DIC = 2401 (pD = 5.0)
Comments	Good fit to spawners at ages 3 to 6 Mostly positive residuals for total spawners Temporal trend in residuals for ages 7 and 8 No autocorrelation for residuals Survival age 3 higher than for ages 4 to 7 which is not consistent with expectations Negative correlation between α and K, α and S[0]

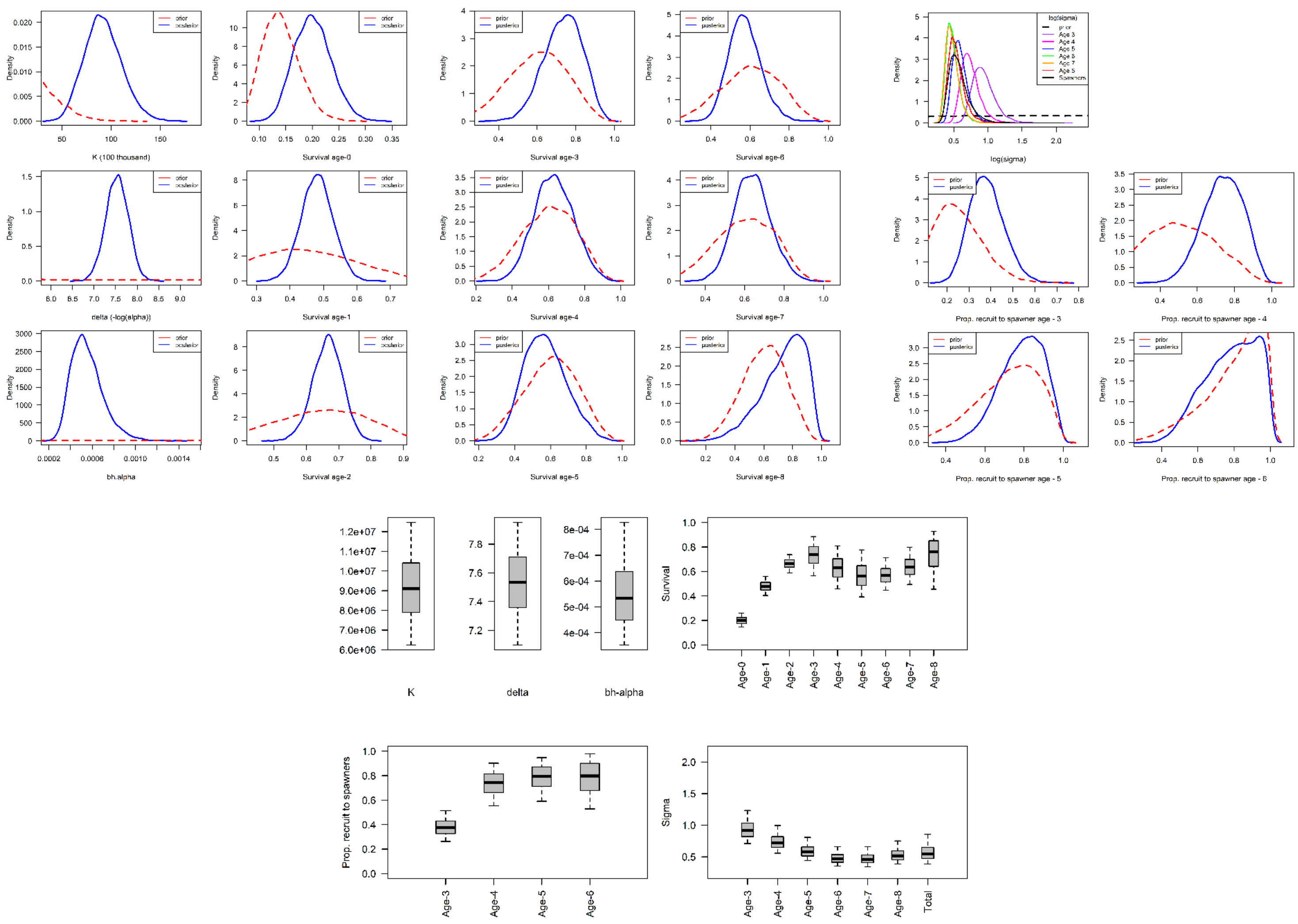


Figure A5.1. Parameter posterior distributions of model 4.

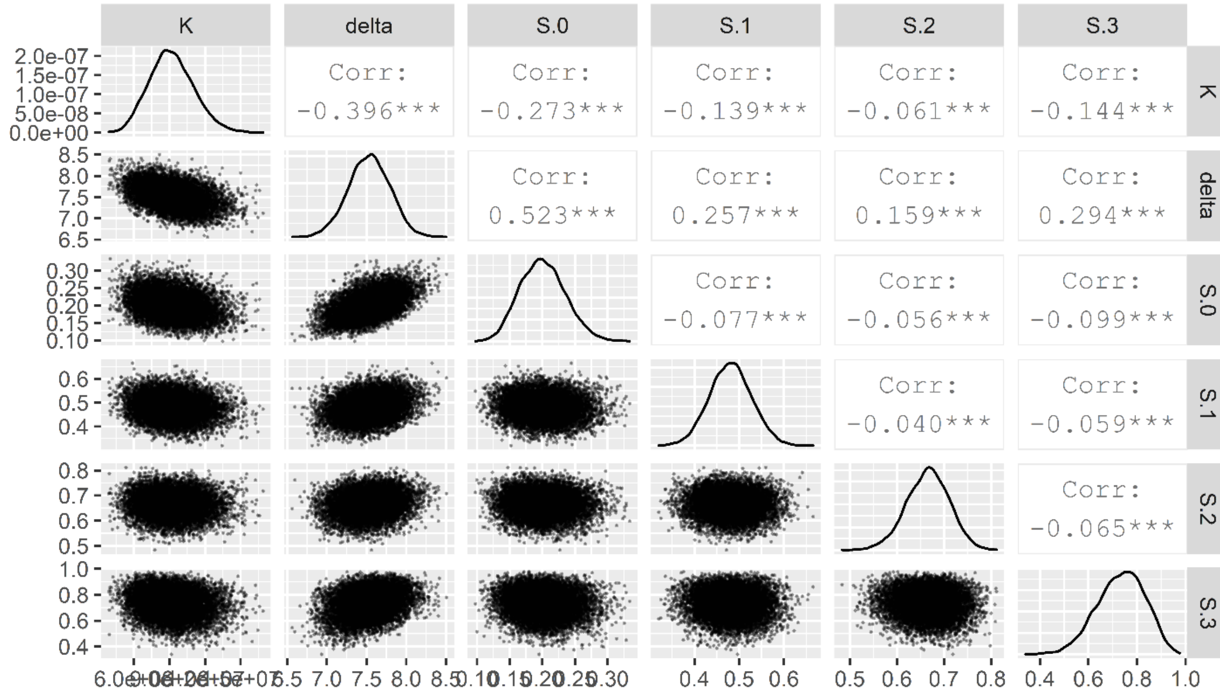


Figure A5.1 (continued). Parameter scatter plots and Pearson correlations of key parameters from the model fits of model 4.

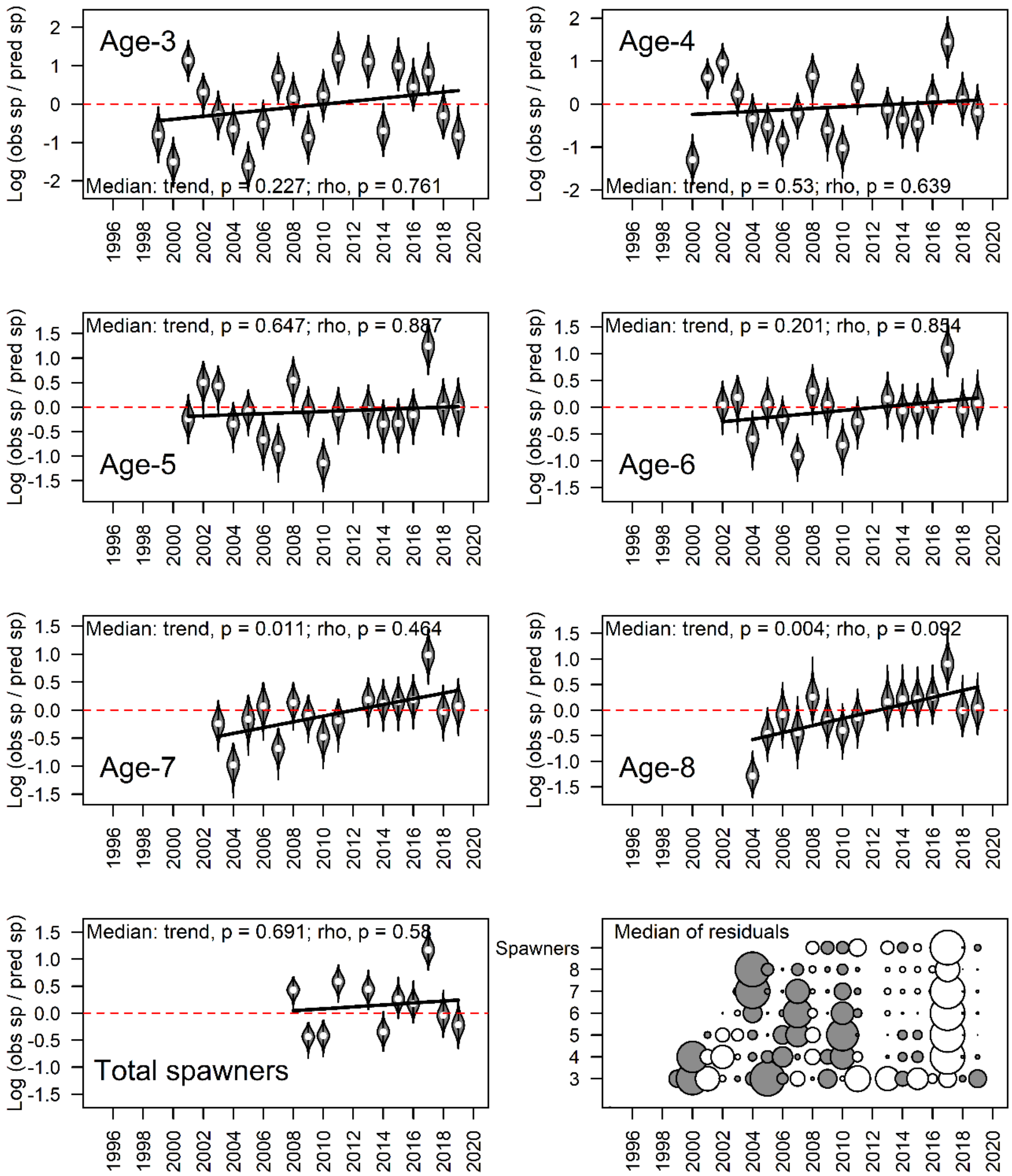


Figure A5.1 (continued). Residual plots expressed as log(assessed abundance / predicted abundance) at ages 3 to 8+, for total spawners, and relative (by age group) bubble plot of logged residual patterns of model 4. Also shown in each panel of residuals are the p-value for the temporal linear trend in residuals and the p-value for the first order autocorrelation of the residuals (from package EnvStats in R).

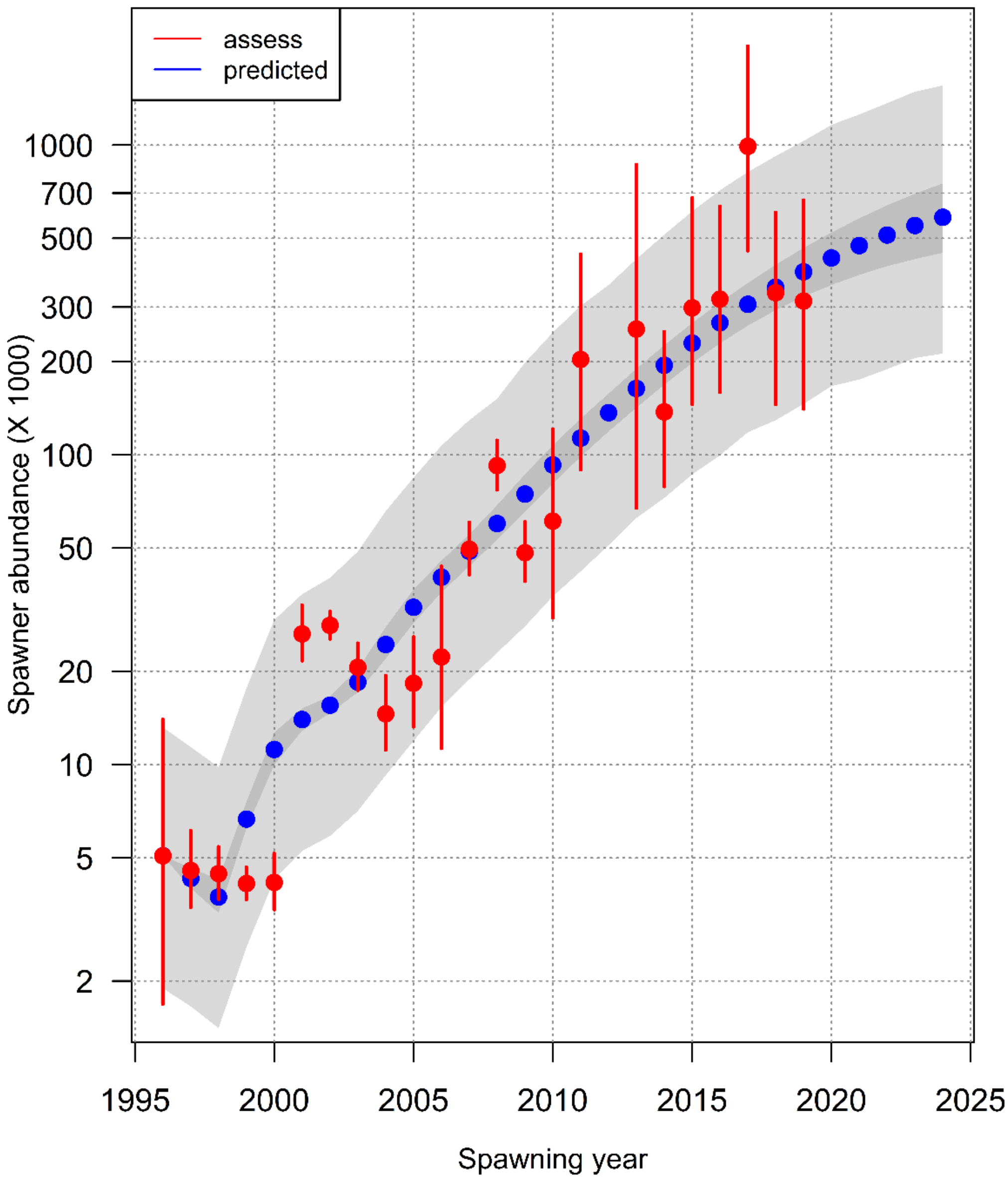


Figure A5.1 (continued). Observed vs predicted total spawners of model 4. The assessed abundances are shown as red symbols for the median with 5th to 95th percentiles ranges as red vertical lines. The blue symbols are the predicted abundances, the darker grey shading is the 5th to 95th percentile range of mean predicted abundance and the light grey shading represents the 5th to 95th percentile range of the predicted spawner abundance accounting for the full process uncertainty (logσ). Note the y-axis abundance is shown on the log scale.

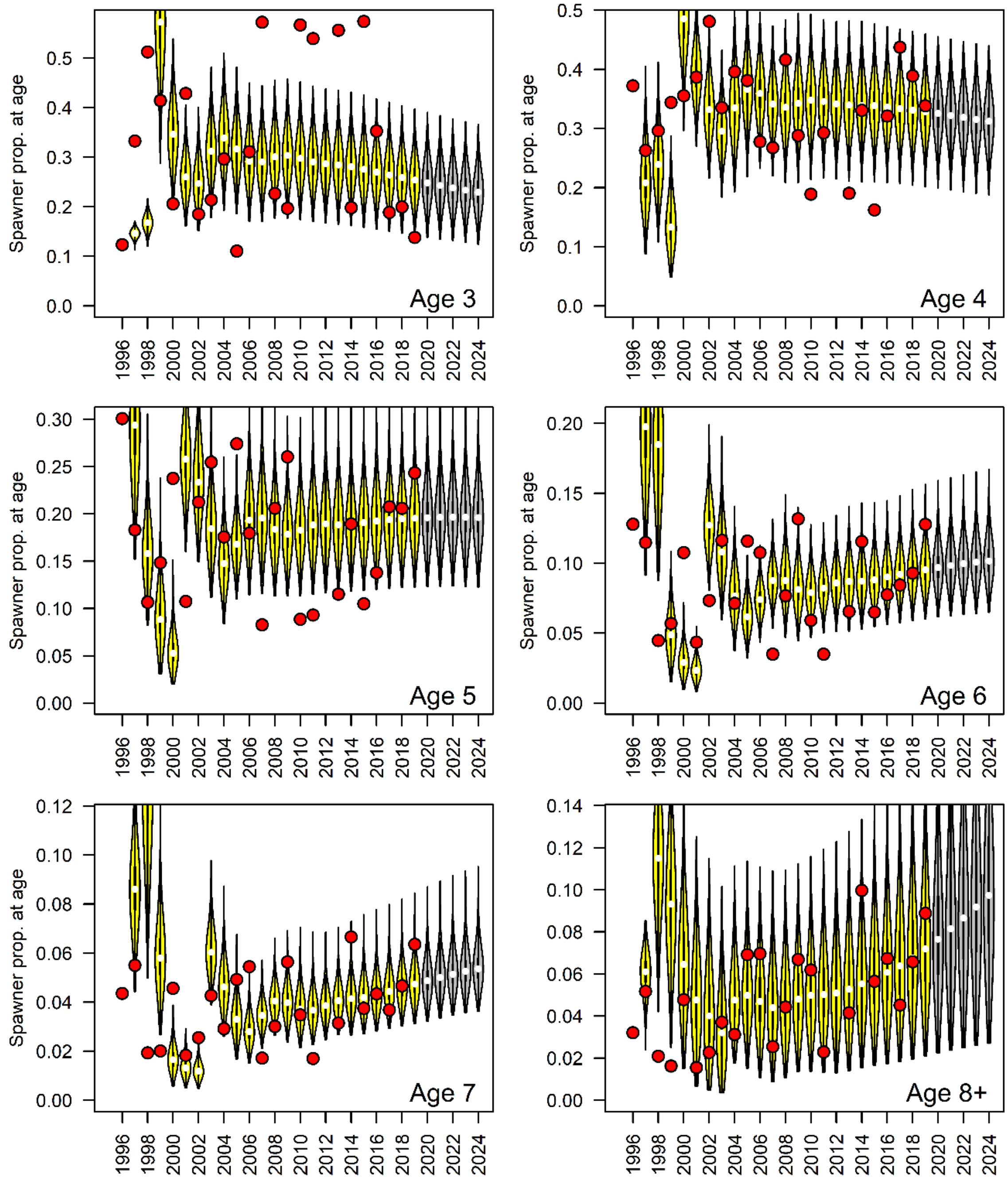


Figure A5.1 (continued). Observed (red symbols) vs predicted (yellow violin plots) proportions at age of spawners, for ages 3 to 7, and for ages 8+ of model 4.

Table A5.2. Parameters, priors and diagnostics of model 5.

Feature	Specifics
Parameters and prior assumptions	Non-informative: Bev-Holt (α, K) σ (3:8, Total) Weakly Informative: S[3:8] p.rec.to.spawner[3:6] S[0to3]
Parameter	Beverton-Holt α = exp(-δ) Z(0to3) = -log(S[0to3]) Z[3:8] = -log(S[3:8]) Z[9:15+] = Z[8] p.rec.to.sp[7:15+] = p.rec.to.sp[6]
Prior	δ ~ N(1,0.001)C(0,) K ~ N(1,0.001)C(1,) S[0to3] ~ Beta(5,45) S[3:8] ~ Beta(6,4) p.rec.to.sp[3] ~ Beta(4,12) p.rec.to.sp[4] ~ Beta(3,3) p.rec.to.sp[5] ~ Beta(5,2) p.rec.to.sp[6] ~ Beta(4,1) log(σ) [3:8, Total] ~ U(0,3)
Fit statistics	Deviance: 2395 Parameters: 20 AIC' = Dev+2*p = 2435 DIC = 2394 (pD = -1.4)
Comments	Good fit to spawners at ages 3 to 6 Better fit to total spawners, balanced residuals Temporal trend in residuals for ages 7 and 8 No autocorrelation for residuals. Survival age 3 higher than for ages 4 to 7 which is not consistent with expectations Negative correlation between α and K, α and S.0to3

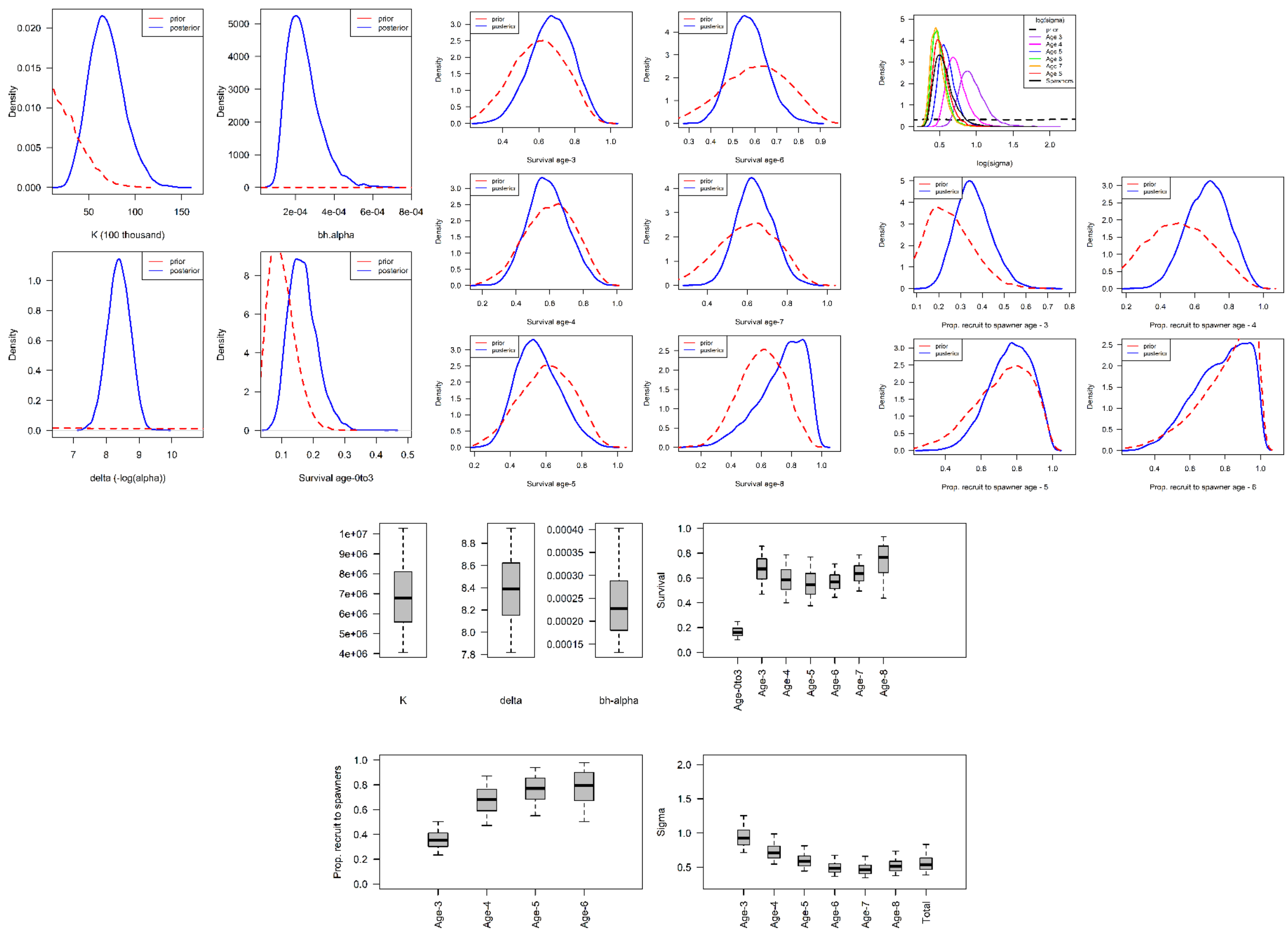


Figure A5.2. Parameter posterior distributions of model 5.

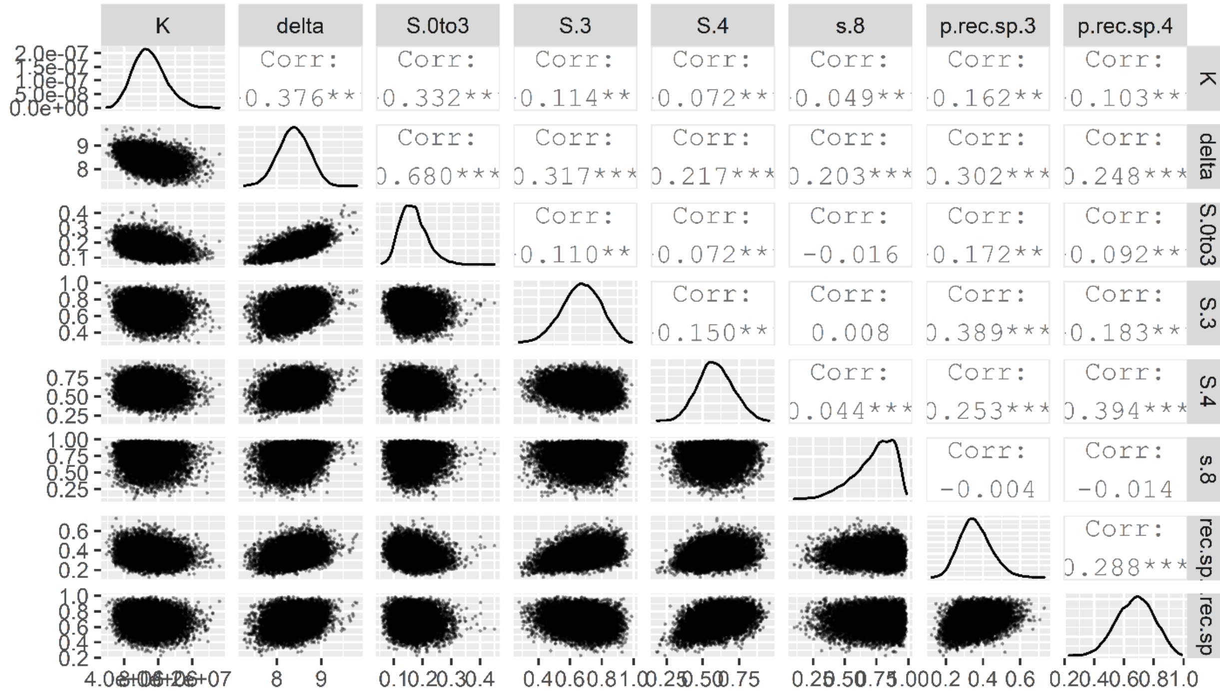


Figure A5.2 (continued). Parameter scatter plots and Pearson correlations of key parameters from the model fits of model 5.

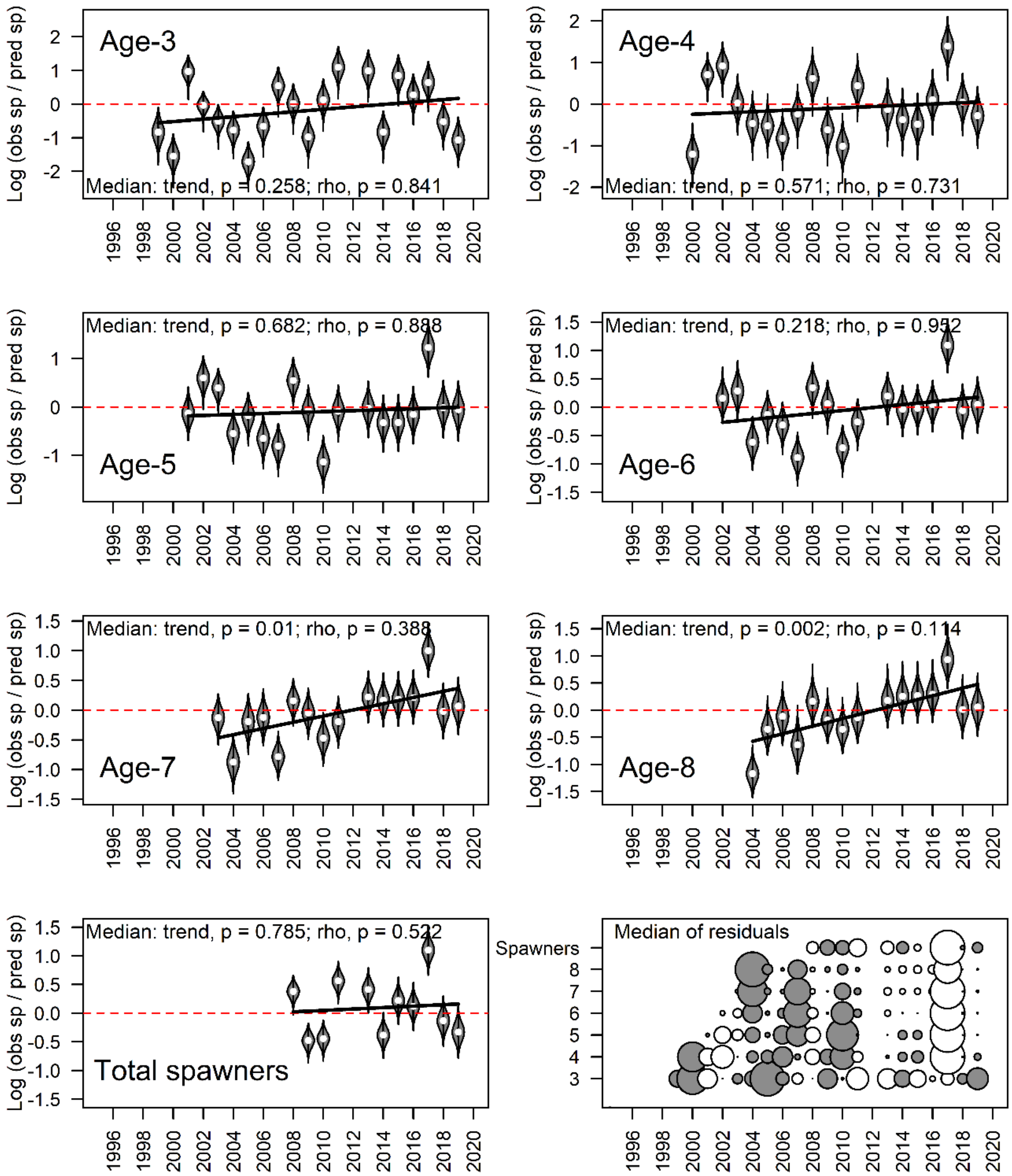


Figure A5.2 (continued). Residual plots expressed as log(assessed abundance / predicted abundance) at ages 3 to 8+, for total spawners, and relative (by age group) bubble plot of logged residual patterns of model 5. Also shown in each panel of residuals are the p-value for the temporal linear trend in residuals and the p-value for the first order autocorrelation of the residuals (from package EnvStats in R).

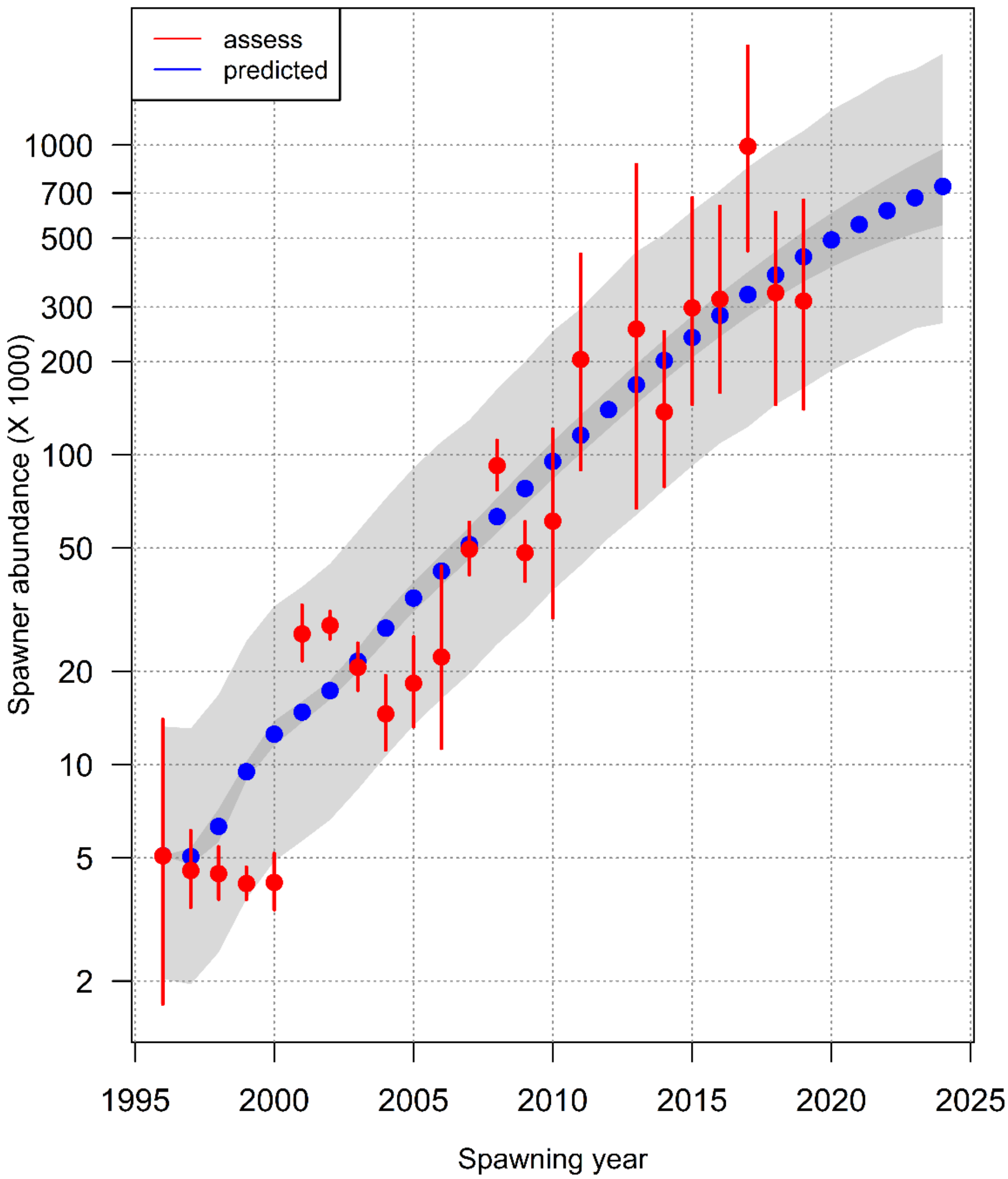


Figure A5.2 (continued). Observed vs predicted total spawners of model 5. The assessed abundances are shown as red symbols for the median with 5th to 95th percentiles ranges as red vertical lines. The blue symbols are the predicted abundances, the darker grey shading is the 5th to 95th percentile range of mean predicted abundance and the light grey shading represents the 5th to 95th percentile range of the predicted spawner abundance accounting for the full process uncertainty (logσ). Note the y-axis abundance is shown on the log scale.

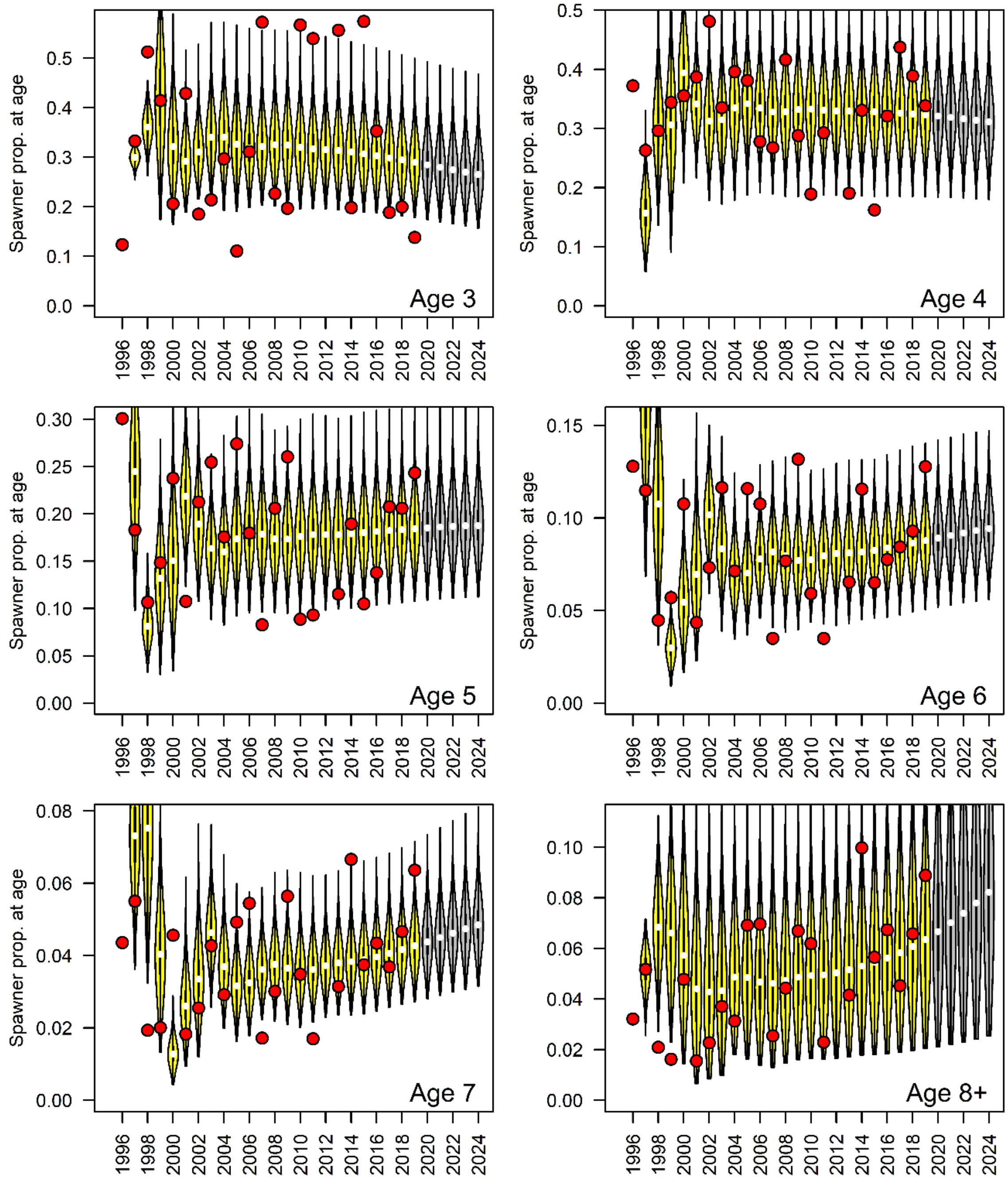


Figure A5.2 (continued). Observed (red symbols) vs predicted (yellow violin plots) proportions at age of spawners, for ages 3 to 7, and for ages 8+ of model 5.

Table A5.3. Parameters, priors and diagnostics of model 6.

Feature	Specifics
Parameters and prior assumptions	Non-informative: Bev-Holt (α, K) for age 3 σ (3:8, Total) Weakly Informative: S[3:8] p.rec.to.spawner[3:6]
Parameter	Beverton-Holt $\alpha = \exp(-\delta)$ Z[3:8] = -log(S[3:8]) Z[9:15+] = Z[8] p.rec.to.sp[7:15+] = p.rec.to.sp[6]
Prior	δ ~ N(1,0.001)C(0,) K ~ N(1,0.001)C(1,) S[3:8] ~ Beta(6,4) p.rec.to.sp[3] ~ Beta(4,12) p.rec.to.sp[4] ~ Beta(3,3) p.rec.to.sp[5] ~ Beta(5,2) p.rec.to.sp[6] ~ Beta(4,1) log(σ) [3:8, Total] ~ U(0,3)
Fit statistics	Deviance: 2391 Parameters: 19 AIC' = Dev+2*p = 2429 DIC = 2392 (pD = 0.3)
Comments	Good fit to spawners at age Temporal trend in residuals for ages 7 and 8 No autocorrelation for residuals. Survival age 3 higher than S for ages 4 to 7 which is not consistent with expectations Positive correlation between Bev-Holt alpha and S[3]

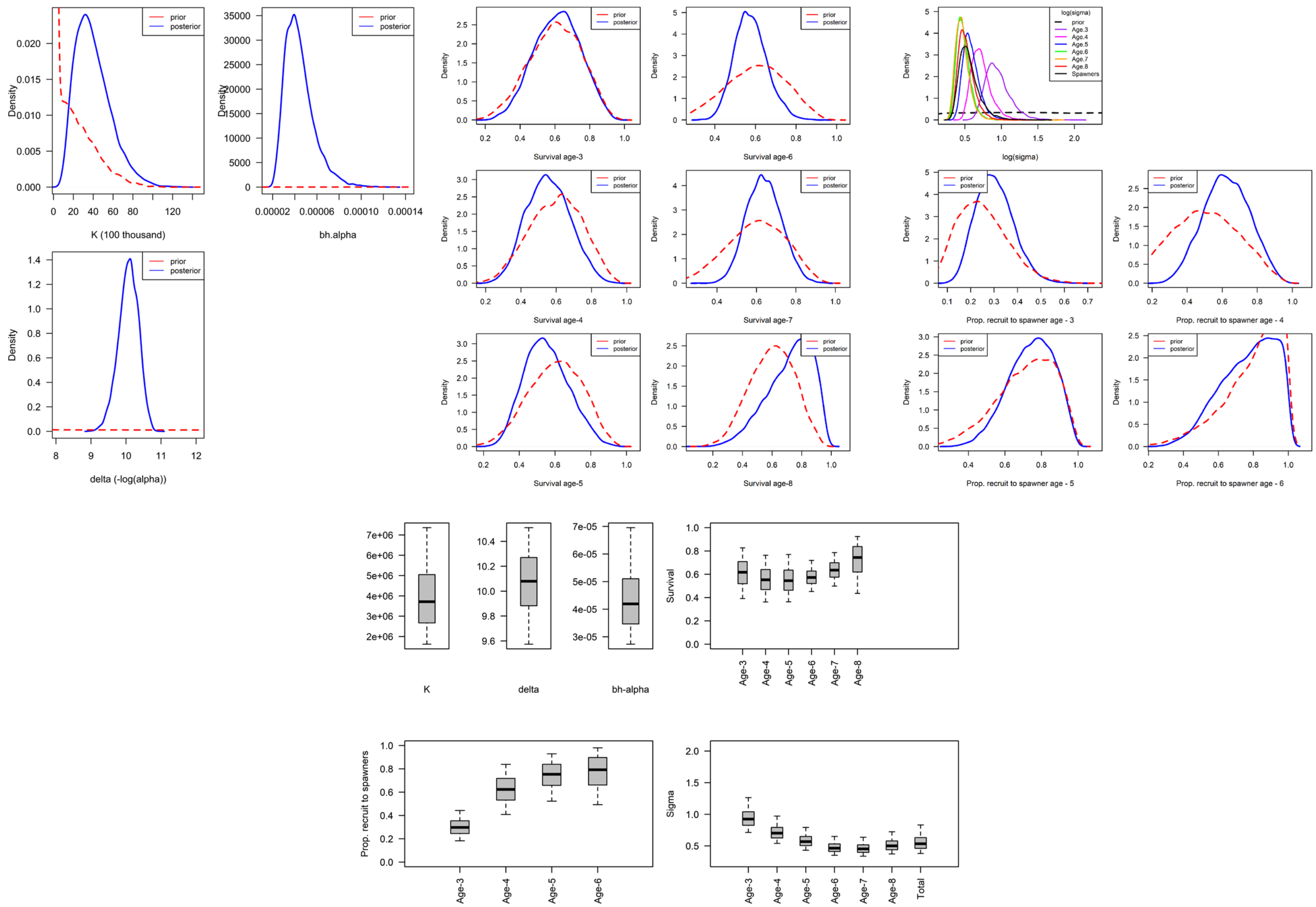


Figure A5.3. Parameter posterior distributions of model 6.

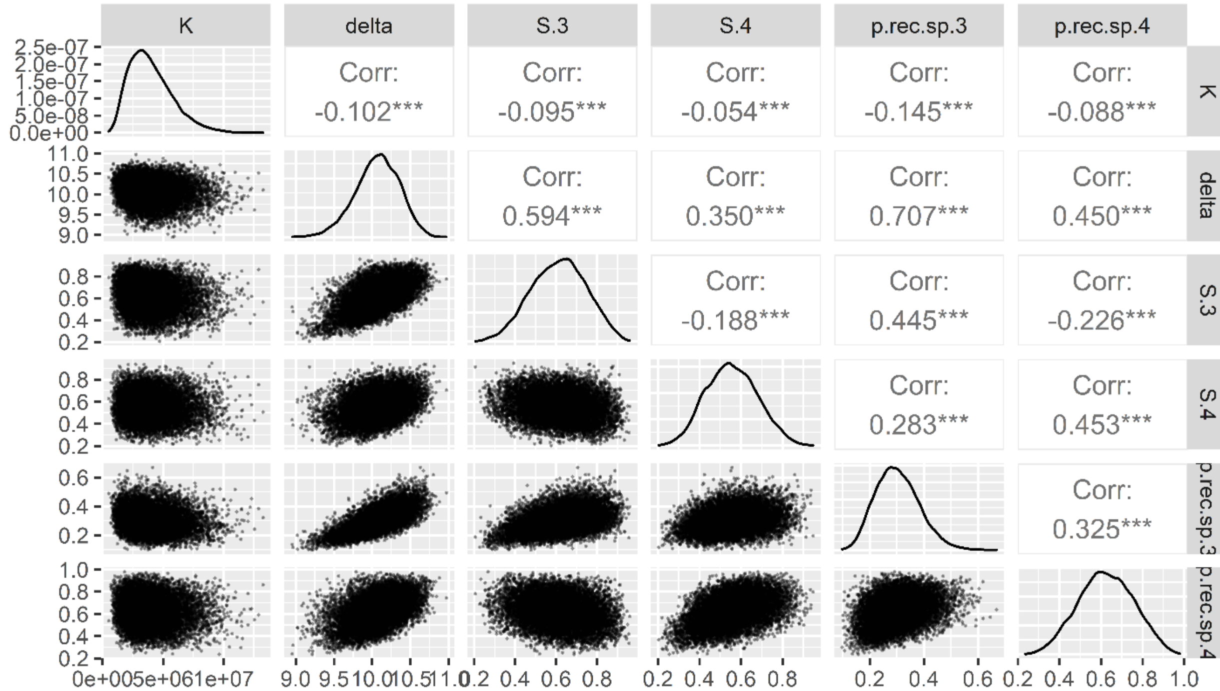


Figure A5.3 (continued). Parameter scatter plots and Pearson correlations of key parameters from the model fits of model 6.

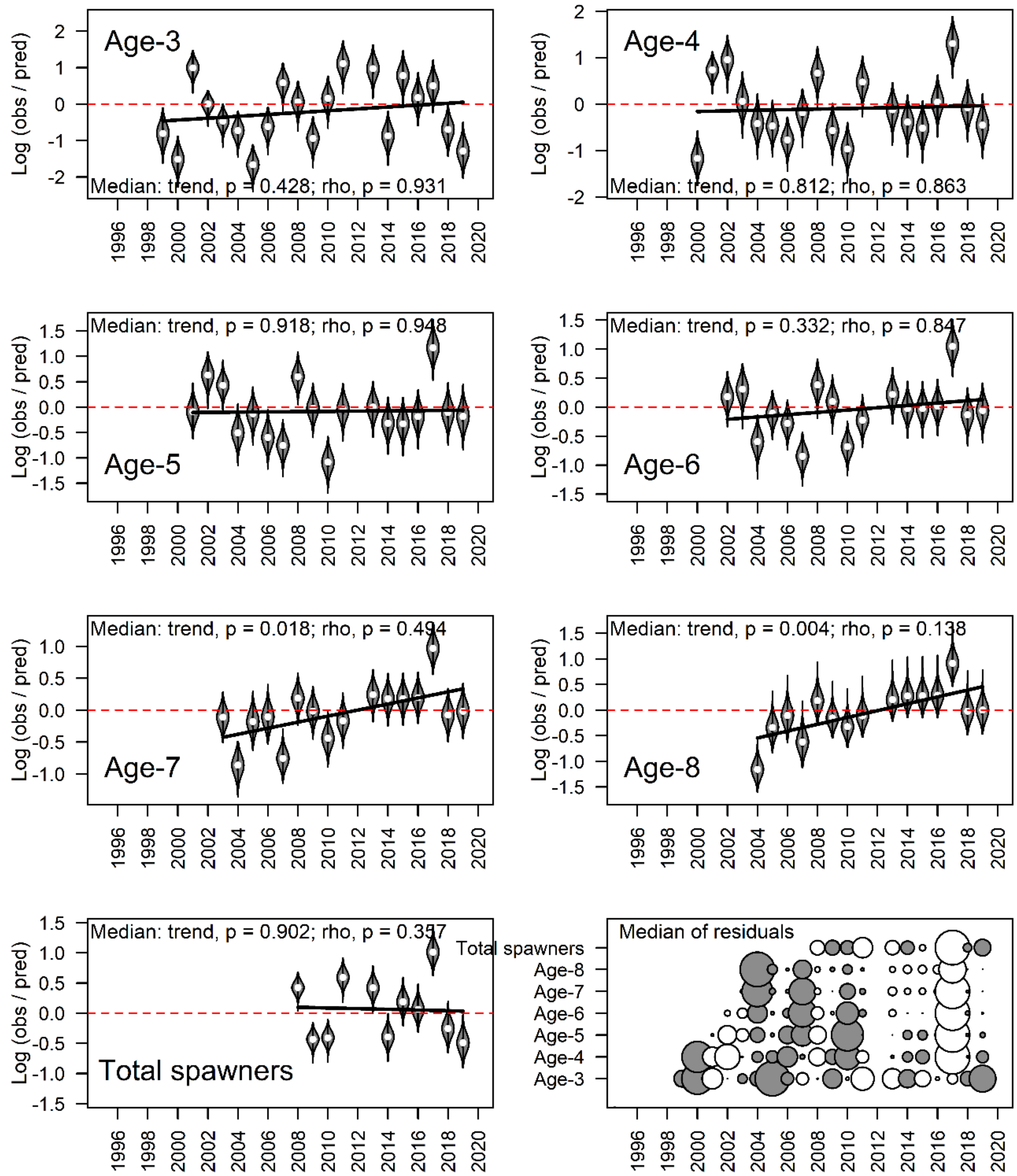


Figure A5.3 (continued). Residual plots expressed as log(assessed abundance / predicted abundance) at ages 3 to 8+, for total spawners, and relative (by age group) bubble plot of logged residual patterns of model 6. Also shown in each panel of residuals are the p-value for the temporal linear trend in residuals and the p-value for the first order autocorrelation of the residuals (from package EnvStats in R).

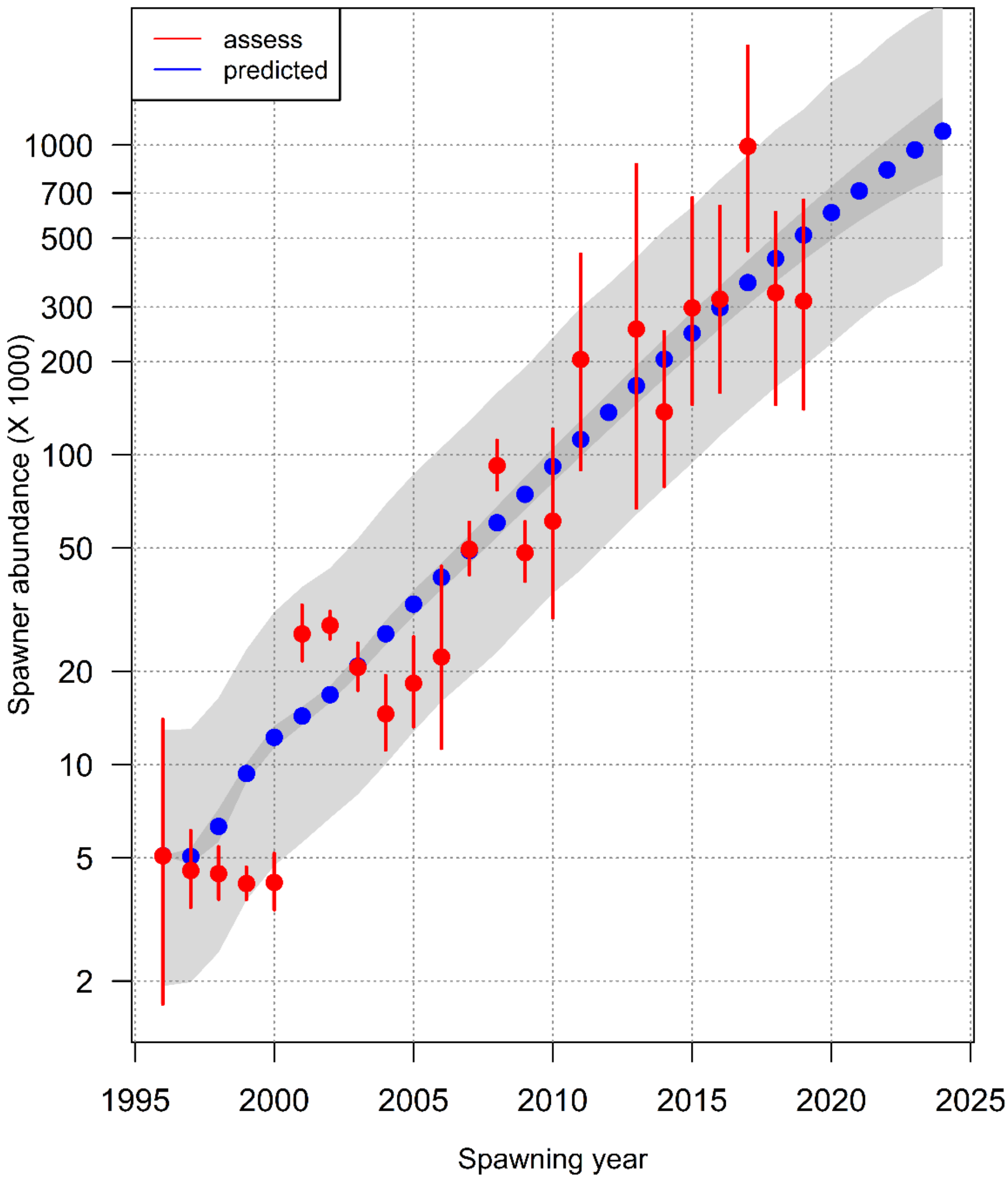


Figure A5.3 (continued). Observed vs predicted total spawners of model 6. The assessed abundances are shown as red symbols for the median with 5th to 95th percentiles ranges as red vertical lines. The blue symbols are the predicted abundances, the darker grey shading is the 5th to 95th percentile range of mean predicted abundance and the light grey shading represents the 5th to 95th percentile range of the predicted spawner abundance accounting for the full process uncertainty (logσ). Note the y-axis abundance is shown on the log scale.

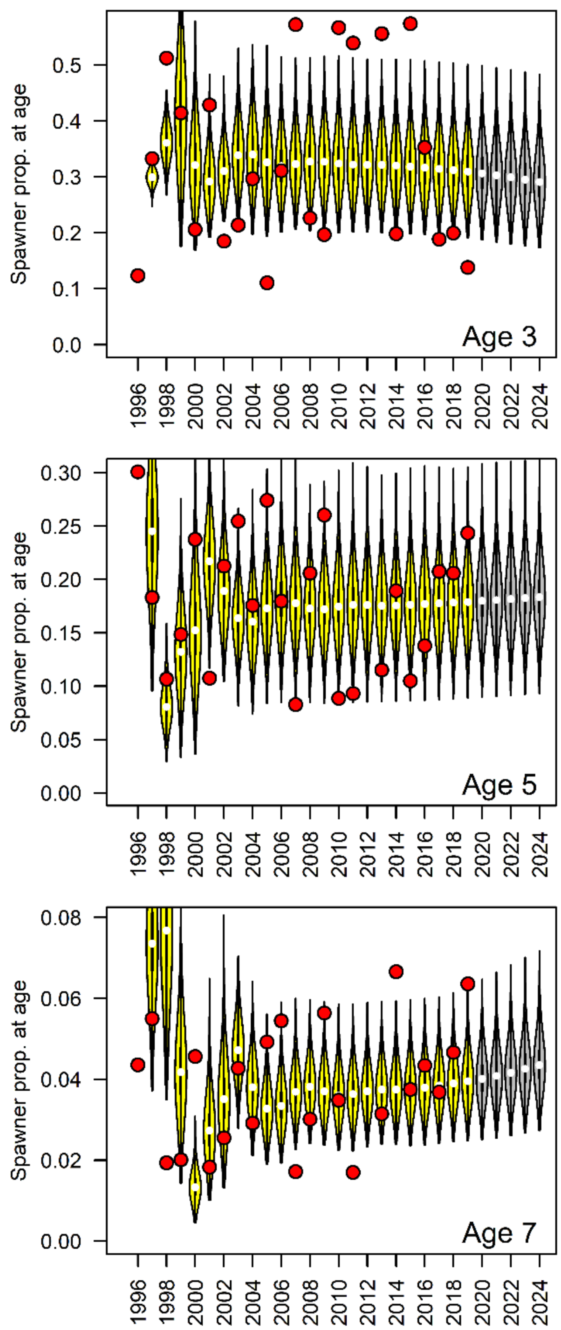


Figure A5.3 (continued). Observed (red symbols) vs predicted (yellow violin plots) proportions at age of spawners, for ages 3 to 7, and for ages 8+ of model 6.