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### **Multi-species Considerations for Defining Fisheries Reference Points for Striped Bass (*Morone saxatilis*) from the Southern Gulf of St. Lawrence**

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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 reference points and management strategies based on single species management approaches for the purpose of optimizing utility functions specific to Striped Bass do not take into account the interactions among multiple species of equally important conservation and fisheries values. Modifying the single species Striped Bass reference points to account for interactions with other species requires evidence of interactions between Striped Bass and the other species. The most direct interaction considered is the predation by Striped Bass on other species with a focus on Atlantic Salmon. Several data sources are presented and examined to inform on these associations, including recorded commercial landings of important diadromous species, indices based on catches at estuarine index trapnets operated by DFO Science, and studies directly related to predation and survival rates of Atlantic Salmon smolts during the seaward migration phase. A cohort model relating population specific indices of juvenile salmon abundance to adult returns is also presented. There is conflicting evidence of reductions in a few anadromous fish species abundance indicators associated with increased abundance of Striped Bass in the southern Gulf. There is direct evidence of predation by Striped Bass on gaspereau, Rainbow Smelt and Atlantic Salmon smolts. Several studies using acoustic tag technologies have inferred predation events and changes in estimated survival rates in the early phase of migration of Atlantic Salmon smolts through Miramichi Bay that point to Striped Bass predation as a likely driver of these variations. It is not clear from the available studies that reducing Striped Bass spawner abundances to a level of the mid 2000s, i.e., 100 thousand spawners or less, would improve the acoustic tagged smolt survival estimates or the population level relative survival rates derived from the cohort model, nor landings of gaspereau and Rainbow Smelt in the commercial fisheries.

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## INTRODUCTION

As the Striped Bass population of the southern Gulf increased in abundance, concerns have been expressed by Atlantic Salmon fishery advocates as well as some gaspereau (river herring, two species) 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. The impact of Striped Bass on these other species is indicated to be associated with high levels of predation by Striped Bass. One can readily find publications that consider correlations between abundance indices of Striped Bass and indices of species that are documented prey of bass to conclude that Striped Bass when abundant are impacting survival and productivity of these other species (see Grout 2006 for example). 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.

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 Maximum Sustainable Yield (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 developed for Striped Bass (DFO 2021; Chaput and Douglas 2022) are based on single species management approaches for the purpose of optimizing utility functions specific to Striped Bass. Modifying the single species Striped Bass reference points to account for interactions with other species requires evidence of interactions between Striped Bass and the other species. This working paper assembles the available information on status of diadromous species that are potential prey of Striped Bass to determine if there is any such evidence that would support modifying the single species reference values developed previously (DFO 2021).

## BACKGROUND ON THE ECOSYSTEM OCCUPIED BY STRIPED BASS

The southern Gulf of St. Lawrence contains a diversity of diadromous fish species, many of which are at the northern limit of their species distribution. The Miramichi River, within the southern Gulf of St. Lawrence contains the largest abundance of these diadromous species including (Chaput 1995):

- The only confirmed spawning population of American Shad (*Alosa sapidissima*) in the southern Gulf (Chaput and Bradford 2003)
- Two species of river herring (Alewife, *Alosa pseudoharengus*; Blueback Herring, *A. aestivalis*) that spawn in the Miramichi and are fished commercially (Chaput and Atkinson 2001);
- Rainbow Smelt (*Osmerus mordax*) that are fished commercially in late fall and during the winter, under the ice (Chaput and LeBlanc 1996);



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- Atlantic Tomcod (*Microgadus poulamon*) that spawn near the head of tide in winter under the ice (Bradford et al. 1997);
  - Atlantic Salmon (*Salmo salar*) whose annual returns historically were the highest of individual rivers in eastern Canada (Moore et al. 1995);
  - The only confirmed and annually predictable spawning area for the Striped Bass (*Morone saxatilis*) population of the southern Gulf of St. Lawrence (Douglas et al. 2011).
  - American Eel (*Anguilla rostrata*) that rear in freshwater and estuarine areas of the Miramichi River and are fished commercially (Cairns et al. 2014).
  - Sea Lamprey (*Petromyzon marinus*), an anadromous lamprey that spawns throughout the Miramichi River (Chaput 1995).

Assessments and stock status updates have been provided annually for Striped Bass (DFO 2020a) and Atlantic Salmon (DFO 2020b) but only infrequently for the other species. Life history and status information for a few species, American Shad and American Eel, have been reviewed in support of the development of COSEWIC status reports or for recovery potential assessments following a COSEWIC status assessment. Atlantic Tomcod has never been assessed even though it is an important commercial bycatch in the Rainbow Smelt fisheries of the southern Gulf (Chaput and LeBlanc 1991; Bradford et al. 1997). Sea Lamprey have never been assessed and are not commercially exploited (Chaput 1995).

Chaput (1995) indicated that the commercial landings of the diadromous species in the Miramichi River area represented approximately 50% of the total landings from the southern Gulf prior to 1940 but the contribution of the Miramichi to the total had declined to just over 30% by the early 1990s.

A summary of the life history characteristics of these species within the Miramichi River including general information on habitat, age at first maturity, fecundity, spawning season, proportion of time spent in freshwater, estuary and marine environments, size variations at maturity, and fisheries is provided in Chaput (1995). An attempt was also made to estimate the relative size, in number and biomass, of the annual returns to the Miramichi of the commercially exploited species based on fisheries landings, or index trapnet catches raised by assumed exploitation rates or efficiencies of trapnets. At the time of the publication, Chaput (1995) reported that the total adult biomass of diadromous fish migrating through the Miramichi estuary exceeded 16,000 t, with Rainbow Smelt accounting for 50% of the biomass and the gaspereau (two river herring species) representing just over 40% of the total biomass. At the time of the publication, Striped Bass were estimated to have been a very minor component of the total biomass, at < 0.1%. Based on the estimated mean weight at age and estimated spawner abundances at age of Striped Bass during 1996 to 2000, the estimated biomass of Striped Bass spawners is the range of 5 and 7 t for those years. Since 2015, the estimated biomass of Striped Bass spawners had increased to between 400 and 1,500 t. Based on the increased abundance of Striped Bass, and all else being equal for the other species, the proportion of the diadromous fish biomass comprised of Striped Bass would have increased from a negligible amount in the mid-1990s (< 0.1%) to between 3% and 10% since 2015.

The question regarding the impact of the increased abundance of Striped Bass on the other diadromous species is important in the context of establishing reference points to guide fisheries management of Striped Bass. The remainder of the document examines the evidence of potential impacts of an increasing Striped Bass population on other species and discusses options for reference points for Striped Bass that take account of these interactions.

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## **STRIPED BASS PREDATOR/PREY INTERACTIONS WITH DIADROMOUS SPECIES OF FISHERIES INTEREST**

Striped Bass is large bodied and piscivorous predator known to prey on valued anadromous fisheries species. The most important interaction is expected to be associated with predation by Striped Bass on these species. NEFSC (2019) summarized studies of Striped Bass along the eastern seaboard of the US and provide the same general descriptions of adult Striped Bass being generalist feeders on a variety of fish and invertebrates with the prey composition dependent upon the predator size (larger bass eat more fish), the time of year, and the foraging habitat. There is no indication from the literature of Striped Bass being a specialist feeder dependent on a particular prey; bass seemingly readily switch among prey based on availability. Andrews et al. (2017) provide information on diet of Striped Bass sampled in the Saint John River (NB) in an area downstream of a large hydro-electric dam. The size range of Striped Bass sampled by Andrews et al. (2017) is very large, essentially all Striped Bass exceeded 70 cm Total Length, and the most common prey item over all samples was gaspereau juveniles.

Vulnerability to predation by Striped Bass would depend on two main factors: body size of prey relative to gape size of the predator (Scharf et al. 2000), and overlapping spatial distribution of the prey and the predator. Based on these two considerations, the diadromous fish species and life stages, and their susceptibilities to predation by Striped Bass are summarized in Table 1.

### **DIET OF STRIPED BASS FROM THE SOUTHERN GULF OF ST. LAWRENCE**

The best information available on Striped Bass diets in the southern Gulf is from the limited study conducted in 2013 to 2105 by DFO (2016) and summarized in Hanson (2020). Striped Bass were sacrifice sampled from angling and trapnet catches during the spawning period (May and June) in the Miramichi River and in the summer and early autumn from various shore locations in the southern Gulf of St. Lawrence (Table 2).

#### **May and June in Miramichi**

The diet of Striped Bass sampled in the Miramichi estuary during May and June was notably consistent between years with the majority (mean 68%, range 63%-77%) of Striped Bass stomachs empty (Figure 1). The highest proportion of empty stomachs occurred in late May and early June, when Striped Bass spawning is usually at its peak, and coincided with lower abundance of Rainbow Smelt and gaspereau at that time (Figure 2). This suggests that the majority of Striped Bass feeding in the Miramichi estuary during the spring occurs before and after the peak spawning time for Striped Bass.

Rainbow Smelt and gaspereau were the most frequently occurring prey in the samples. Despite their low occurrence in Striped Bass stomachs, gaspereau were the most important species in terms of prey weight (Figure 1). Gaspereau were absent from samples collected by angling which suggests that gaspereau were especially vulnerable to Striped Bass when both were captured in trapnets.

Striped Bass in the Miramichi River during the spring fed opportunistically and changed prey species as they became available (or unavailable) during different migration times (Figure 2). Rainbow Smelt were present when Striped Bass began feeding in the spring and were the first to be consumed, while gaspereau were the last to arrive in the estuary and also the last to be consumed. Small numbers of Atlantic Salmon smolts and in a low proportion of stomachs sampled were observed during the three years. Atlantic Salmon smolts were identified from samples collected during a relatively brief interval of time in late May to early June in the three

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years of sampling and the occurrence of smolts corresponded to the timing of the smolt migration in the Miramichi River. The highest occurrence of salmon smolts was approximately 30% of stomachs sampled in late May 2014; on all other sampling dates when salmon smolts were identified, they were identified from less than 10% of the stomachs sampled on that day (Figure 2).

Over all years and capture methods, the remaining prey species or prey categories were present in  $\leq 2\%$  of Striped Bass stomachs sampled and contributed on average  $\leq 3\%$  of the prey biomass during May and June in the Miramichi estuary (Figure 1).

### **Summer and Autumn Southern Gulf of St. Lawrence**

Striped Bass were also sampled opportunistically during the months of June to October in 2013 to 2015 across the southern Gulf of St. Lawrence, from south of Chaleur Bay to Cape Breton (Table 2). Striped Bass were captured in a variety of habitats from a freshwater riverine location to saline coastal locations. The average fork length of Striped Bass sampled was 38.4 cm (range 21.3 – 73.1 cm). The diet of Striped Bass in the southern Gulf of St. Lawrence is diverse and consistent with the species that occupy estuarine and near shore coastal habitats (Hanson 2020). Eighteen species of fish, eight crustacean groups, three insect groups, marine worms, and a gastropod were identified in these stomach samples (Table 3).

## **EVIDENCE OF STRIPED BASS IMPACTS ON DIADROMOUS SPECIES OF FISHERIES INTEREST**

As indicated previously, assessments and stock status have only been completed annually for Striped Bass (DFO 2020a) and Atlantic Salmon (DFO 2020b) however no assessment to date of Atlantic Salmon includes estimates of annual survival rates or considers the role that Striped Bass may play in the status of the resource. An updated assessment of the fisheries and status of the gaspereau stocks is anticipated in early 2021. Updates on status of the other species are not on the current schedule of assessments. For Atlantic Salmon, for which there have been studies on the survival rates of acoustically tagged smolts migrating through the Miramichi River (Chaput et al. 2018; Daniels et al. 2018, 2019).

The potential consequences of the increased abundance of Striped Bass on other diadromous species could potentially be indicated by correlations between Striped Bass abundance indicators and time series of recorded commercial harvests and to indicators of abundance based on catches at estuarine index trapnets, of other species.

### **INDICATORS OF CHANGES IN ABUNDANCE BASED ON LANDINGS**

Annual recorded landings data of diadromous species by province within DFO Gulf Region were obtained from the [DFO website](#) for the years 1990 to 2018. For a number of years and species, the landings data are suppressed to meet confidentiality requirements. The recorded landings (t) by species / species group (gaspereau, Rainbow Smelt, American Eel) for the years 1990 to 2018 are summarized in Figure 3.

The gaspereau landings data from the DFO website for the 1990 to 1999 calendar years are essentially similar to the gaspereau landings data for Gulf NB reported in Chaput and Atkinson (2001), providing some level of confidence of the completeness of the aggregated data. Annual variations in the landings for the three species are likely in part due to differences in effort, changes in the number of active licences, and some differences in sales to buyers versus local sales (for bait) over time.

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Gaspereau landings in Gulf NB have historically been dominated by the statistical districts that include the Miramichi River (Chaput 1995; Chaput and Atkinson 2001). There is a steep decline in recorded landings of gaspereau in the NB portion of the southern Gulf beginning in 2010 and continuing into 2017; landings data of 2015 were suppressed (Figure 3). In NS, gaspereau landings show a steep decline beginning in 1990 to 2000 with landings since 2000 remaining low although with a slight increase to 2018. Gaspereau landings in PEI are highly variable, but the lowest landings were consistently recorded during 2013 to 2018. The percentage decline in the mean landings for the recent period, 2011 to 2018, relative to the mean of an earlier period during 1995 to 2000 corresponding to low Striped Bass abundance was greatest for NB (74%) and least in PEI (125) (Figure 3).

For the NS area, Rainbow Smelt landings show a similar pattern of decline to gaspereau, with landings very low in the recent period 2011 to 2018 (Figure 3). Landings of smelt in NB show a steep decline beginning in 2008 to the lowest of the time series in 2015. In PEI, smelt landings have also declined since 2006 to reach the lowest levels of the times series in the recent five years. There was a large percentage decline in the mean landings during the recent period relative to the mean value of the earlier period in all three provinces, 70% in NB to 96% in NS (Figure 3).

American Eel show large annual variations, with only an observable decline in landings from NS (Figure 3). In PEI, recorded landings of American Eel currently surpass those of either Rainbow Smelt or gaspereau. In the other two provinces, the gaspereau harvests exceed those of Rainbow Smelt and American Eel. Changes in mean landings of the latter period relative to the earlier period ranged from a decrease of 58% in NS to an increase of 133% in PEI (Figure 3).

The only information on population size and fishing mortalities for these species is for the gaspereau stocks of the Miramichi River (NB) and the Margaree River (NS) up to the 1996 fishery year (Chaput and Atkinson 2001; Chaput et al. 2001). For the Miramichi, spawning escapements for both Alewife and Blueback Herring in the Miramichi River were decreasing and estimated fishing mortalities were high (above the reference  $F = 0.4$  to  $0.5$ ) and increasing. Estimated fishing mortality rates in the Margaree River gaspereau fishery were also estimated to have been above the reference  $F = 0.5$  (Chaput et al. 2001).

Associating the declines in gaspereau landings in Gulf NB to the increased abundance of Striped Bass is speculative. It is unclear what would be the cohort link between the species; if the predation effect is most important on the adult spawners or on the young of the year, then the lag between predation and recruitment would be 3 to 4 years, the dominant ages of maturity of gaspereau in this region. Hence, declines in landings that began in 2010 would have been associated with lower gaspereau spawner abundances of 2006 and 2007, corresponding to the years when Striped Bass spawner abundances were estimated to have been at low levels of 25 to 50 thousand spawners.

Rainbow Smelt are relatively short lived, the dominant ages in the fishery catches are 2 and 3 years old (Chaput and LeBlanc 1996). Using a similar premise to gaspereau of associating declines in Rainbow Smelt landings to increased predation by Striped Bass, then the link would have to be on young of the year recruitment rather than on post-spawned fish (Table 1). Therefore, the first year of low catches of smelt in NB recorded in 2011 would mechanistically have been the result of predation on young of the year smelt from the 2009 and 2010 year classes, when Striped Bass abundances were estimated at 50 to 60 thousand fish.

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## INDICATORS OF CHANGES IN ABUNDANCE BASED ON INDEX TRAPNET CATCHES

DFO has operated index estuary trapnets in the Northwest Miramichi (since 1998) and the Southwest Miramichi (since 1994) rivers for the purpose of monitoring the annual migrations and characteristics of diadromous and other fish species in the Miramichi River. The details of operation and the type of information obtained from the catches at the index trapnets are described by Hayward et al. (2014).

Briefly, live capture estuarine trapnets are installed in the tidal portion of the upper estuary of the river from mid to late May and are fished once a day, until mid to late October. All catches of fish are identified to species or species group (gaspereau), counted individually or batch estimated when there are large daily catches, and a subset or all are measured with additional data collected based on the species and the program objective. The majority of the fish are returned live to the water post-sampling. The important point is that these trapnets have been installed at the same location and monitored using similar procedures and protocols over the entire time series (Hayward et al. 2014). Annual start and end dates may vary somewhat and there are occasional, usually short term, periods that the traps are not operating due to high water discharges which can damage the gear or in recent years due to high water temperatures which would otherwise lead to stress and excess mortalities of the catches.

The data from these trapnets and supplementary catches from other fishing gears in the Miramichi are used in a mark and recapture experiment to estimate the annual returns of Atlantic Salmon by size group to each of the Northwest and Southwest Miramichi (DFO 2020b). The Atlantic Salmon assessment model also provides estimates of the annual catchabilities of each trapnet for Atlantic Salmon; the catchabilities vary annually but without a trend (DFO 2020c). The catches of Striped Bass in the spring and in the autumn months have also been presented as a supplementary index of trends in abundance of Striped Bass (DFO 2020a).

Figure 4 summarizes the total annual catches of gaspereau (Alewife and Blueback Herring combined), American Shad, Atlantic Salmon (anadromous adults size groups combined), and Striped Bass for each trapnet in the Northwest and Southwest Miramichi rivers. There are strong and consistent trends observed for these time series of data:

- Striped Bass catches were low, generally less than 500 fish annually, until 2010 when a rapid increase in annual catches were recorded at both facilities. The percent change in the mean abundance during 2015 to 2019 relative to the mean abundance during 1998 to 2002 was approximately 13,000% in the Northwest Miramichi and 7,300% in the Southwest Miramich (Figure 4). The annual catches are highest in June, and again in October, with particularly lower catches in August and September (Claytor 1996; Hayward 2001).
- Annual catches of American Shad also show an increase over the time period of monitoring, of 47% at the Northwest Miramichi facility and 259% at the Southwest Miramichi facility (Figure 4). The majority of these fish are spawners, catches are highest during the month of June and early July (Hayward 2001). Shad are a legally retained bycatch in the commercial gaspereau fishery and the fish are landed by the fishers.
- Catches of gaspereau are highly variable at the Northwest Miramichi trapnet, with an estimated decline of 27% in the mean catch of the 2015 to 2019 time period relative to the mean catch of the period 1998 to 2002 (Figure 4). The decline is more important in the Southwest Miramichi, at 86%, and the decline is generally continuous beginning in approximately 2005 (Figure 4). Whereas annual estimated catches of gaspereau at the Southwest Miramichi trapnet exceeded 150 thousand fish annually in the mid to late 1990s, estimated annual catches during 2011 to 2019 range from 11 to 35 thousand fish. Of note,

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the commercial gaspereau fishery trapnets are located in the main stem of the Miramichi River and the Northwest Miramichi River; there were in some years one or two commercial gaspereau fishery trapnets in the Southwest Miramichi, of low catch intensity. Similarly, the Striped Bass spawner aggregations occur in the staging area below the confluence of the Northwest and Southwest Miramichi rivers and in the Northwest Miramichi River. Movements of Striped Bass do occur between the Southwest and Northwest Miramichi rivers in May and June but the bulk of the bass spawners are located in the Northwest Miramichi and downstream (Douglas et al. 2009).

- Atlantic Salmon (anadromous adults sizes combined) catches also show a decline at both facilities, but again with a more important decline at the Southwest Miramichi trapnet (43% decline) than in the Northwest Miramichi (27% decline) (Figure 4). The commercial gaspereau fishery is the only commercial fishery that can have an important bycatch of anadromous Atlantic Salmon adults returning to the Miramichi but in all fisheries in the DFO Gulf Region, Atlantic Salmon bycatch must be returned to the water as quickly as possible and in a manner that results in the least harm to the fish. In terms of Indigenous peoples fisheries, the most important fishery occurs in the Northwest Miramichi River, downstream of the Northwest Miramichi index trapnet whereas there are minimal Indigenous fisheries in the tidal waters of the Southwest Miramichi.

Collectively, Striped Bass predation and commercial fisheries removals of the diadromous fish would be expected to be most important in the Northwest Miramichi, however the declines in the indices of catches of gaspereau and salmon are more important in the Southwest Miramichi. The larger increased catches in the Northwest Miramichi of Striped Bass are expected given the estimated increase in the population size of the spawning stock located primarily in the Northwest Miramichi. The abundance indices of American Shad have increased at both facilities but with a larger increase in the Southwest Miramichi; there is a recognized shad spawning area in the Southwest Miramichi whereas the spawning area in the Northwest Miramichi is not known (Chaput and Bradford 2003).

## **SUMMARY OF INDICATORS OF CHANGES IN ABUNDANCE OF DIADROMOUS FISH**

Gaspereau and Rainbow Smelt were important (occurrence) prey identified in Striped Bass stomachs sampled in May and June in the Miramichi River (Figures 1, 2). It has been argued that the declines in commercial landings of gaspereau and Rainbow Smelt in the Miramichi area are directly associated with the increased predation pressure of a recovered Striped Bass stock and visually the declining trends are compelling. However, commercial fisheries harvests are generally not proportional to abundance, unless fishing effort and catchability are similar over time, which is almost never the case. In the Miramichi River gaspereau fishery, there have been important changes in licence holders and fishing effort over the past decade, with effort (opening date of the fishery) and fishing practices modified to minimize the bycatch, handling, and discarding of Striped Bass. There have been equally important changes in licence holders in the commercial smelt fishery; fishers are getting older and there is less interest in continuing to fish using historical and labour intensive fishing methods.

Gaspereau abundance indices, either from reported commercial landings or from annual catches at the index estuarine trapnets of the Miramichi show the largest declines occurring post-2010, approximating an inverse trend of increased abundance of Striped Bass. However, the decline in the trapnet indices for gaspereau is more important in the Southwest Miramichi which has less commercial fishery pressure than in the Northwest Miramichi. The gaspereau in the Southwest Miramichi would have less temporal overlap with Striped Bass aggregated on the spawning grounds of the Northwest Miramichi.

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In a very simplistic way, landings in NB prior to the steep observed declines after 2005 were maintained at approximate levels of 3,000 t for gaspereau and 600 to 800 t for Rainbow Smelt. Prior to 2005, the corresponding Striped Bass spawner abundance was less than 25,000 fish and this level of Striped Bass abundance did not provide any fisheries opportunities for Striped Bass. As for Atlantic Salmon, the low indices of abundance recorded post 2010, particularly in the Southwest Miramichi correspond to the period when Striped Bass spawner abundances exceeded 100 thousand spawners. It was only after 2010 that re-opening of fisheries for Striped Bass were considered.

In the absence of assessments of population size, fishing mortality rates, and recruitment estimates for gaspereau and Rainbow Smelt, there is insufficient information to provide suitable guidance on reference points for Striped Bass that consider the potential predator effects on these species. There is substantially more information on the question of potential impacts of Striped Bass predation on Atlantic Salmon smolt survival and this is considered in greater detail in the next section.

## **ATLANTIC SALMON SPECIFIC INTERACTIONS**

Adult anadromous Atlantic Salmon returning to DFO Gulf Region rivers, including the Miramichi River, range in size from approximately 50 cm to greater than 100 cm fork length. This fundamentally puts them outside the size range of potential prey of Striped Bass. The most likely interaction between Atlantic Salmon and Striped Bass is expected to occur at the juvenile smolt stage during the seaward outmigration phase. Atlantic Salmon smolts range in size from just over 10 cm fork length to generally less than 18 cm fork length (Chaput et al. 2016) which is suitable prey size range for most adult Striped Bass that exceed 40 cm fork length, based on observations that the diets of many marine fish are dominated by fish prey that are 10–20% of the predator's length (Scharf et al. 2000).

The Atlantic Salmon smolt migration timing and corridor from freshwater to the sea has smolts from the Northwest Miramichi River in particular migrating through the spawning area and the staging areas of Striped B at approximately the same time as Striped Bass are aggregating and spawning in the Northwest Miramichi. As the spawning ground for Striped Bass is located in the Northwest Miramichi, the expectation is that smolts from the Northwest Miramichi would be most vulnerable to predation. Fortunately, there is an increasing body of research to draw on in understanding the potential interactions between Striped Bass and Atlantic Salmon smolts in the Miramichi River. In the following sections, we review several studies describing potential predator-prey interactions of Atlantic Salmon smolts and Striped Bass and examine evidence for population level effects of Striped Bass predation on abundance of anadromous adult Atlantic Salmon in the Miramichi River.

## **DIRECT EVIDENCE OF STRIPED BASS PREDATION ON ATLANTIC SALMON**

Andrews et al. (2019) provide a literature review of available information regarding predation by Striped Bass on Atlantic Salmon, which is essentially very sparse.

DFO (2016) provides direct evidence of predation by Striped Bass on Atlantic Salmon smolts in the Miramichi River. A total of 48 Atlantic Salmon smolts were identified from 28 Striped Bass stomachs sampled during the 3-year diet study of Striped Bass in the Miramichi River (Table 4). Many of these could only be confirmed based on otoliths. The majority of Striped Bass stomach samples that contained salmon smolts were collected by angling over a one (2015) or two week (2013, 2014) period in late May (Figure 2). The short duration of smolt predation by Striped Bass is consistent with the typical one to two week period corresponding to the peak smolt migration period (Chaput et al. 2002, 2016). The seaward migration of Atlantic Salmon smolts

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typically overlaps with the exit of post-spawned Rainbow Smelt through the estuary, returning to the ocean (Chaput et al. 2002). Atlantic Salmon smolts identified from sampled Striped Bass stomachs generally occurred as Rainbow Smelt presence declined and disappeared from the stomach samples (Figure 2). Additionally, one Atlantic Salmon, classified as a parr (non-migrating juvenile) was identified from the stomach of one Striped Bass captured in the Margaree River in the spring of 2014 (Table 3; DFO 2016).

## **INDIRECT EVIDENCE OF STRIPED BASS PREDATION BASED ON ACOUSTIC TAGGING AND TRACKING**

### **Classification based on movement tracks**

The use of acoustic tags and subsequent movement behaviours of tagged fish have been used to infer potential predation events of Striped Bass on acoustically tagged Atlantic Salmon smolts (Gibson et al. 2015; Daniels et al. 2018). Movement patterns of acoustically tagged Atlantic Salmon smolts migrating to sea and Striped Bass spawners in the Miramichi River were detected on common acoustic receiver deployments within the Miramichi River estuary in 2013 to 2016. Eight variables characterizing movement patterns were compiled including the average speed through system, the time between first and last detection within the study period, and the count of switches in upstream and downstream movement direction. Movement patterns consistent with a smolt that had not been predated (training set) were described based on tracks of smolts subsequently detected at the Strait of Belle Isle array to the Labrador Sea. A Random Forest classification model was developed and the proportions of acoustically tagged Atlantic Salmon smolts that had movement patterns more similar to Striped Bass than to smolts that had been detected at the Strait of Belle Isle receiver array were estimated (Daniels et al. 2018). Atlantic Salmon smolts that had survived the exit to the Labrador Sea had movement patterns typically characterized by unidirectional downstream movements, in contrast to Striped Bass movement patterns which had more frequent up and downstream reversals (Daniels et al. 2018). Based on the classification model, the inferred percentages of smolts which displayed characteristic Striped Bass movement patterns, hence were concluded to have been eaten by Striped Bass with the tag present and transmitting in the body cavity of the Striped Bass, were highly variable ranging from 2.6% to 19.9% among years and between tag release locations within the Miramichi River. The inferred percentages of predation were higher for Northwest Miramichi tagged and released smolts (9.2 to 19.9%; versus 2.6 to 16.5% for the Southwest Miramichi) which is consistent with the higher estimated spatial and temporal overlap between the two species in the Northwest Miramichi (Table 5; Daniels et al. 2018).

### **Inference of predation based on predator tags**

Daniels et al. (2019) tagged Atlantic Salmon smolts in the Northwest Miramichi River with novel acoustic tags, referred to as predator tags, that are used to directly detect the occurrence of a predation event. The predator tags will switch identification code triggered by a change in pH associated with the gastrointestinal tract. The tags (Amirix/Vemco V5 predator tags, 5.6 mm diameter by 12.7 mm length, 0.68 g in air) were small and programmed to transmit at random time intervals between 15 and 25 s at a frequency of 180 kHz. A total of 50 smolts were selected, ranging in fork length from 11.0 to 16.5 (0.5 cm bins), tagged and released between May 17 and May 29, 2017 (Daniels et al. 2019). Fish were released after a short recovery time, usually a minimum of one hour, with relatively small daily tag and release groups ranging from three to eight fish over a period of 13 days. Of the 50 smolts tagged and released, 41 were subsequently detected on downstream receivers in the Northwest Miramichi River and estuary. Of the 41 tags detected, 24 (59%) were detected with an identification code switch, indicating a predation event. The tags do not indicate what kind of predator would have consumed the



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acoustically tagged smolt. The high rate of predation inference was consistent with the high abundance of Striped Bass in the Miramichi River in 2017 although the authors caution against inferring mortality rates of wild and unmanipulated salmon smolts from acoustically tagged and tracked individuals (Daniels et al. 2019).

### **Time series estimates of relative survival from index rivers**

A long term acoustic tagging and tracking study has been conducted by the Atlantic Salmon Federation (ASF) since 2003 in four rivers in the southern Gulf of St. Lawrence. A large part of the data from the ASF program were analysed by Chaput et al. (2018). The analyses included the annual tagging data from the Southwest Miramichi during 2003 to 2016, tagging data from the Northwest Miramichi during 2003 to 2008, 2013 to 2016, tagging data from the Restigouche River (Chaleur Bay) during 2004 to 2016 and tagging data from the Cascapedia River (Chaleur Bay) during 2006 to 2016 (Figures 5, 6). The value of this project in particular is the time series of relative survival rates which can be derived from such data and the comparisons between two neighbouring bays (Miramichi, Chaleur) with different ecosystems, primarily Striped Bass abundant in Miramichi Bay and not so in Chaleur Bay.

During 2003 to 2016, a total of 2,862 Atlantic salmon smolts from four river populations and two neighbouring bays in eastern Canada were intercepted during their spring seaward migration and tagged with acoustic transmitters. The movements, detection rates and apparent survivals were estimated to the head of tide, at exit to the Gulf of St. Lawrence and at exit to the Labrador Sea, a migration covering a period of up to two months at sea and offshore marine distances of 800 km (Figure 5).

The study results can be summarized as follows (Chaput et al. 2018):

- Survival rates of “tagged smolts” through Chaleur Bay (Restigouche, Cascapedia) were relatively high (67% to 95%), with no change over time (Figure 7).
- Survival rates of “tagged smolts” through Miramichi Bay were lower (28% to 82%) and showed a decline in survival beginning in 2010 (Figure 7).
- The Northwest Miramichi River estimated survival rates through the bay actually show two clusters of survival rates corresponding to two experimental periods with different experimental conditions (Figure 7). During 2003 to 2008, the smolts were captured in the Little Southwest Miramichi, tagged, and released at that same location (Figure 5). During 2013 to 2016, the smolts were captured in the Northwest Miramichi, transported upstream a distance of less than 20 km before being tagged and released at the upstream site.
- The differences in apparent survival rates in two neighbouring coastal embayments have been hypothesized to be in part related to differences in predation pressure on migrating smolts from Striped Bass present in the Miramichi Bay during the smolt migration period but not in the Chaleur Bay (Chaput et al. 2018; Daniels et al. 2018).

The tagging and tracking experiments have continued into 2020 but the results have not been reported or peer reviewed. The multi-year and multi-river aspects of the ASF study provide particular advantages to describing and modelling smolt migrations and estimating survival rates that otherwise would not be possible from single year and single river experiments. Specifically, the time series estimates of survival rates can be used to examine possible associations with changes in abundance with other components of the ecosystem, such as predators of salmon smolts.

Figure 8 shows the scatter plot of Striped Bass spawner abundance estimates and the estimated survival rates of Northwest Miramichi and Southwest Miramichi acoustically tagged

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smolts. For both the Southwest Miramichi and Northwest Miramichi tagged smolts, the lowest survival rates from head of tide to bay exit were estimated in the recent period (2013 to 2016) when the estimated abundance of Striped Bass was greater than 100 thousand spawners. The linear association between bass abundance and survival is strong for the Northwest Miramichi data but weaker for the Southwest Miramichi smolts which show more variation in estimated survival over the time series (Figure 8). In showing these relationships, it is assumed that the time series of estimates of survival and Striped Bass abundance estimates are exchangeable. This is the case for the Striped Bass abundance estimates and the Southwest Miramichi smolt survival estimates, but it may not be for the Northwest Miramichi survival estimates. As indicated previously, during 2003 to 2008 the smolts were captured in the Little Southwest Miramichi, tagged and released at the point of capture whereas during 2013 to 2016, the smolts were captured in the Northwest Miramichi, transported upstream prior to being tagged and released.

An important concern regarding the use of marked animals to draw inferences on survival of unmarked/unhandled animals is the consequence of tagging and handling effects on the estimates of survival. It is extremely difficult to make the case that a tagged smolt would have the same mean probability of survival as an untagged smolt as the capture, handling, tagging procedures in addition to introducing stress and injury to individual animals (Amman et al., 2013) also interrupt the migration during a particularly sensitive period (Riley et al. 2007). The removal of individuals from schooling with conspecifics can result in increased vulnerability to predation (Furey et al. 2016).

If the experimental conditions of long term studies are standardized to ensure that the observations reflect to the extent possible the variations in the phenomenon of interest, rather than differences in experimental methodologies (design, technology), then the time series trends from acoustically tagged animals may well reflect the time series trends of un-manipulated animals. The case could be made that the data for the Southwest Miramichi experiment would meet the criteria of standardized experimental conditions, in which case, the estimated trends in survival rates of acoustically tagged smolts and the association with Striped Bass abundance may in fact correspond to trends in survival rates of un-manipulated Atlantic Salmon smolts from the Miramichi River.

The next section models the population dynamics of Atlantic Salmon in the Miramichi River using the annual indices of juvenile salmon abundance and the estimated returns of 1SW and 2SW salmon adults. The point of interest in this exercise is to estimate relative sea survival rates during the first year at sea and examine correlations of these to abundance estimates of Striped Bass, hence, we are looking for population level effects.

## **POPULATION LEVEL ESTIMATES OF RELATIVE SURVIVAL OF ATLANTIC SALMON**

It has been shown that Striped Bass will consume Atlantic Salmon smolts in the Miramichi River (DFO 2016). Inferences of predation by Striped Bass on salmon smolts have also been reported based on acoustically tagged salmon smolt behaviours and using predator tag technologies (Gibson et al. 2015; Daniels et al. 2018, 2019), and from time series modelling of survival rates correlated to time series of Striped Bass spawner abundances (Chaput et al. 2018; this manuscript).

Based on estimates of survival of acoustically tagged salmon smolts in the Miramichi River, the pattern is of decreased survival during the early stage of migration in the Miramichi but no change for the rivers of Chaleur Bay. Whether these decreases or no change in survival rates of tagged smolts are reflected in the return rates as 1SW and 2SW fish over the entire period of

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marine life is not known. Atlantic Salmon marine return rates to adults in many monitored rivers of eastern Canada have declined over the past four decades (ICES 2020), however, since 1996 the return rates to 1SW salmon for four monitored rivers in the Maritime provinces and Quebec show variable but non-statistically significant linear trends (Figure 9).

There are very few reliable estimates of smolt production and marine return rates of Atlantic Salmon in the Miramichi River (Chaput et al. 2016), and too few over the time series of assessed Striped Bass spawner abundances with which to examine population level of predation by Striped Bass on Atlantic Salmon smolts.

The population dynamics of Atlantic Salmon in the Miramichi River were modelled using the annual indices of juvenile salmon abundance and the estimated assessed returns of 1SW and 2SW salmon adults. The point of interest in this exercise is to estimate relative sea survival rates during the first year at sea to see if there has been any trend in these rates and how these trends may correlate with the abundance estimates of Striped Bass. If predation by Striped Bass on Atlantic Salmon smolts is intense enough during the early post-smolt phase, we would expect to see a signal in the relative return rates of adult salmon.

## Data

Annual indices of juvenile Atlantic Salmon, by size/age group (fry = young of the year, small parr = 1-year old juveniles; large parr = 2+ year old juveniles), were obtained by electrofishing at fixed sites throughout the Miramichi River. Sampling methods and models for estimating densities (number of fish per 100 m<sup>2</sup>) by size / age group are described in Chaput et al. (2005) and Moore and Chaput (2007). The new Bayesian model developed by Dauphin et al. (2019) has not yet been applied to the time series of observations used in this analysis. The juvenile abundance time series for the four main branches (rivers that have a confluence in tidal waters) of the Miramichi River to 2019 are presented in DFO (2020b; Figure 10). Juvenile indices of abundance by size group for the Northwest Miramichi system (Little Southwest Miramichi habitat area = 807 ha; Northwest Miramichi habitat area = 823 ha) and for the Southwest Miramichi system (Renous habitat area = 582 ha; Southwest Miramichi habitat area = 2,953 ha) were obtained as a habitat weighted mean of the mean densities in the appropriate tributaries (Figure 11).

Adult Atlantic Salmon returns to each of the Northwest Miramichi and Southwest Miramichi rivers have been estimated since 1992 and the time series of estimates for small salmon (< 63 cm fork length, primarily 1SW salmon) and large salmon (>= 63 cm fork length, majority 2SW and repeat spawners) to 2019 are presented in DFO (2020b, 2020c). Sea age composition of adult salmon are determined from interpretation of scales which are sampled from returning adult salmon captured at the DFO index estuary trapnets of the Northwest and Southwest branches of the Miramichi. From these data and the estimated returns of large salmon, the returns of 2SW maiden salmon are estimated; 2SW salmon comprised annually varying proportions of the large salmon returns, between 0.41 and 0.85 during the period 1992 to 2019. The time series of estimated 1SW (small salmon) and 2SW salmon for the two main branches of the Miramichi River are shown in Figure 12.

The juvenile indices and the branch specific adult returns by sea age group time series use the population model begins in 1993 and extends to 2019.

## Dynamic equations and cohort model

A cohort model was coded that tracks a cohort of salmon beginning at the juvenile fry stage (1993 to 2018), through small parr (1994 to 2018), large parr (1995 to 2018) and to returns of 1SW (1997 to 2019) and 2SW (1998 to 2019) adult salmon assessed in the river for each main

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branch of the Miramichi. Smolt output at age 2 in year  $y$  is an intermediate state derived from small parr abundance of year-1. Smolt output at age 3 in year  $y$  is an intermediate state derived from large parr abundance of year -1. Total smolts going to sea is the sum of smolts at age-2 and age-3 in year  $y$  and 1SW salmon returns in year  $y+1$  are calculated from total smolts going to sea in year adjusted for marine survival in year and the proportion of the smolt cohort that matures at 1SW of age. The equations for the model are summarized in Table 6.

Three model variants were examined:

1. A river independent model in which the parameters were estimated independently for the Southwest and Northwest dynamics with no linkage between river dynamics (Appendix 1).
2. A model that assumed a common trend in smolt to 1SW survival for the two rivers but with a constant intercept shift for one of the rivers. All other parameters were set independent between the rivers.
3. A model that assumed a single common trend over time for the rivers in the proportion of small parr that become smolts age 2 and a single common trend for smolt to 1SW survival for the two rivers. All other parameters were set independent between the rivers.

### Likelihoods and priors

The model was coded in OpenBugs (Appendix 1) and the posterior distributions of the parameters were obtained by MCMC sampling (Lunn et al. 2013).

Lognormal likelihoods for the abundance of fry, small parr, large parr, 1SW returns and 2SW returns were used.

Non-informative priors were set on the precisions (inverse variance) for each of the life stages, excluding fry. Fry were the initiating life stage; the likelihood of the mean fry index from sampling for river  $r$  and year  $t$  was assumed lognormal with  $\log(u.fry_{y,r})$  drawn from a prior distribution for year and river and a precision by river for all years set to the mean coefficient of variation of the fry abundance indices over years by river ( $cv = 0.14$  for Southwest,  $0.22$  for Northwest).

Priors for the other parameters (Appendix 1) were variously set using a conjugate distributions or censored distributions (Table 7).

### Results

All the models converged rapidly. A total of 100,000 iterations was used for a burn-in. A subsequent 25000 iterations with 2 chains and thinning by 10 were used to extract 5,000 MCMC samples to characterize the posterior distribution. All posterior parameter distributions were unimodal. Model diagnostics are summarized in Appendix 2 and the indicators of model adequacy to data are summarized in Table 8.

The model that fits the juvenile and adult return time series independently between rivers (model 1) was retained (Table 8; Appendix 2).

Conditional on model structure and assumptions, the fry and small parr survival rates are estimated to be higher in the Northwest Miramichi compared to the Southwest Miramichi (Figure 13). The proportion of smolts that mature as 1SW is also estimated to be higher for the Northwest Miramichi (Figure 13); this is consistent with other life history characteristics which indicate a higher proportion female in the 1SW maiden returns of the Northwest Miramichi compared to the Southwest Miramichi (Chaput et al. 2016).

The proportions of the small parr that were estimated to become smolt age 2 have declined in both the Northwest and Southwest Miramichi rivers (Figure 14). In terms of relative smolt

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production at age 2 and age 3, there has been a decline in the estimated relative number of smolts age 2 but no change in the estimated production of smolts age 3 (Figure 14). This is also consistent with data; generally small parr indices have been declining at a faster rate than the large parr indices (Figure 10).

The relative smolt to 1SW survivals show large variation in both the Southwest and Northwest Miramichi rivers, but without a statistically significant linear trend over the time series 1996 to 2018 (Figure 15). The term relative survival rate is used because the estimated smolt production is raised using the total habitat area of the rivers, which exaggerates the smolt production from juvenile indices; the juvenile indices are derived for specific components of the habitat, classic juvenile rearing habitat. The relative return rates are generally higher in the Southwest Miramichi relative to the Northwest Miramichi. Survival rates of the 2009 smolt migration year were high for both rivers.

When the relative survival rates are plotted against the corresponding Striped Bass spawner abundances for the year of smolt migration (and the year of potential predation by bass), there is an apparent decline in relative survival rates of smolts from the Southwest Miramichi, especially for the 2006 to 2018 migration years (the highest relative survival rates were estimated for the 2009 smolt migration year) associated with increasing Striped Bass abundance (Figure 15). However, low relative survival rates for the Southwest Miramichi were estimated in the late 1990s when Striped Bass abundances were low. The negative relationship between relative survival rates and Striped Bass spawner abundances is less clear to non-existent for the Northwest Miramichi smolts (Figure 15); in fact estimated relative survival rates have been variable over the entire time series with equally high and low relative survival rates in the late 1990s when Striped Bass abundances were low and again in the 2010s when Striped Bass abundances were high.

Relative survival rates from smolt to 1SW salmon are plotted against the survival rates through the bays of acoustically tagged smolts for the smolt migration years 2003 to 2016 of the Southwest Miramichi, and the smolt migration years 2003 to 2008 and 2013 to 2016 for the Northwest Miramichi (Figure 16). The survival rates of acoustically tagged smolts in the Southwest Miramichi are highly variable for corresponding low relative survival rates but generally, modelled relative survival rates from smolts to 1SW correspond to years when the survival rates of smolts through the bay were higher, with a statistically weak linear relationship ( $p = 0.045$ ; Figure 16). For the Northwest Miramichi, there is no association between the survival rate estimates through the bay and the estimated relative survival rates from smolts to 1SW salmon (Figure 16).

## **Discussion**

The cohort modelling of the juvenile to adult return indices for the Miramichi River provide indications at least for the Southwest Miramichi that relative survival rates of smolts to 1SW salmon may be negatively associated with Striped Bass abundances, at least for the period of 2006 to 2018. In part, this pattern matches the association between the acoustic tagged smolt derived survival rates through Miramichi Bay and Striped Bass abundances for the Southwest Miramichi, and suggests that early post-smolt survival perhaps driven by predation may define the total annual survival rate trends to 1SW adult returns. On the other hand, the relative survival rates of smolts to 1SW salmon for the Northwest Miramichi time series do not correspond to the acoustic tagged smolt derived survival rates nor are they associated with the variations in Striped Bass spawner abundances, thus providing no evidence of a survival variation driven by Striped Bass predation on smolts.

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If we were to accept that there is a population level effect of predation on smolts by Striped Bass, it is not clear what would be an appropriate abundance of Striped Bass spawners that would not induce excessive early mortality on smolts. For the Southwest Miramichi, there have been equally low relative survival rates at very low and very high Striped Bass spawner abundances, with higher relative survivals of salmon at Striped Bass abundances of 20 to 100 thousand spawners. The relative survival rate estimated for the 2009 smolt cohort is anomalously high (Figure 15). However, similarly high survival rates of the 2009 smolt cohort relative to the river-specific time series were noted for the Nashwaak River (NB), LaHave River (NS) as well as in the two index rivers in Quebec (Figure 9) which indicates that in some years, broad ocean scale factors dominate the marine survival dynamics of Atlantic Salmon rather than nearshore or early post-smolt survival conditions.

## CONCLUSIONS

The analyses of information provides conflicting evidence of reductions in a few anadromous fish species abundance indicators associated with increased abundance of Striped Bass in the southern Gulf. The recorded commercial landings of gaspereau and Rainbow Smelt have greatly declined in the Gulf NB portion of the southern Gulf of St. Lawrence, particularly since 2010. Higher landings of the period prior to 2010 were associated with Striped Bass spawner abundances of less than 5,000 to 50 thousand spawners.

The indices of abundance based on estuarine index trapnet catches in the two main branches of the Miramichi show a decline in total annual catches of gaspereau and adult Atlantic Salmon, with the more important declines in the Southwest Miramichi compared to the Northwest Miramichi. The declines in the Southwest Miramichi for those two species seemingly began in 2005, and has been less abrupt than indicated by the commercial landings of gaspereau. In contrast, American Shad catches have increased in both the Northwest and Southwest Miramichi, despite increased catches and spawner abundance estimates of Striped Bass.

There is direct evidence of predation by Striped Bass on Atlantic Salmon smolts and several studies using acoustic tag technologies have inferred predation events and changes in estimated survival rates in the early phase of migration through Miramichi Bay that point to Striped Bass predation as a likely driver of these variations in estimated survival rates. Based on acoustic tagging estimates of survivals through Miramichi Bay, the years when Striped Bass spawner abundances exceeded approximately 100 thousand spawners corresponded to year with visibly lower estimated survival rates.

Population level effects, described by estimates of relative survival rates of smolts in the first year at sea based on juveniles indices as proxies for smolt output, are contradictory between the two branches of the Miramichi. Whereas the relative survival rates of smolts from the Southwest Miramichi are associated with variations in Striped Bass abundance indices, it is not the case for the Northwest Miramichi which was expected to be more impacted by predation considering the spatial and temporal overlap of Striped Bass spawner aggregations and the smolt migration window. These analyses are not conclusive of effects or no effects of Striped Bass on smolt to adult returns and point to the need for conducting carefully designed ecological experiments to directly resolve the mechanisms and cause/effect of interactions between Striped Bass and other anadromous species in the Miramichi River.

Striped Bass abundances in the range of 100 thousand spawners in the past corresponded to high landings of gaspereau and smelt, and the highest survival rates of acoustically tagged smolts through Miramichi Bay. Setting a management objective for Striped Bass at approx. 100 thousand spawners, perhaps calling this a target reference point (rather than upper stock reference), will result in large reductions of the potential fisheries yield of Striped Bass. Based

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on the populations models and equilibrium abundance estimates presented in Chaput and Douglas (2022), maintaining spawner abundances at 100 thousand fish would be equivalent to a fishing rate that exceeds  $F = 0.50$ , yields that are substantially lower than what could be realized at MSY, and an abundance which is less than the single species Limit Reference Points regardless of the population model selected.

It is not clear from these time series of data, that reducing Striped Bass spawner abundances to the level of the early 2000s, i.e., less than 100 thousand spawners, would improve the acoustic tagged smolt survival estimates, the population level relative survival rates derived from the cohort model, or the landings trends of gaspereau and Rainbow Smelt in the commercial fisheries. It is not possible to suggest a reference level to address the multiple species concerns based on the information and analyses presented in this working document. Ultimately, the decision to use an alternate “target” Striped Bass reference point to account for the multi-species interactions will be made by fisheries managers. A carefully designed and monitored ecological experiment, could be envisioned to resolve the question of these species interactions. Such an experiment would require a long time series of monitoring and should include a control site, such as the Restigouche in which the Atlantic Salmon smolts and other species are not subject to Striped Bass predation in the spring, that is geographically proximate to the Miramichi River such that climate factors and other inriver dynamics closely resemble the conditions in the Miramichi River.

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## TABLES

*Table 1. Summary of fish species characteristics including life stage, body size, and location of most probable interaction with adult (age 3+) Striped Bass in the Miramichi River.*

Species	Lifestage	Approx. body size (cm)	Location and time of overlap with Striped Bass
Rainbow Smelt	Spawners / postspawners	13 to 21	Estuary April to June
	Juveniles	< 10	Estuary and bay Autumn
Gaspereau	Spawners / postspawners	22 to 30	Estuary mid-May to early July
	Young of the year	< 8 cm	Lower portions of rivers, estuaries late summer onward
American Shad	Young of the year	< 8 cm	Lower portions of rivers, estuaries late summer onward
Atlantic Salmon	Smolt stage	10 to 18 cm	Estuary mid-May to early June; 3 to 4 week period
American Eel	Yellow phase	15 to 50	Estuaries April to October
Sea Lamprey	Ammocoetes	10 to 15	Estuaries May and June associated with metamorphosis to parasitic stage and migration to the sea
Atlantic Tomcod	Adult	14 to 25	No overlap with Striped Bass; migrate to estuaries in late autumn, spawn in the winter, return to Miramichi Bay and southern Gulf by April

Table 2. Summary of sampling effort for Striped Bass diets during 2013 to 2015. Samples are summarized by season (spring = May and June in Miramichi only; other = all samples other than those collected in the Miramichi during spring), capture location, capture date range, and capture method (angling or trapnet). GNS = Gulf Nova Scotia, NNB = northern New Brunswick, and SENB = southeastern New Brunswick. Summary table is from DFO (2016).

Year	Season	Region	Location	Capture date range		Capture method	
				Min	Max	Angling	Trapnet
2013	spring	Miramichi	Northwest	5-May	26-Jun	153	320
			Southwest	25-Jun	26-Jun	0	30
			Main Miramichi	1-May	17-May	77	0
	other	Miramichi	Northwest	24-Sep	30-Sep	0	9
			Southwest	23-Sep	10-Oct	0	76
Subtotal 2013						230	435
2014	spring	Miramichi	Northwest	9-May	25-Jun	178	295
			Southwest	15-May	20-Jun	34	30
			Main Miramichi	22-May	29-May	78	0
	other	GNS	Margaree	6-Jun	6-Jun	0	23
			Miramichi	Main Miramichi	6-Oct	22-Oct	18
		NNB	Shippagan	6-Oct	6-Oct	1	0
			Burnt Church	7-Oct	16-Oct	3	0
			Inkerman	16-Oct	16-Oct	3	0
		SENB	Cocagne	10-Jul	11-Jul	11	0
			Cote-Ste-Anne	28-Sep	28-Sep	13	0
Subtotal 2014						339	348
2015	spring	Miramichi	Northwest	15-May	29-Jun	162	299
			Southwest	12-May	2-Jun	8	12
			Main Miramichi	20-May	22-May	143	0
			Striper cup	30-May	31-May	25	0
	other	GNS	Margaree	6-Jun	20-Oct	81	9
			Antigonish	22-Jun	22-Jun	4	0
			Pictou	23-Jun	30-Jul	34	0
			Grand Etang	24-Aug	24-Aug	8	0
			Miramichi	Main Miramichi	5-Aug	14-Sep	10
		NNB	Burnt Church	16-Jun	7-Oct	26	0
			Tracadie	14-Aug	14-Aug	1	0
			Inkerman	4-Oct	14-Oct	8	0
		SENB	Little Bouctouche	25-Jul	27-Sep	73	0
			Bouctouche	27-Sep	11-Oct	23	0
				Cocagne	28-Sep	13-Oct	26
		St. Edouard	15-Oct	20-Oct	7	0	
Subtotal 2015						639	320
Grand total 2013-2015						1,208	1,103

Table 3. Diet, as % occurrence of prey species or prey categories, of Striped Bass (21 to 73 cm fork length) collected from various locations throughout the southern Gulf of St. Lawrence in 2013-2015, other than in the Miramichi estuary during May and June. The % occurrence has been rounded to the nearest percentage and the total may be greater than 100% due to individual stomachs containing more than one prey type.

Prey	% Occurrence			
	2013	2014	2015	Combined
Decapoda ( <i>Crangon septemspinosa</i> , <i>Neomysis</i> spp., <i>Palaemonetes vulgaris</i> )	1	38	39	32
Crustacean (Green crab, Rock crab)	1	0	1	1
Insect (Anisoptera, Ephemeroptera, Plecoptera)	1	1	2	1
Gastropod (Common periwinkle)	0	0	1	0
Other invertebrates (Gammarid amphipod, isopod, mysid, polychaete)	0	3	6	4
Atlantic Silverside	0	1	12	8
Stickleback (3-spine, 4-spine, <i>Gasterosteus</i> spp.)	0	13	9	8
Mummichog	0	1	5	3
Speckled Trout	0	0	5	3
Flatfish (Smooth Flounder, Winter Flounder)	2	0	4	3
Eels (American Eel, sea lamprey ammocoete)	1	0	4	3
Rainbow Smelt	0	0	3	2
Atlantic Tomcod	1	6	0	1
American Sand Lance	0	4	1	1
White Hake	1	6	0	1
Atlantic Salmon parr	0	1	0	0
Other fish (Atlantic Herring, Cunner, Greenland Cod, Pipefish)	0	3	1	1
Unidentified fish remains	5	3	7	6
Number of stomachs processed	85	72	310	467
% Empty	86	53	35	47

Table 4. The number of Atlantic Salmon smolts identified in Striped Bass stomach samples collected from the Miramichi River in May and June 2013 to 2015. The collection date, location, and method of capture for the individual Striped Bass containing Atlantic Salmon smolts are identified. The location refers to where the stomach samples containing salmon smolts were collected. "NW comm gasp" refers to samples from a commercial gaspereau trapnet in the Northwest Miramichi River. Striper cup refers to stomach samples extracted from incidental mortalities during the live release only Striped Bass fishing derby in the Miramichi on 30 and 31 May 2015. All other dates and locations are detailed in Table 1. Data are from DFO (2016).

Year	Date	Location	Stomach samples	Stomach samples with smolts	Total number of smolts identified	
					Angling samples	Trapnet samples
2013	10-May	Cassilis	15	1	0	1
	14-May	Beaubear's Island	25	1	1	0
	16-May	Beaubear's Island	20	1	1	0
	27-May	NW comm gasp	32	1	0	3
	28-May	Millstream	30	4	13	0
	29-May	NW comm gasp	30	1	0	1
	all other dates	all other locations	428	0	0	0
Sub total			580	9	15	5
2014	23-May	Beaubear's Island	21	2	2	0
	26-May	Hackett's Beach	13	4	4	0
	28-May	Strawberry Marsh	30	3	3	0
	2-Jun	Cassilis	64	2	3	0
	4-Jun	Cassilis	14	1	0	1
	5-Jun	Cassilis	31	1	1	0
	all other dates	all other locations	442	0	0	0
Sub total			615	13	13	1
2015	26-May	NW comm gasp	31	2	0	3
	28-May	Millstream	32	1	1	0
	28-May	NW comm gasp	30	2	0	8
	30-May	Striper cup	25	1	2	0
	all other dates	all other locations	531	0	0	0
Sub total			649	6	3	11
Grand total			1,844	28	31	17

*Table 5. Summary of number of Atlantic Salmon smolts tagged with acoustic tags and released in the Northwest Miramichi and Southwest Miramichi rivers during 2013 to 2016 and the inferred percentages of the tagged smolts by river and year which had characteristic Striped Bass movements through the estuary areas of the Miramichi River. Data are from Daniels et al. (2018).*

Year	River	Number of smolts tagged and released	Inferred % of tagged smolts showing Striped Bass movement patterns	Striped Bass spawner abundance estimates (median, 5 <sup>th</sup> to 95 <sup>th</sup> percentile; thousand)
2013	Northwest	40	19.4%	255 (67 to 864)
	Southwest	65	16.5%	
2014	Northwest	50	19.9%	138 (79 to 250)
	Southwest	80	9.0%	
2015	Northwest	80	9.2%	299 (146 to 675)
	Southwest	80	2.6%	
2016	Northwest	60	17.6%	318 (160 to 633)
	Southwest	59	8.2%	

Table 6. Cohort dynamics model equations of Atlantic Salmon juveniles to adult returns. The notations in bold identify the data.

$$Psm_{r,t+1} \sim \mathbf{Fry}_{r,t} * S_r^{fry}$$

With  $Fry_{r,t}$  the end of summer / fall index of fry (fish per 100 m<sup>2</sup>) for river r in year t,

$S_r^{fry}$  the survival rate [0,1] of fry to small parr for river r (assumed similar over years but differing by river),

$Psm_{r,t+1}$  the end of summer / fall index of small parr (fish per 100 m<sup>2</sup>) for river r in year t+1,

$$Sm_{r,t+1}^{a,2} \sim \mathbf{Psm}_{r,t} * S_r^{psm} * pSm_{r,t}^{a,2} * \mathbf{Hab}_r$$

With  $Sm_{r,t}^{a,2}$  the total number of smolts at age 2 leaving river r in year t+1,

$Psm_{r,t}$  the small parr index (fish per 100 m<sup>2</sup>) for river r in year t,

$S_r^{psm}$  the survival rate of small parr from summer/fall to smolt in the spring, expressed as  $e^{-Z/2}$  with  $e^{-Z} =$

$S_r^{psm}$  the annual survival from small parr to large parr,

$pSm_{r,t}^{a,2}$  the relative proportion of small parr that survived to the spring that become smolts age 2 in river r in year t,

$Hab_r$  is the habitat area of river r (in 100 m<sup>2</sup>).

$$Plg_{r,t+1} \sim \mathbf{Psm}_{r,t} * S_r^{psm} * (1 - pSm_{r,t}^{a,2})$$

$Plg_{r,t+1}$  the large parr index in the summer / fall in river r in year t+1 from survivors of small parr in river r and year t that did not become smolts age 2, and other parameters as above.

$$Sm_{r,t+1}^{a,3} \sim \mathbf{Plg}_{r,t} * S_r^{psm} * \mathbf{Hab}_r$$

With  $Sm_{r,t+1}^{a,3}$  the total number of smolts at age 3 leaving the river r in year t+1, and other parameters as above.

$$Sm_{r,t} = Sm_{r,t}^{a,2} + Sm_{r,t}^{a,3}$$

With  $Sm_{r,t}$  the total number of smolts (ages 2, 3) leaving freshwater in river r in year t

$$\mathbf{A.1sw}_{r,t+1} \sim Sm_{r,t} * S1sw_{r,t} * p1sw_r$$

With  $A.1sw_{r,t+1}$  the abundance of 1SW returning to river r in year t+1;

$Sm_{r,t}$  the total number of smolts (ages 2, 3) leaving freshwater in river r in year t;

$S1sw_{r,t}$  the marine survival rate from smolt to 1SW from river r and migration year t (model dependent)

$p1sw_r$  the probability of maturing to 1SW for smolts from river r.

$$\mathbf{A.2sw}_{r,t+2} \sim Sm_{r,t} * S1sw_{r,t} * (1 - p1sw_r) * S2sw_r$$

With  $A.2sw_{r,t+2}$  the abundance of 2SW salmon returning to river r in year t+2;

$S2sw_r$  the survival rate of a 1SW non-maturing in the second year at sea for river r, and other parameters as above.

### Simplifying assumptions

- $S_r^{psm}$  differs by river r but is similar over years;
- $S_r^{psm}$  Large parr to smolt age 3 survival is similar to small parr survival, but for half the year ();
- $pSm_{r,t}^{a,2}$ , the proportion of small parr that become smolt age 2 is either similar for the rivers but annually variable or annually variable and different between rivers (dependent upon model);
- $S2sw$  the sea survival rate in the second year at sea is assumed known and similar for rivers and years. Because there are three marine dynamics parameters ( $S1sw, p1sw, S2sw$ ) but only two observations (returns of 1SW and 2SW), one of the parameters must be fixed. Following the modelling approach of ICES (2020), the sea survival in the second year is fixed at 0.70 ( $e^{-0.03*12}$ ), assumed an instantaneous monthly mortality rate of 0.03 per month for 12 months of life at sea.

### Indices:

- r in 1:2 (Southwest Miramichi, Northwest Miramichi)
- y in 1993 to 2019



Table 7. Parameters and their prior distributions for the Atlantic Salmon cohort model.

Parameter	Prior
$S_r^{fry}$	Beta(2,3)
$S_r^{psm}$	Beta(3,2)
$pSm_{r,t}^{a,2}$	Beta(5,5)
$\text{Log}(u.fry_{y,r})$	$N(2,10) C(1, )$
$S1sw_{y,r} = e^{-Z_{r,t}}$	$Z \sim N(1,10) C(0.1, )$
$p1sw_r$	Beta(5,5)
$S2sw$	Beta(72,28)
Precision ( $1/\sigma^2$ )	$\sigma \sim U(0,5)$

Table 8. Summary of the Atlantic Salmon cohort model structures and diagnostics.

Model	Effective number of parameters	DIC value	Comment
1	67	2719	DIC values of this model cannot be compared to model 2 and model 3 as the estimates between rivers are fully independent. The fits to juvenile indices and to adult returns are better than models 2 and 3. Temporal trend in residuals of juveniles and adult returns
2	80	2700	Some misfitting of juvenile indices, temporal trend in residuals of juveniles and 1SW returns. Some systematic misfitting of 1SW returns to both rivers but not as severe as in model 3.
3	73	2677	Reasonable fit to juvenile indices. Some temporal trends in residuals of juveniles and 1SW returns but fewer than in model 2. Systematic misfitting of 1SW returns for the Southwest Miramichi.

## FIGURES

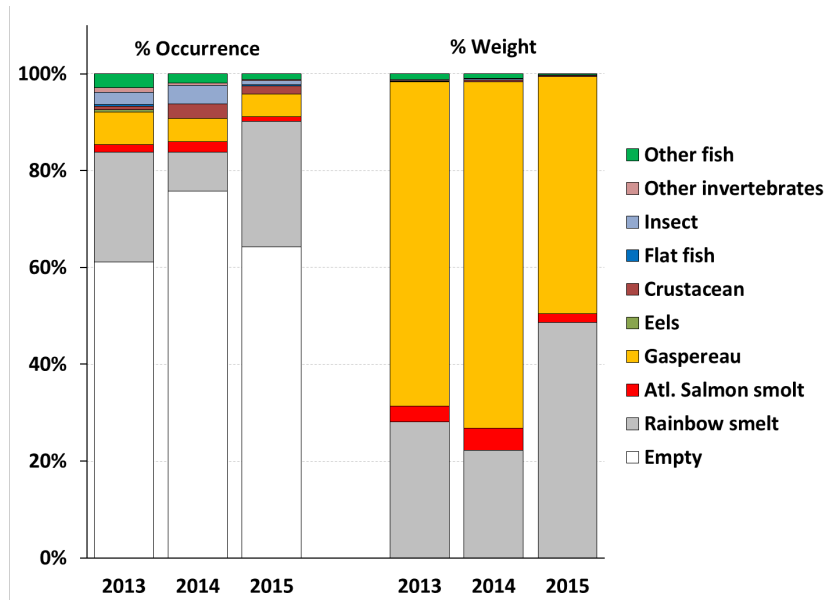


Figure 1. Summary of the percent occurrence of prey species or prey categories (left) and their corresponding percent weight (right) in the stomachs of Striped Bass collected from the Miramichi River in May and June, 2013 to 2015. The figure is copied directly from DFO (2016).

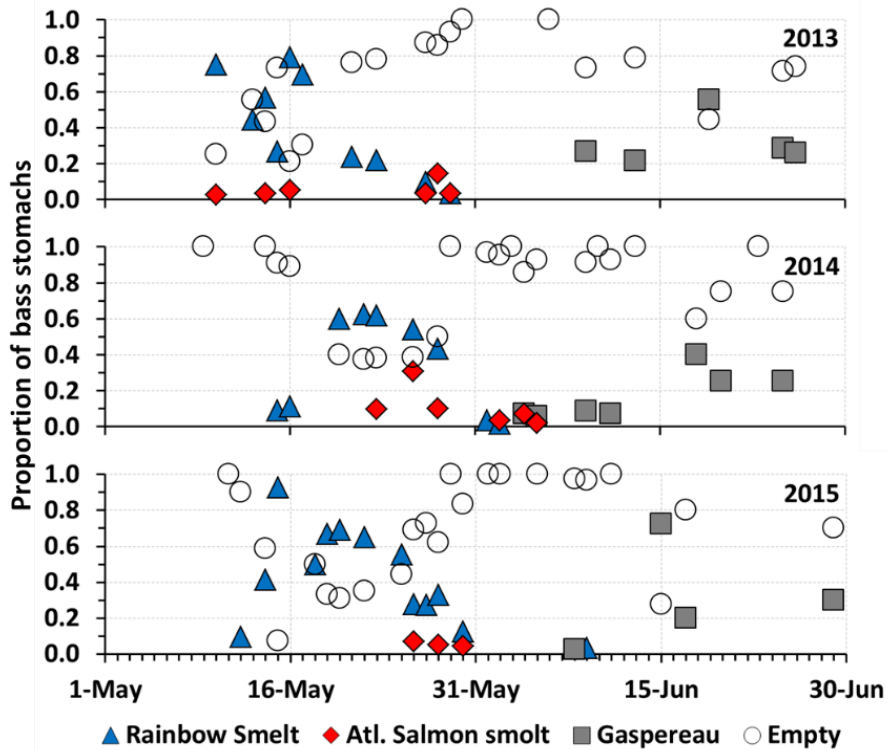


Figure 2. The proportion of Striped Bass stomachs by date that were empty, contained Rainbow Smelt, contained Atlantic Salmon smolt, and/or gaspereau in the May and June period from the Miramichi River in 2013 to 2015. Only dates for which  $\geq 3$  stomach samples were collected are shown. Proportions may not add to one because not all prey groups are shown or multiple prey groups may occur in one sample. The figure is copied directly from DFO (2016).

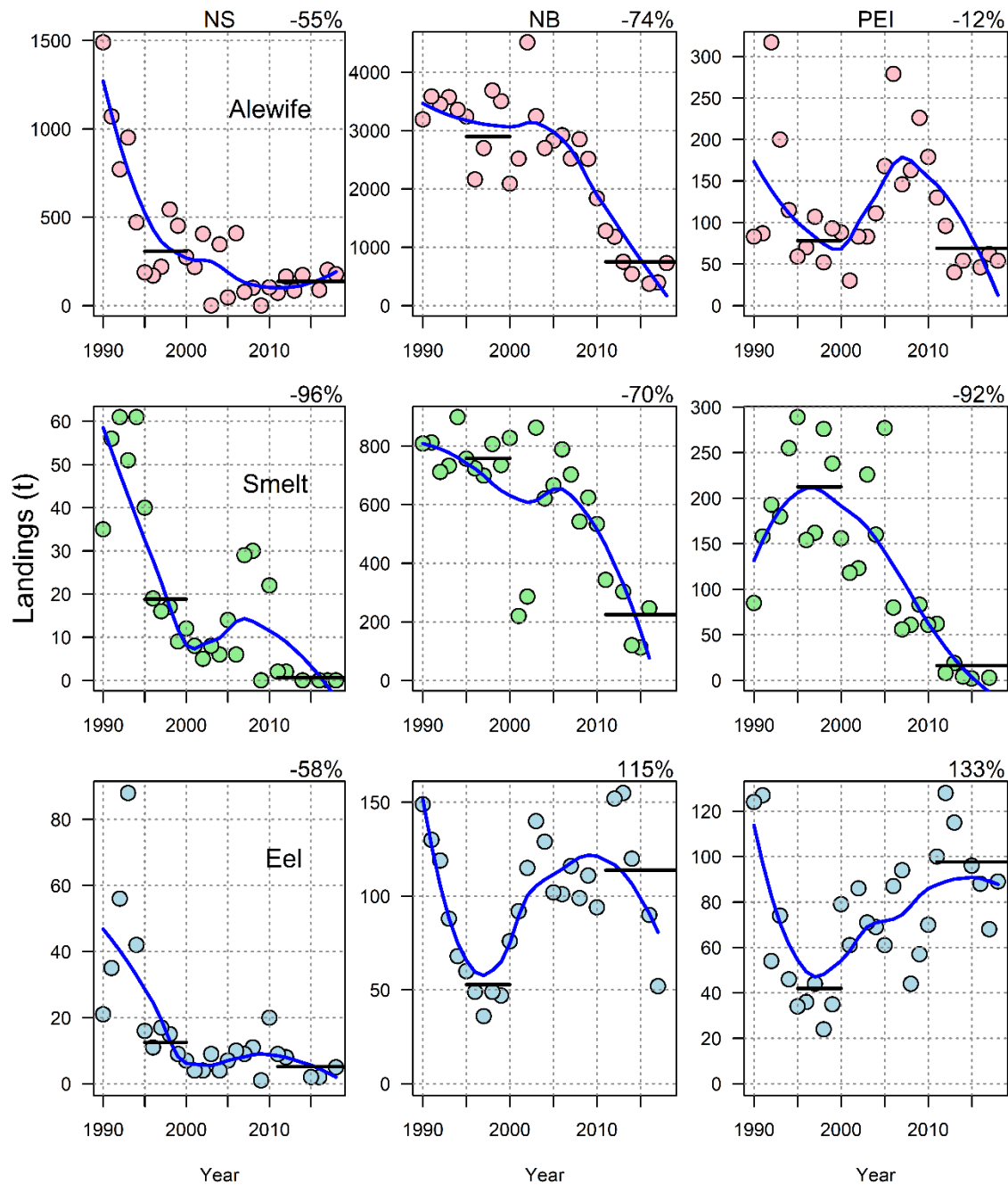


Figure 3. Summary of recorded landings (t) of three diadromous fish species (gaspereau = Alewife and Blueback Herring, smelt = Rainbow Smelt; Eel = American Eel) by province within DFO Gulf Region, 1990 to 2018. Some data are missing due to confidentiality restrictions. A value of 0 represents a landings record < 0.5 t. The blue line in each plot is a loess smoother using a span value of 0.8. The mean landings for the periods 1995 to 2000 and 2011 to 2018 are shown as black horizontal lines and the percent change of the 2011 to 2018 period relative to the 1995 to 2000 period is shown in the top right above each panel.

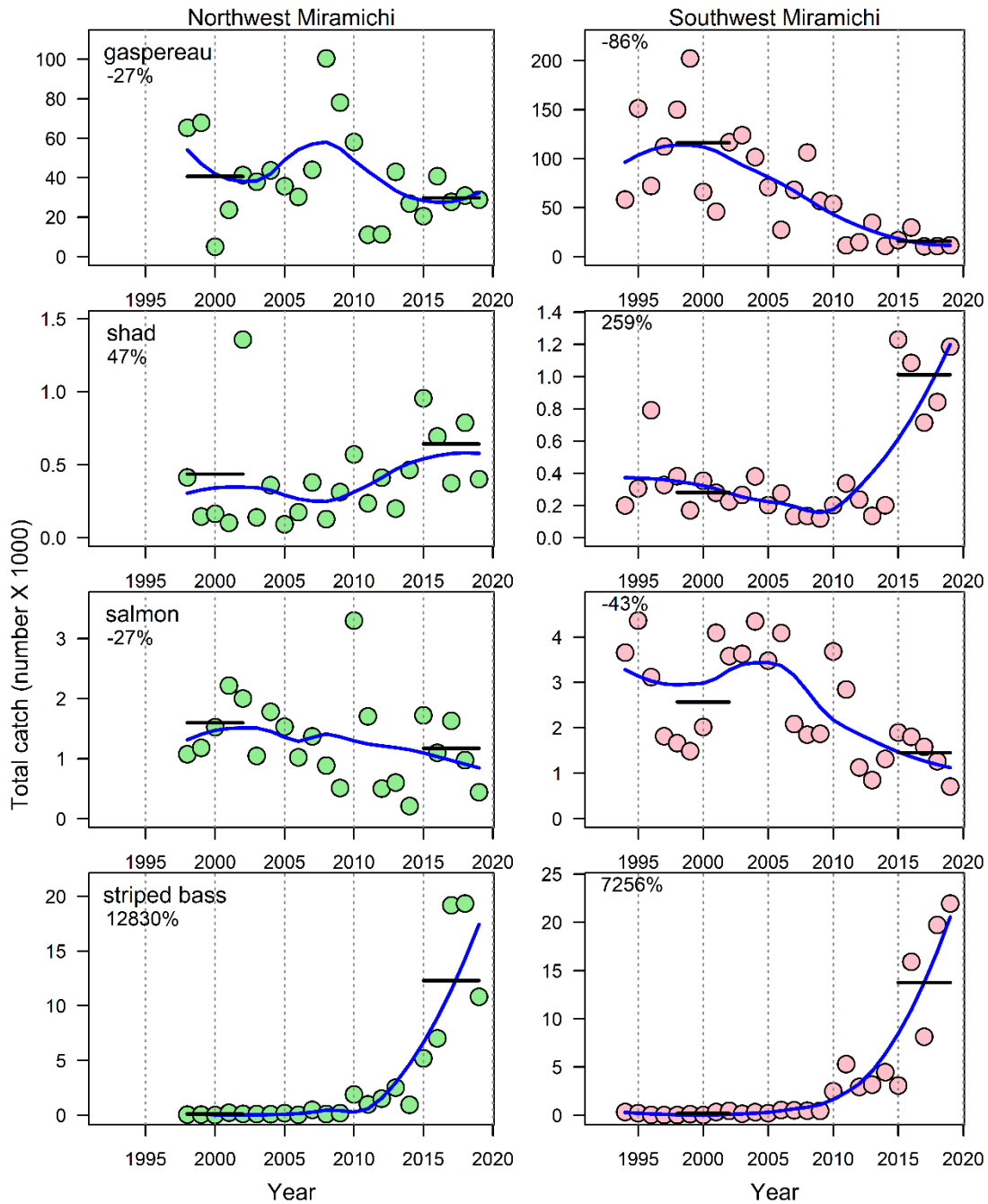


Figure 4. Summary of total catches (number, thousands) of diadromous fish species (gaspereau = *Alosa pseudoharengus* and *A. aestivalis*, top row; shad = *A. sapidissima*, second row; salmon = *Salmo salar* (adults), third row; striped bass = *Morone saxatilis*, fourth row) at the DFO index estuary trapnets in the Northwest Miramichi (left column) and the Southwest Miramichi (right column), 1994 (1998 for Northwest Miramichi) to 2019. Total catches are not corrected for dates of operation which can vary between years and between trapnets. The blue line in each plot is a loess smoother using a span value of 0.8. The mean catches for the periods 1998 to 2012 and 2015 to 2019 are shown as black horizontal lines and the percent change of the 2015 to 2019 period relative to the 1998 to 2002 period is shown in the top left corner of each panel.

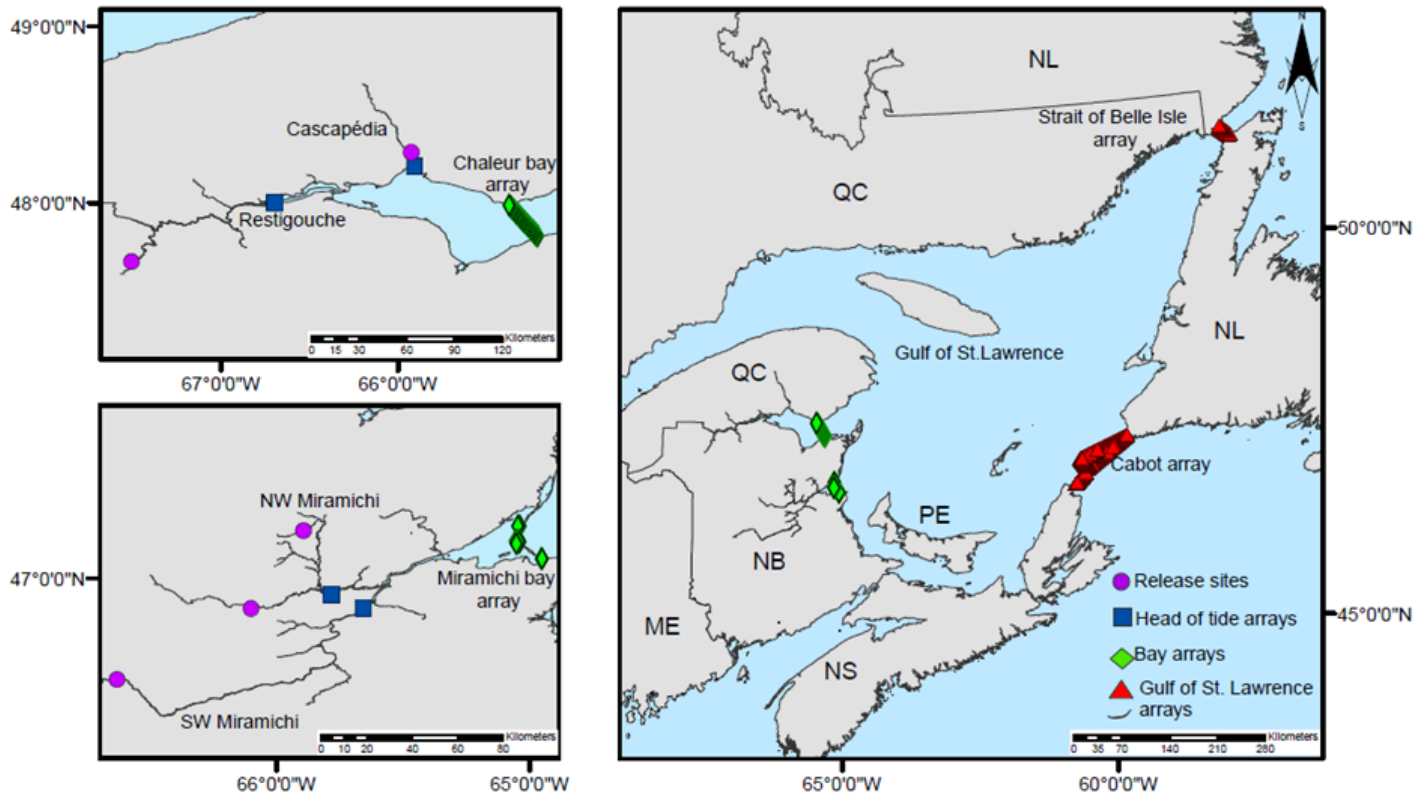


Figure 5. Geographic references of the Atlantic Salmon smolt tagging and tracking experiment conducted by the Atlantic Salmon Federation in four rivers of the southern Gulf of St. Lawrence. The release locations by study river, the head of tide receiver locations, and the respective bay receiver lines are shown. The right panel shows the bay exits and the Strait of Belle Isle receiver array. The figure is from Chaput et al. (2018).

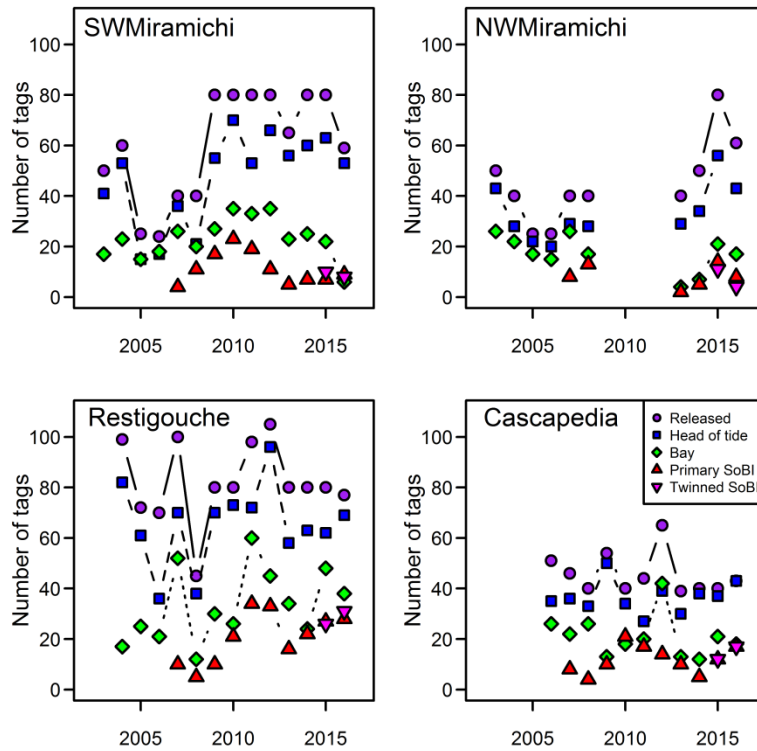


Figure 6. Summary of the number of tagged fish released and number of tags detected at the respective receiver lines for four rivers during 2003 to 2016. The figure is from Chaput et al. (2018).

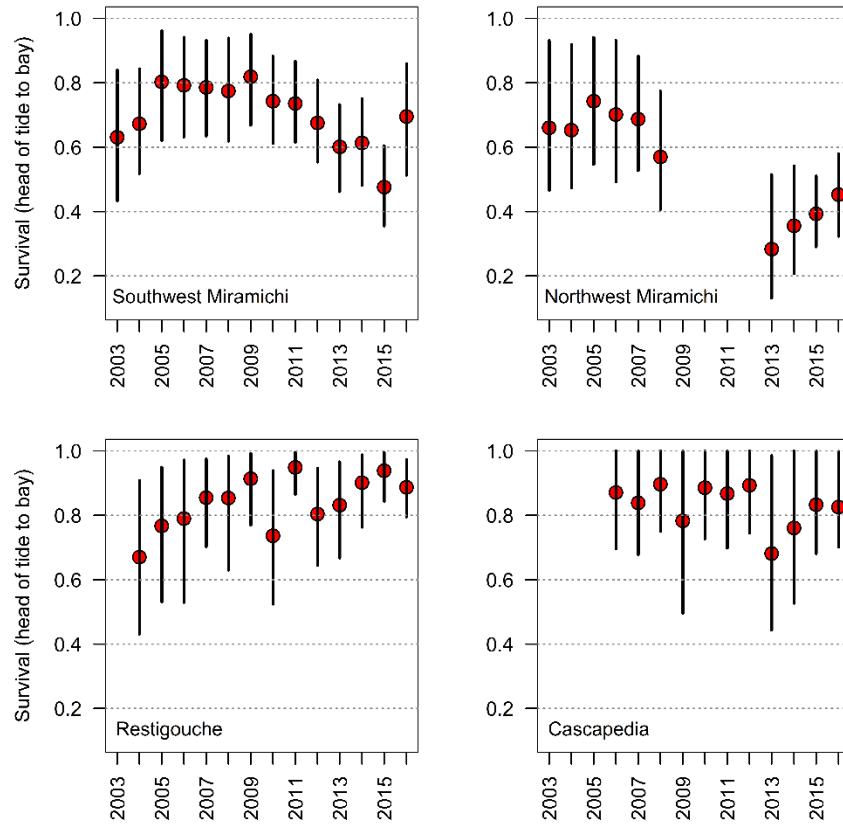


Figure 7. Posterior distributions (median, 5th to 95th percentile range) of estimated survival rates through the bay (head of tide to bay exit, Miramichi in upper row, Chaleur in lower row) of acoustically tagged smolts from four rivers of the southern Gulf of St. Lawrence. The survival rates are for a smolt of centered length 14.6 cm fork length. Data are summarized from the study reported by Chaput et al. (2018).



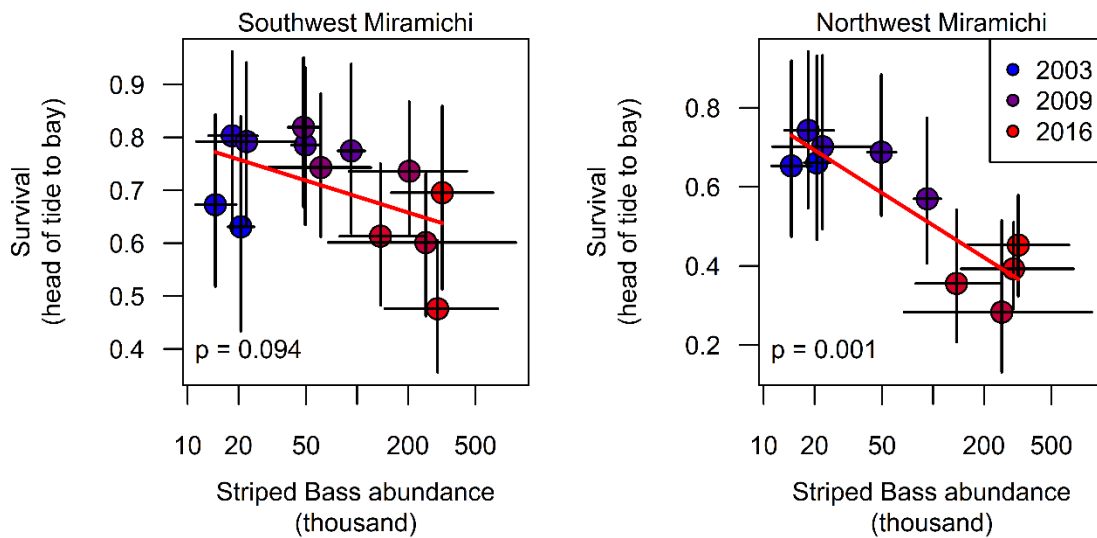


Figure 8. Correlations between the estimated survival rates from head of tide to bay exit of acoustically tagged smolts (Southwest Miramichi left panel, Northwest Miramichi right panel) and the estimated spawner abundance of Striped Bass (log scale) in the Miramichi River, 2003 to 2016. For both the survival rates and spawner abundance values, the symbol is the median and the black lines are the respective 5<sup>th</sup> to 95<sup>th</sup> percentile range of the estimates. The linear relationship (red line) and the corresponding p-value of the slope of the regression = 0 is shown in the lower left corner of each panel. Survival rate data are from the study results of Chaput et al. (2018) mfork length. The survival rates are for a smolt of centered length 14.6 cm fork length. Data are summarized from the study reported by Chaput et al. (2018).

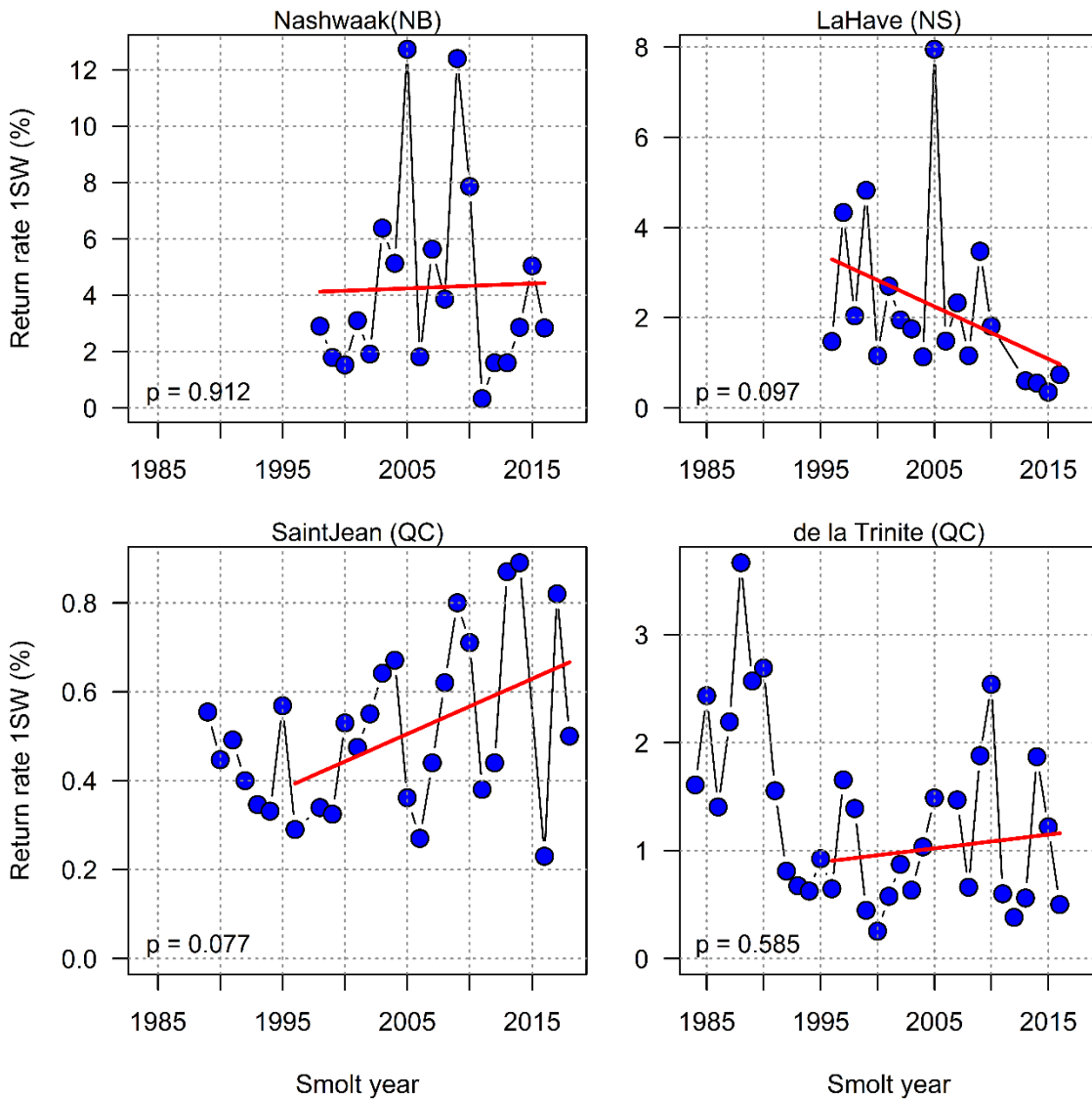


Figure 9. Point estimates of the return rate (%) by year of smolt migration of 1SW Atlantic Salmon to four index rivers of eastern Canada. The red line shows the linear fit to the time series (1996 to present) and the p-value for the null hypothesis of the slope = 0 is shown in the lower left corner of each panel.

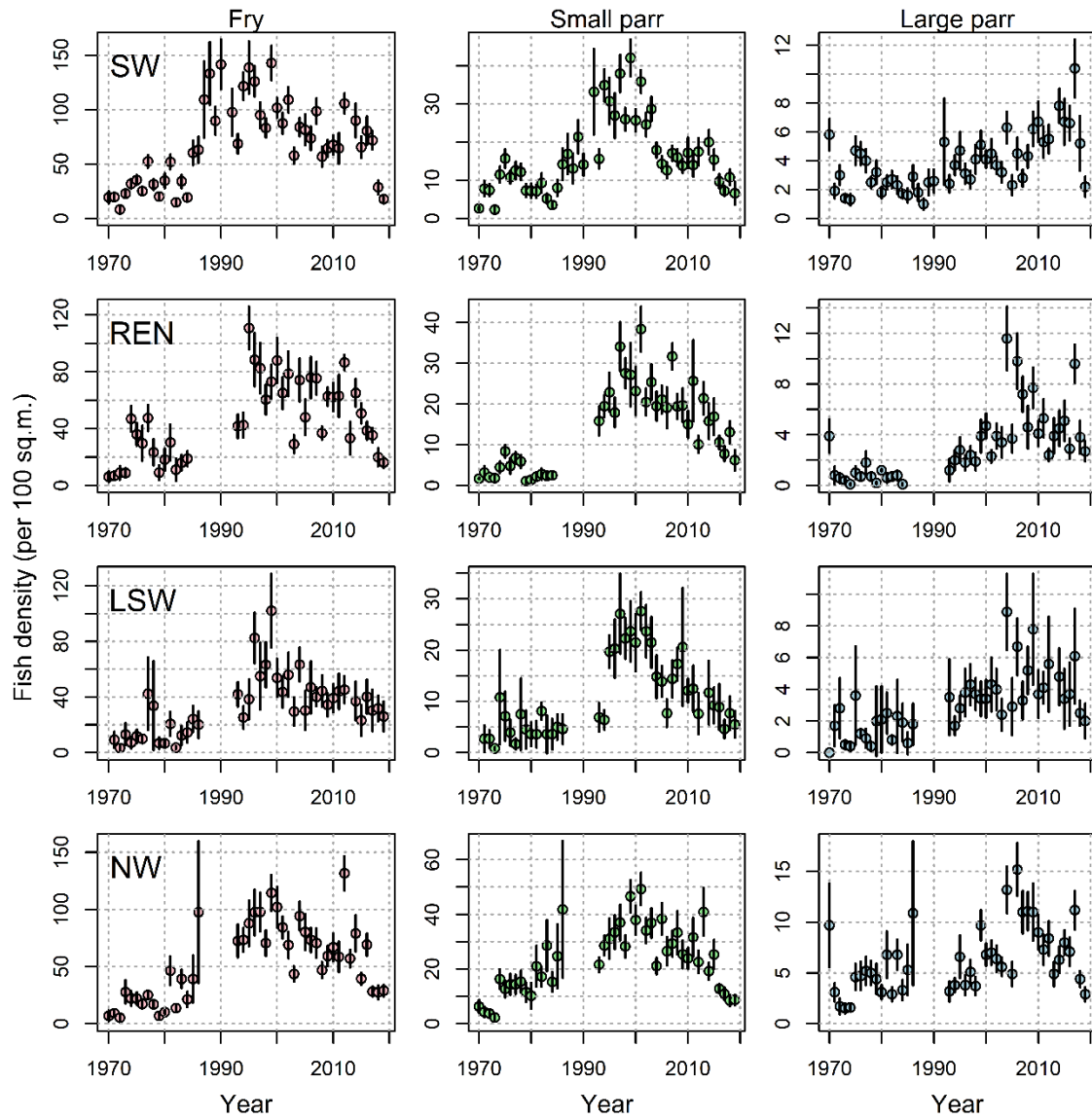


Figure 10. Time series of juvenile Atlantic Salmon indices (fish per 100 m<sup>2</sup>; mean and one standard deviation error bar) by life stage (columns) in the four main tributaries (rows; SW = Southwest Miramichi; REN = Renous; LSW = Little Southwest Miramichi; NW = Northwest Miramichi) for the years 1970 to 2019. Only the years in which at least four sites were sampled within each of the tributaries are shown. Figure is available in DFO (2020b).

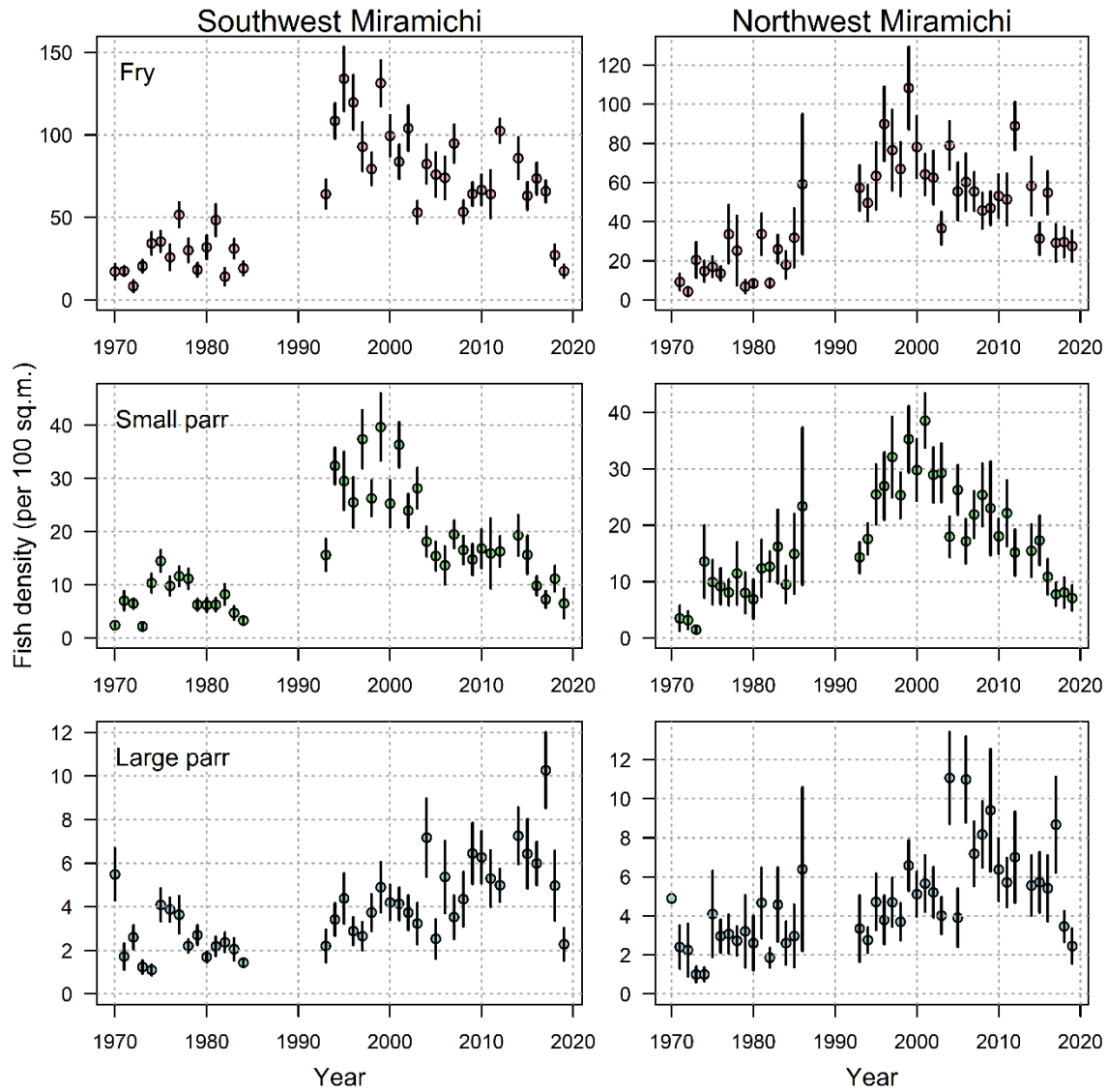


Figure 11. Habitat weighted juvenile Atlantic Salmon abundance indices (fish per 100 m<sup>2</sup>; mean and one standard deviation error bar) by life stage (rows) in the two main branches of the Miramichi River (columns), 1970 to 2019. The standard deviations for the main branches are calculated as the mean of the standard deviations from the tributary estimates shown in Figure 10.

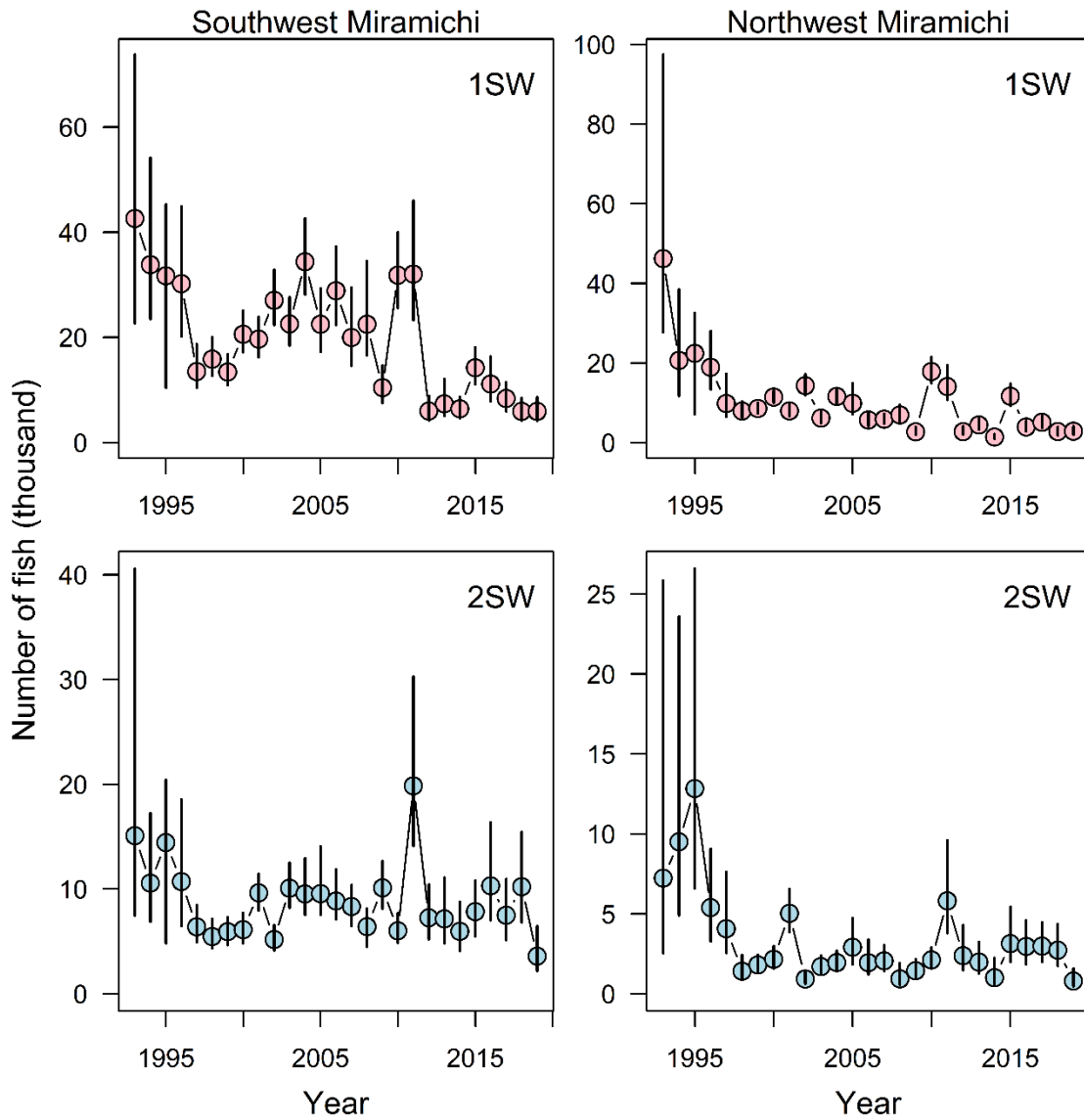


Figure 12. Estimated returns (before inriver fisheries; median and the 5<sup>th</sup> to 95<sup>th</sup> percentile range) of Atlantic Salmon by sea age group (1SW upper row, 2SW bottom row) to the Southwest Miramichi (left column) and the Northwest Miramichi (right column) for the assessment period 1993 to 2019.

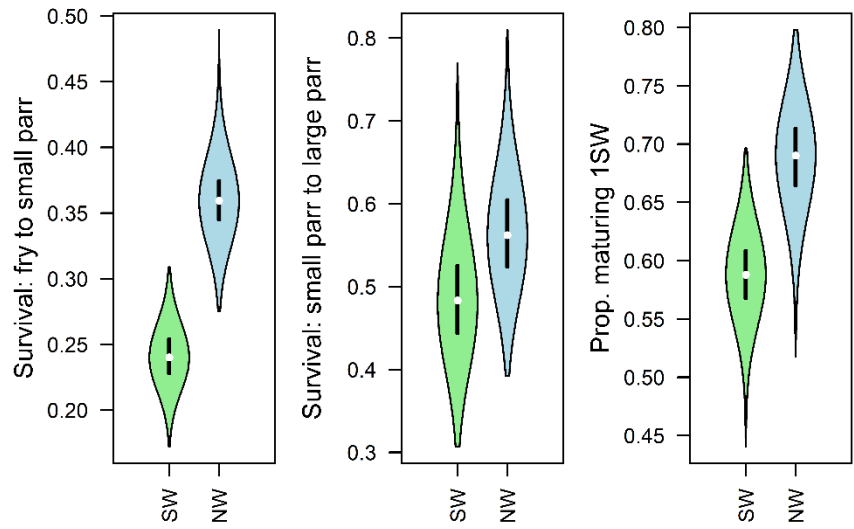


Figure 13. River specific posterior distributions of parameters that were common across years but differed between rivers.

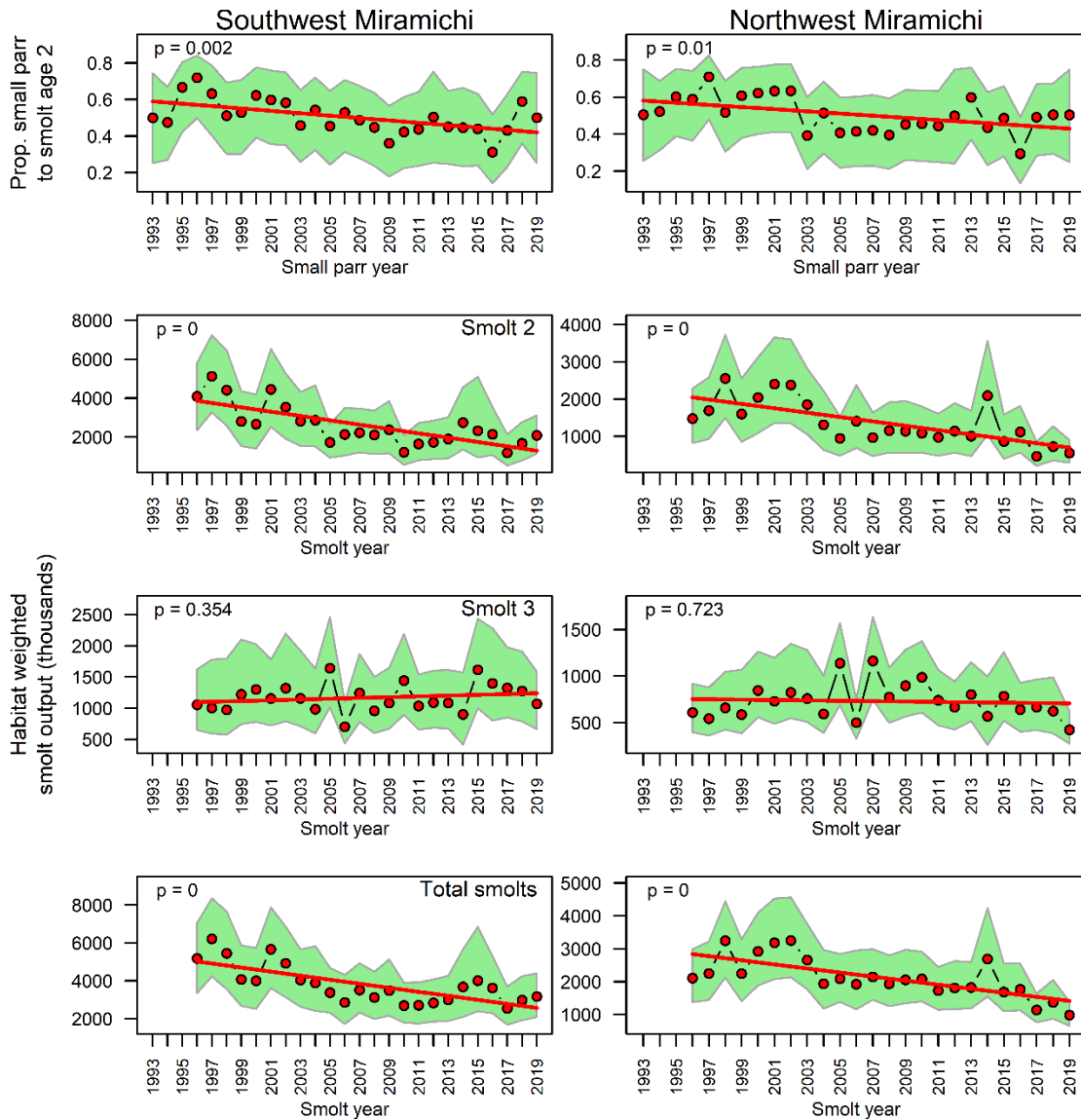


Figure 14. Posterior distributions of the annual proportions of small parr that smolt at age 2, by river (upper row) and estimated relative smolt production at age 2, age 3 and total smolts by year and river (second to fourth rows) for the Southwest and Northwest Miramichi. The red symbols and shaded polygons are the median and the 5<sup>th</sup> to 95<sup>th</sup> percentile range of the posterior distribution. The solid horizontal line is the linear regression of the medians and the p-value for the null hypothesis of the slope = 0 is shown in the lower left corner of each panel.

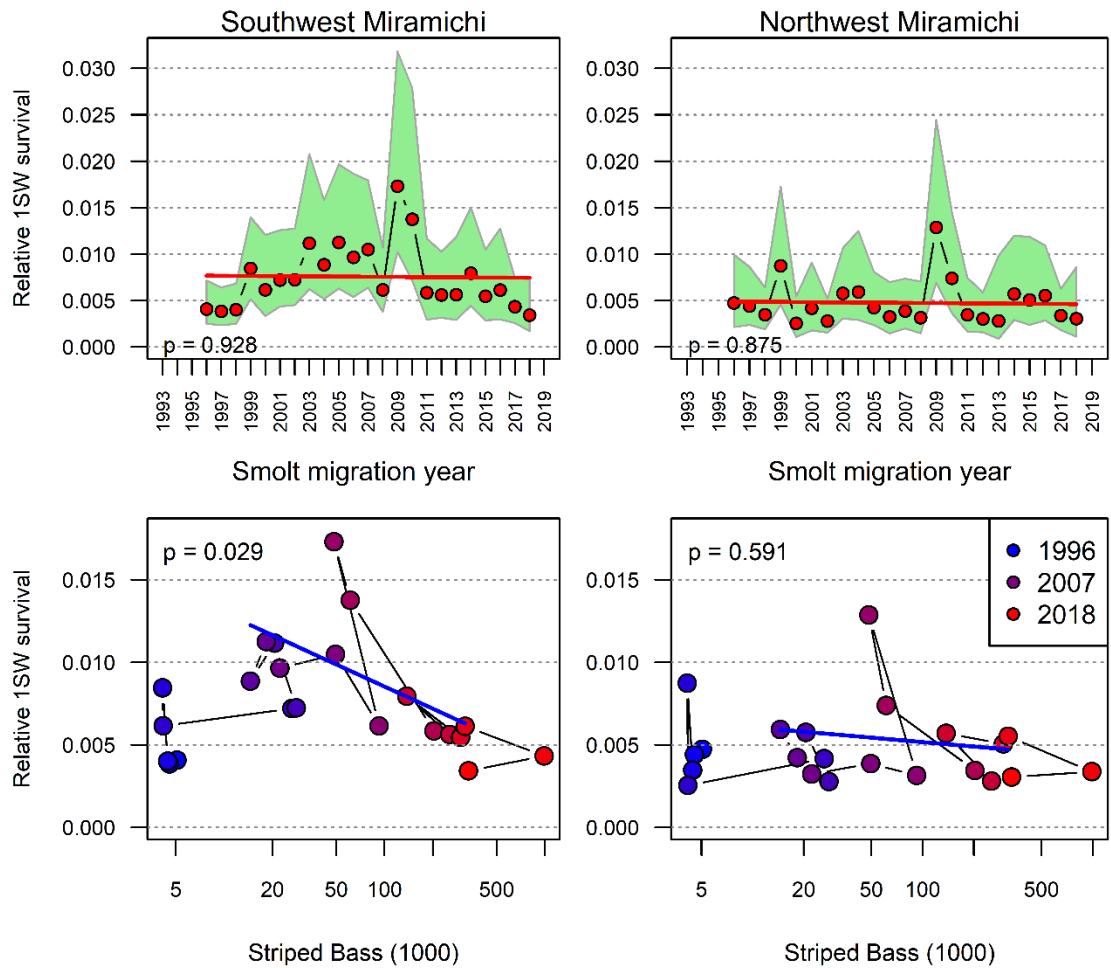


Figure 15. Posterior distributions of the relative survival rates from smolt to 1SW maiden returns to the Southwest (left column) and Northwest (right column) Miramichi rivers for the smolt migration years 1996 to 2018 (top row). The bottom row shows the relative smolt to 1SW survival rates by river plotted against the estimated (log scale) Striped Bass spawner abundances in the Miramichi River for the smolt and Striped Bass spawning years 1996 to 2018. The solid blue line is the linear regression of relative survival rates to log of Striped Bass abundances for the 2003 to 2016 years corresponding to the acoustic tagged smolt survival time series of the Miramichi River (see Figures 7 and 8).



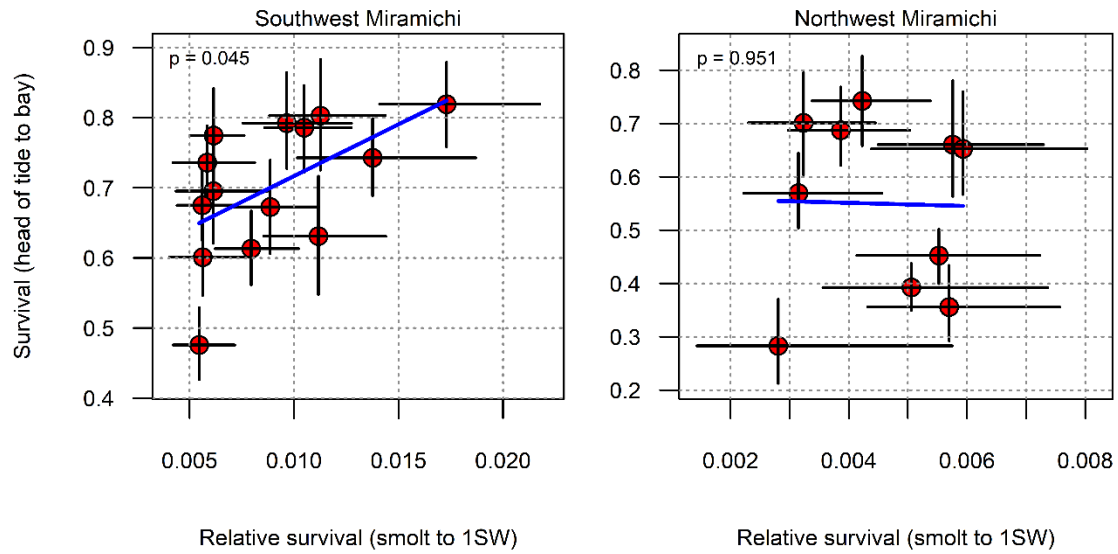


Figure 16. Scatter plot of the posterior distribution (medians) of the relative survival rates from smolt to 1SW maiden returns and the estimated survival rates through the bays of acoustically tagged smolts for the Southwest (left panel; 2003 to 2016 smolt years) and Northwest (right panel; 2003 to 2008, 2013 to 2016 smolt year). The error bars are the 25<sup>th</sup> to 75<sup>th</sup> percentile ranges of the posterior distributions. The blue line is the linear relationship and the p-value of the null hypothesis of slope = 0 is shown in the upper left corner of each panel.

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## APPENDICES

### APPENDIX 1. OPENBUGS MODEL CODE OF THE COHORT MODEL RUNNING INDEPENDENT ESTIMATES BY RIVER

```
# habitat area in 100's of square meters to translate parr to similar scale as maiden adult returns
# data variable names
# Parr.sm = small parr index (fish per 100 sq. m.)
# Parr.lg = large parr index (fish per 100 sq. m.)
# N.1sw = number of maiden 1SW adult returns
# N.2sw = number of maiden 2SW adult returns
# cv.fry is the mean coefficient of variation of the annual fry index from sampling by river
# S.fry is the fry to small parr survival rate
# S.psm is the small parr to large parr survival rate
# p.Sm2 is probability small parr becomes smolt age 2
# p.1sw probability smolt matures at 1sw
# S.1sw survival rate for 1sw year
# S.2sw survival rate in the second year at sea = exp(-0.03*12)
model {
# priors for life history parameters
for (r in 1:2){
  tau.fry[r] <- pow(cv.fry[r],-2)
  S.fry[r] ~ dbeta(2,3)
  Z.fry[r] <- -log(S.fry[r])
  S.psm[r] ~ dbeta(3,2)
  Z.psm[r] <- -log(S.psm[r])
  p.1sw[r] ~ dbeta(5,5) # prob maturing at 1SW
  S.2sw[r] ~ dbeta(72,28) # single essentially fixed parameter
  tau.parr.sm[r] <- pow(sig.psm[r],-2)
  sig.psm[r] ~ dunif(0,5)
  tau.parr.lg[r] <- pow(sig.plg[r],-2)
  sig.plg[r] ~ dunif(0,5)
  tau.1sw[r] <- pow(sig.1sw[r],-2)
  sig.1sw[r] ~ dunif(0,5)
  tau.2sw[r] <- pow(sig.2sw[r],-2)
  sig.2sw[r] ~ dunif(0,5)
} # end river loop
for (y in 1:Y){
  for (r in 1:2){
    log.u.fry[y,r] ~ dnorm(2,0.01) C(1, )
    p.Sm2[y,r] ~ dbeta(5,5) # prop small parr becomes smolt age 2, by river
    Z.1sw[y,r] ~ dnorm(0.1,0.01) C(0.1, )
    S.1sw[y,r] <- exp(-Z.1sw[y,r])
  } # end river loop
} # end year loop
# life history dynamic equations for fry and parr
for (r in 1:2){ #begin river loop
# year loop for fry
for (y in 1:Y){
  fry[y,r] ~ dlnorm(log.u.fry[y,r], tau.fry[r])
  log(u.fry[y,r]) <- log.u.fry[y,r]
  res.fry[y,r] <- log(fry[y,r]/u.fry[y,r])
} # end year loop for fry
# year loop for small parr
for (y in 2:Y){
  parr.sm[y,r] ~ dlnorm(log.u.psm[y,r], tau.parr.sm[r])
  log(u.parr.sm[y,r]) <- log.u.psm[y,r]
  log.u.psm[y,r] <- log.u.fry[y-1,r] + log(S.fry[r])
  res.parr.sm[y,r] <- log(parr.sm[y,r]/u.parr.sm[y,r])
  tot.parr.sm[y,r] <- u.parr.sm[y,r] * hab[r]
} # end year loop for small parr
```

---

```

# year loop for large parr
for (y in 3:Y){
  parr.lg[y,r] ~ dlnorm(log.u.plg[y,r], tau.parr.lg[r])
  log(u.parr.lg[y,r]) <- log.u.plg[y,r]
  log.u.plg[y,r] <- log.u.psm[y-1,r] + log(S.psm[r] * (1-p.Sm2[y-1,r]))
  res.parr.lg[y,r] <- log(parr.lg[y,r]/u.parr.lg[y,r])
  tot.parr.lg[y,r] <- u.parr.lg[y,r] * hab[r]
} # end year loop
# smolts
for (y in 4:Y){
  Sm.2[y,r] <- tot.parr.sm[y-1,r] * exp(-Z.psm[r]/2) * p.Sm2[y-1,r]
  Sm.3[y,r] <- tot.parr.lg[y-1,r] * exp(-Z.psm[r]/2)
  Sm[y,r] <- Sm.2[y,r] + Sm.3[y,r]
} # end year loop
# 1sw loop
for (y in 5:Y){
  N.1sw[y,r] ~ dlnorm(log.u.1sw[y,r], tau.1sw[r])
  log(u.1sw[y,r]) <- log.u.1sw[y,r]
  log.u.1sw[y,r] <- log(Sm[y-1,r]) + log(S.1sw[y-1,r]) + log(p.1sw[r])
  res.1sw[y,r] <- log(N.1sw[y,r]/u.1sw[y,r])
} # end year loop
# 2sw loop
for (y in 6:Y){
  N.2sw[y,r] ~ dlnorm(log.u.2sw[y,r], tau.2sw[r])
  log(u.2sw[y,r]) <- log.u.2sw[y,r]
  log.u.2sw[y,r] <- log(Sm[y-2,r]) + log(S.1sw[y-2,r]) + log(1-p.1sw[r]) + log(S.2sw[r])
  res.2sw[y,r] <- log(N.2sw[y,r]/u.2sw[y,r])
} # end year loop
} # end river loop
} # end model

```

## APPENDIX 2. DIAGNOSTICS OF COHORT MODEL 1

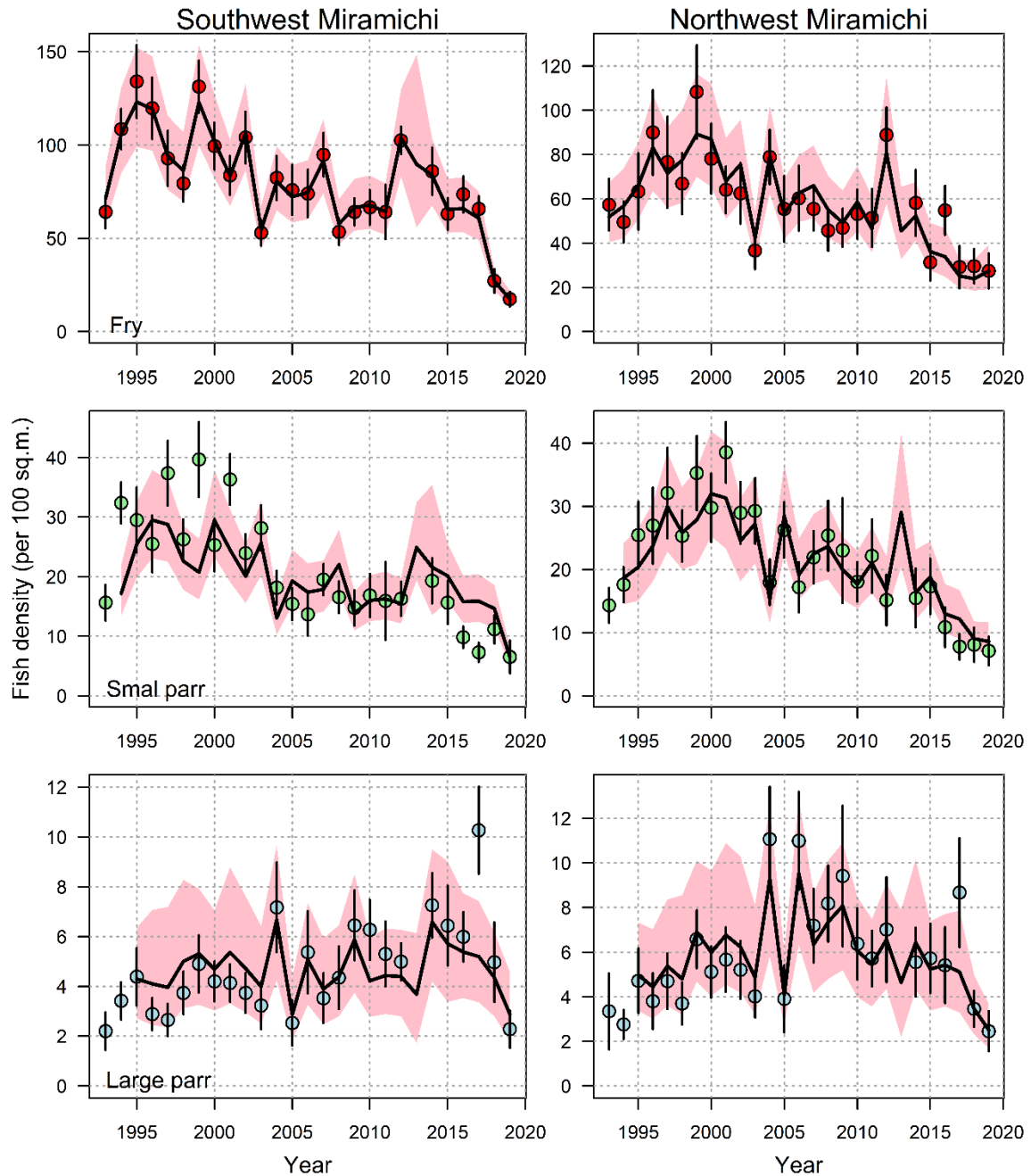


Figure A2.1. Fits to juvenile indices. The symbols and vertical bars are the mean and one standard deviation distributions from sampling. The black line and the shaded polygon are the median and 5<sup>th</sup> to 95<sup>th</sup> percentile range from the posterior distributions.

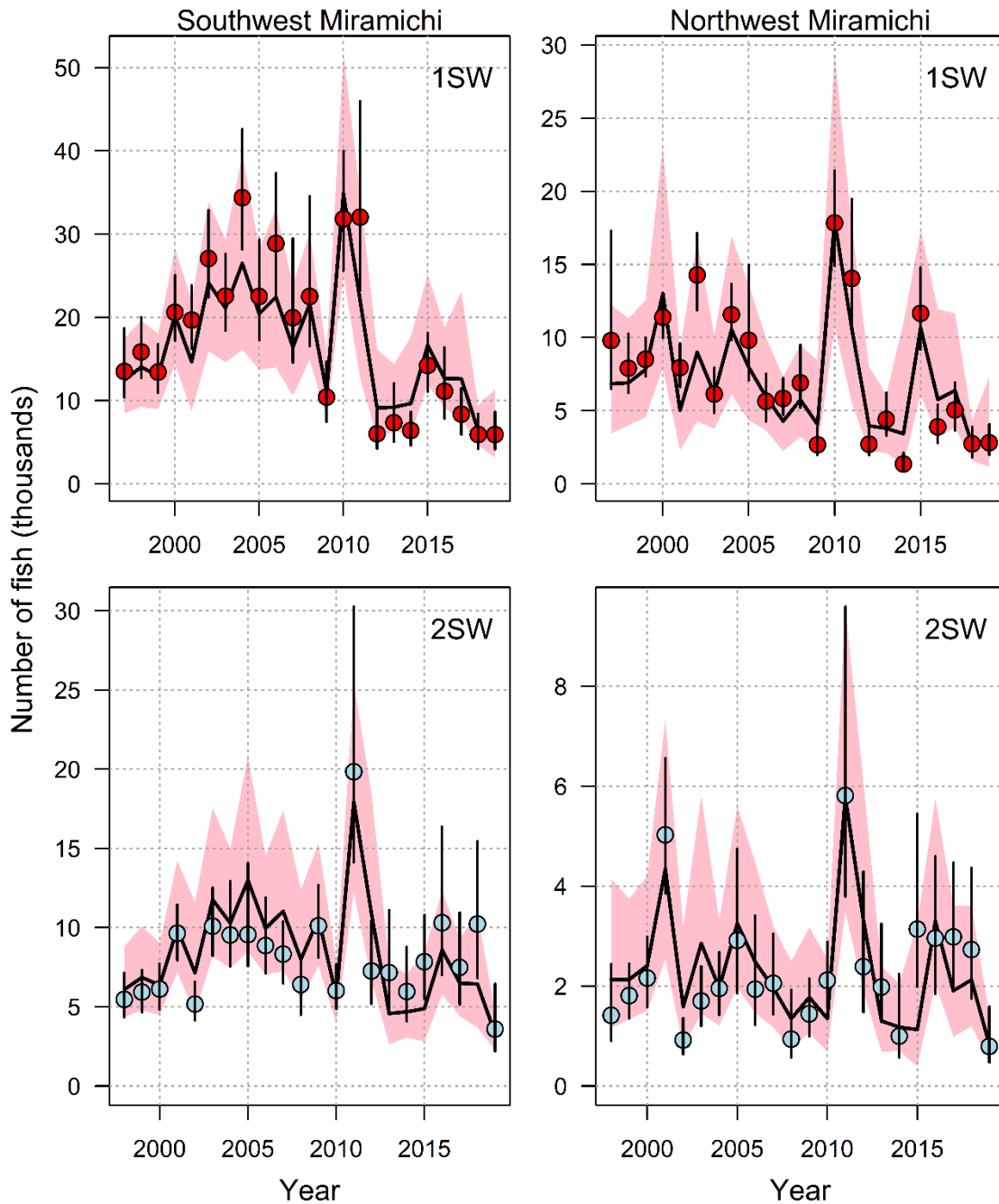


Figure A2.2. Fits to 1SW and 2SW return estimates in the Southwest Miramichi (left column) and Northwest Miramichi (right column). The symbols and vertical bars are the mean and one standard deviation distributions from sampling. The black line and the shaded polygon are the median and 5<sup>th</sup> to 95<sup>th</sup> percentile range from the posterior distributions.

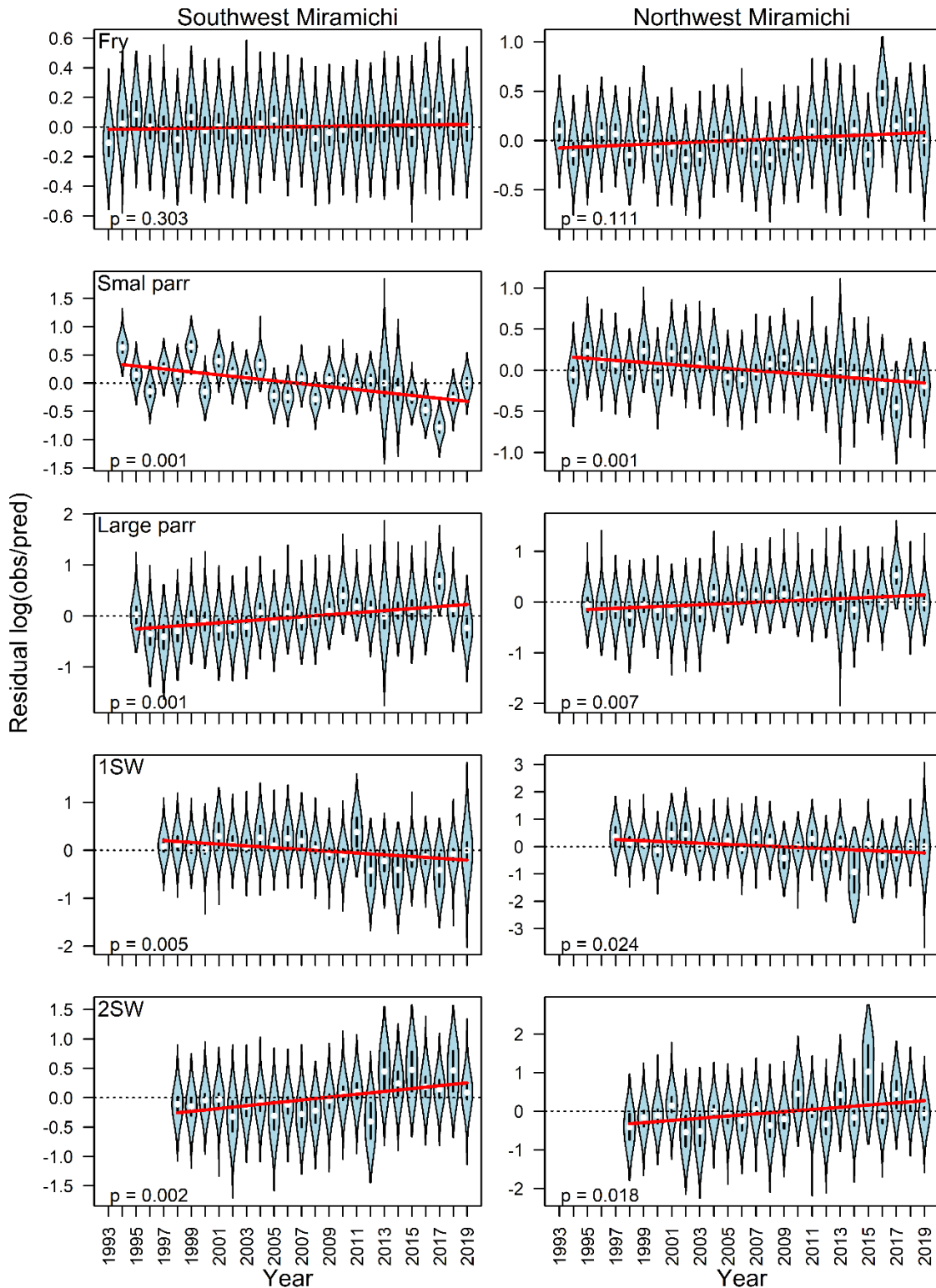


Figure A2.3. Residuals from the fits of model 1. The solid red line is the linear trend of the median of the posterior distribution of the annual residual and the p-value for the null hypothesis of the slope = 0 is shown in the lower left corner of each panel.

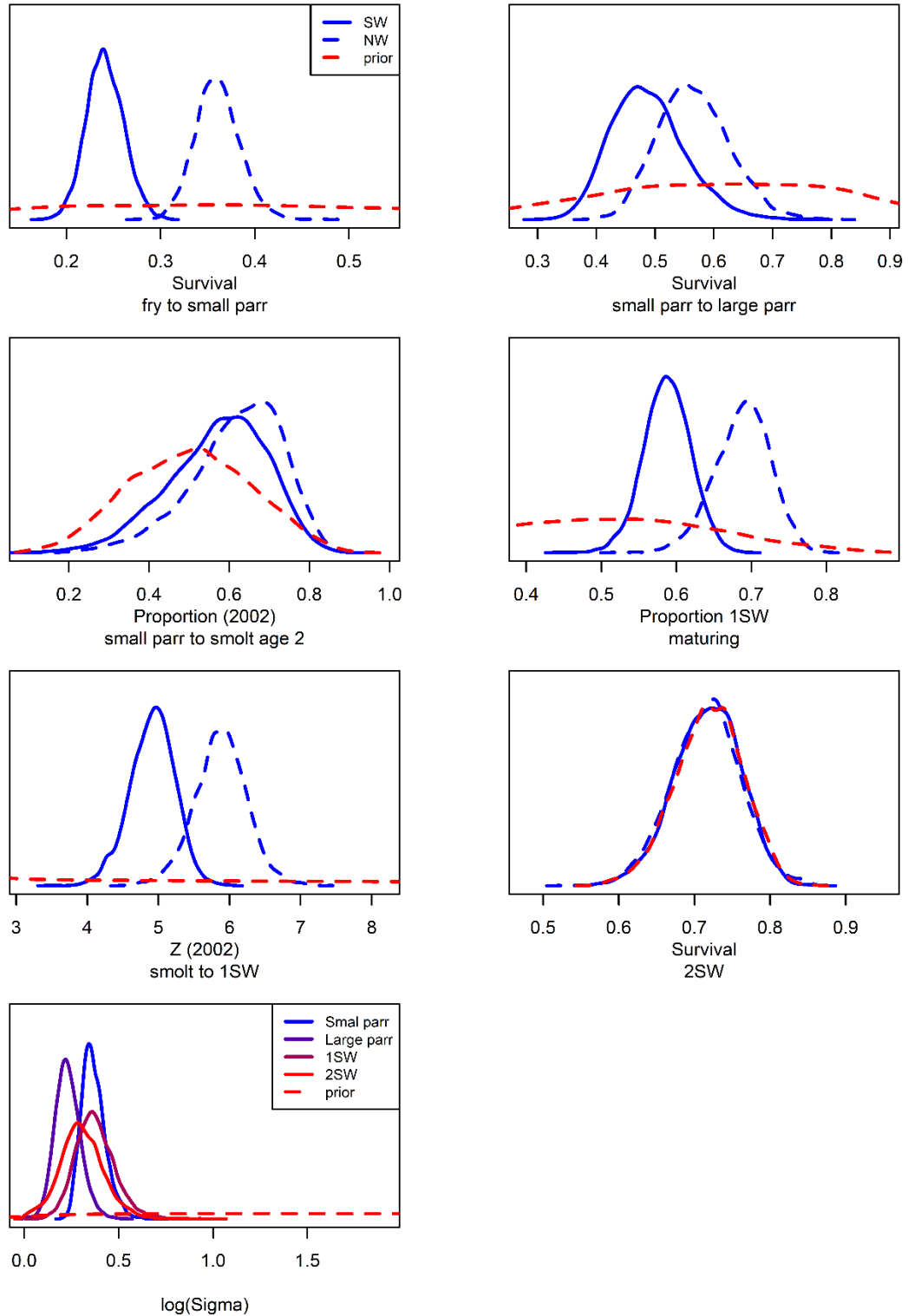


Figure A2.4. Prior versus posterior distributions of the model parameters.

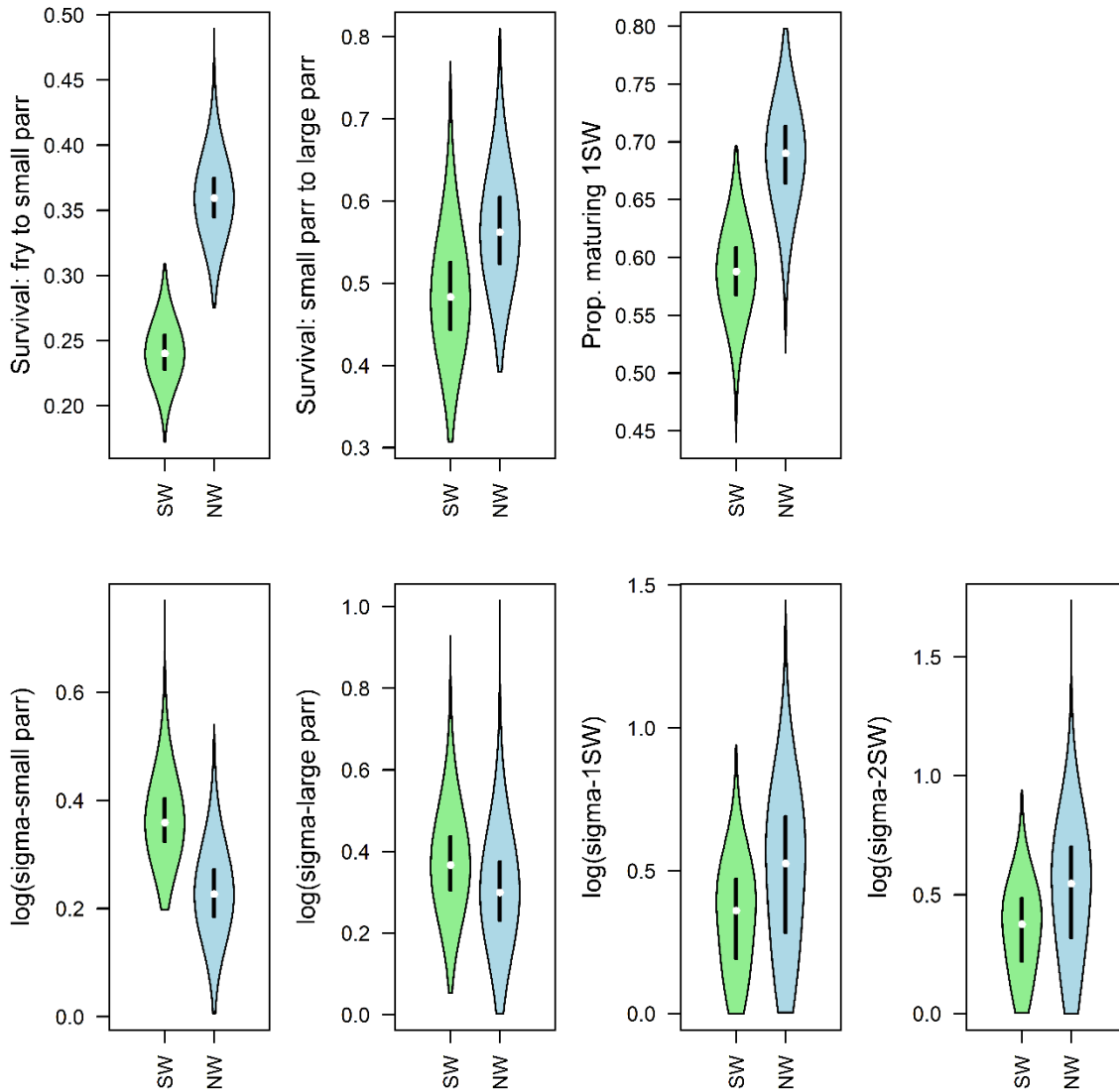


Figure A2.5. Posterior distributions of common over years but river specific parameters.



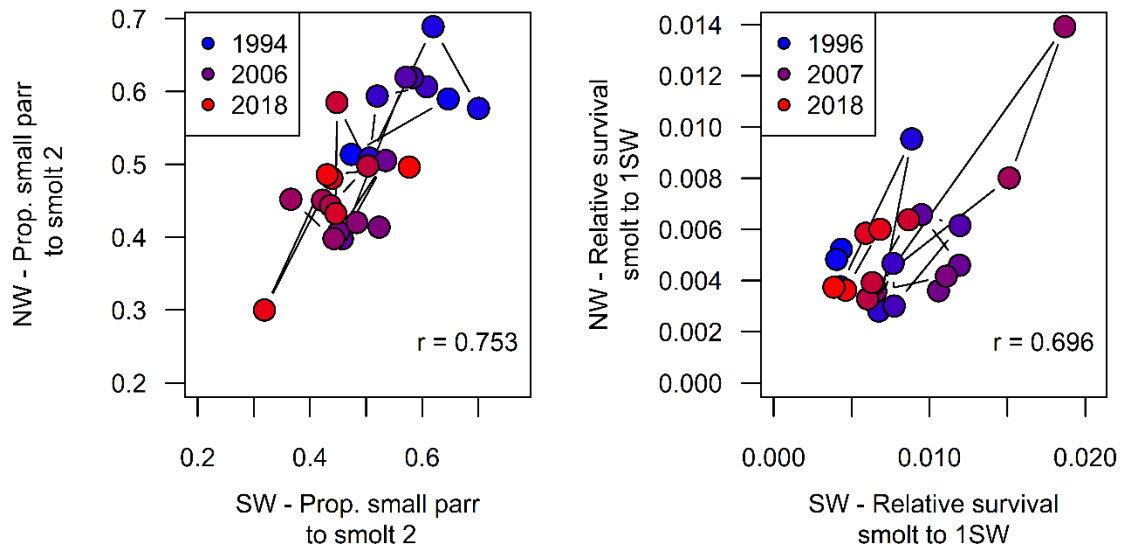


Figure A2.6. Correlations of parameter estimates between rivers.