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Definition of Upper Stock Reference, Target Reference and Maximum Removal Rate Reference Points for Atlantic Salmon (*Salmo salar*) of DFO Gulf Region

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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

Fisheries and Oceans Canada (DFO) is developing a precautionary approach (PA) framework for the management of Atlantic Salmon fisheries for DFO Gulf Region rivers. DFO (2018) previously defined river-specific Limit Reference Points (LRPs) for Atlantic Salmon rivers in DFO Gulf Region. This document addresses the definition of the Upper Stock Reference (USR), the Target Reference (TR), and the maximum Removal Rate (RR) reference points in the healthy zone. The USR is defined as 80% of recruitment at maximum sustainable yield and the TR is recruitment at maximum sustainable yield. The maximum removal rate is the exploitation rate that results in maximum sustainable yield. Reconstructed time series of anadromous Atlantic Salmon returns and spawners from two rivers of DFO Gulf Region augmented by data from twelve rivers of the province of Quebec that are proximate to the rivers of the Gulf Region are analyzed. An approach using ratios is proposed to define the USR and TR values based on the defined LRP values. The ratio quantifies the spread between LRP and USR values derived from adult to adult data which is then applied to the LRP which is defined using only the freshwater phase of the salmon life cycle. The mean ratio of USR to LRP for the twelve rivers analyzed is 3.8 and the ratio of TR to LRP is 4.7. The resulting boundary of the cautious / healthy zones is approximately four times higher than the boundary of the critical and cautious zones. The maximum removal rate is taken directly from the adult to adult stock and recruitment analyses and equals 0.6. The LRP, USR, and TR are defined for each river of DFO Gulf Region known or assumed to have an anadromous salmon run. The reference points are expressed in units of eggs contributed by all anadromous sea age and size groups.

INTRODUCTION

The Sustainable Fisheries Framework encompasses a number of policies to guide management decisions for ensuring that Canadian fisheries are conducted in a manner which supports conservation and sustainable use objectives. One of the policies of the framework is “A Fishery Decision-Making Framework Incorporating the Precautionary Approach” that applies directly to fisheries harvest strategies (DFO 2009). Canada’s Wild Atlantic Salmon Conservation Policy (DFO 2018a) and its associated implementation plan (DFO 2019a) identified the development and implementation of the Precautionary Approach as a priority action for the conservation of Atlantic Salmon in eastern Canada. In the progression of policies to support sustainable use fisheries, DFO (2019b) published guidelines for rebuilding stocks that have fallen into the Critical Zone. All these policies are relevant to the current initiative to establish the Precautionary Approach framework for Atlantic Salmon (*Salmo salar*) rivers of DFO Gulf Region. There are three main components to the Precautionary Approach framework (PA):

- Reference points that define stock status zones (Healthy, Cautious and Critical),
- A defined harvest strategy and associated harvest decision rules, and
- The need to take into account uncertainty and risk when developing reference points and developing and implementing decision rules.

In support of the development of the PA for Atlantic Salmon, DFO (2015) provided advice on the development of reference points including consideration of candidate reference points, the appropriateness of using reference points when productivity varies, candidate values of reference points, and methods to transfer reference points from monitored rivers to data limited rivers. Guided by the advice in DFO (2015), DFO (2018b) defined river-specific Limit Reference Points (LRPs) for Atlantic Salmon rivers in DFO Gulf Region.

This document addresses the remaining elements of the first component of the PA, defining the Upper Stock Reference (USR), the Target Reference (TR), and the maximum Removal Rate (RR) reference points in the healthy zone. It also addresses some of the uncertainties and risks of defining reference points, as prescribed in the third component of the PA.

DFO (2009) speaks to the concept of a TR and DFO (2021a) expands on the interpretation of the USR and the TR. The USR can be considered as the boundary between the Cautious and Healthy Zones whereas the TR represents a desirable stock status state intended to be met on average, i.e. about 50% of the time (DFO 2021a). Treating the primary role of the USR as a threshold to progressive reduction of the fishing mortality rate to avoid stock status reaching the LRP, one can see that this is not a state that should be attained on average, hence justification for setting the TR above the USR on the stock status axis.

The maximum removal rate reference (RR) that would apply in the healthy zone would be the rate corresponding to the TR. For example, if the USR is chosen as 80%Bmsy (example from DFO 2009), then the TR could be Bmsy which is a desirable state for the fishery as it can provide equilibrium maximum sustainable yield. The corresponding removal rate at Bmsy would be Fmsy. The catch that could be realized at 80%Bmsy, the USR, is less than the catch that could be realized at Bmsy (TR) and the removal rate to obtain the catch at 80%Bmsy is higher than Fmsy (RR).

To define the remaining elements of the PA for Atlantic Salmon, a suite of reconstructed time series of adult Atlantic Salmon spawners and returns from two rivers of DFO Gulf Region augmented by data from twelve rivers of the province of Quebec, proximate to the rivers of the Gulf Region is analyzed. An approach is proposed using reference point ratios from the adult to

adult relationships to define the USR and TR based on the defined LRP values of the DFO Gulf Region rivers. The maximum removal rate is taken from the adult to adult stock and recruitment analyses. Uncertainties and knowledge gaps from this approach are discussed.

The definition of an USR, a TR and the RR, combined with the previously defined LRP, are used in a second working paper (Breau and Chaput 2023) to evaluate proposed harvest decision rules for the Atlantic Salmon recreational fishery of the Miramichi River.

CONTEXT FOR ATLANTIC SALMON

Atlantic Salmon of DFO Gulf Region is one of the 180 fish stocks that is tracked for its implementation to the Sustainable Fisheries Framework using the sustainability survey for fisheries. The Fish Stock provisions of the revised *Fisheries Act* (Bill C-68; June 21 2019) apply to major fish stocks prescribed under regulation (DFO 2021a). Although Atlantic Salmon Gulf is not identified as a priority stock under batch 1 actions that would apply to the major stocks are relevant in the development of the PA framework for salmon.

The first important element is the definition of the stock, taking account of biological and management considerations (DFO 2021a). The management of Atlantic Salmon recreational fisheries generally occurs at the provincial level which aggregates a large number of rivers whereas Indigenous peoples' access is community-specific and may include one or several geographically proximate rivers. Within the provincial scale of recreational fisheries management, area specific measures may apply; for example the closure of Atlantic Salmon recreational fisheries in Salmon Fishing Area (SFA) 23 in NB (DFO Maritimes Region), closure of the Atlantic Salmon fisheries in the rivers of the NB southeast portion of SFA 16 (DFO Gulf Region), and river-specific management measures associated with daily retention limits or closures due to warm and low water conditions as occurs in the Miramichi River, Nepisiguit River and Restigouche River (NB) and the Margaree River (NS). At the international level, advice is provided and fisheries management decisions are made for the fisheries at West Greenland based on the status of six large geographic units of Atlantic Salmon in eastern North America (ICES 2020a). When moving from the river scale to the international scale, reference values are summed over the appropriate spatial scale for the provision of advice.

Assessments of Atlantic Salmon in DFO Gulf Region are provided for a small number (usually less than twelve) of individual rivers in the provinces of New Brunswick (NB), Nova Scotia (NS), and Prince Edward Island (PEI; DFO 2020a). River-specific assessments and status relative to LRPs are also reported for a limited number of rivers in DFO Maritimes Region (DFO 2020b) and DFO Newfoundland and Labrador Region (DFO 2020c). River-specific reference points and annual assessments are provided for the rivers of the province of Quebec (MFFP 2016; MFFP 2021).

River-specific LRPs for Atlantic Salmon have been defined for DFO Gulf Region (DFO 2018b). in terms of the total eggs in spawners of all sea-age / size groups that result in a low probability (25% or less) of the resulting recruitment (expressed in terms of smolts) being less than 50% of maximum recruitment. The LRPs were derived using data from the freshwater phase of anadromous Atlantic Salmon from fourteen rivers of eastern Canada. The egg deposition and smolt production data set included observations from two rivers in DFO Gulf Region: the Margaree River and the Kedgwick River (tributary of the Restigouche River) (Chaput et al. 2015). For these rivers, a Beverton-Holt stock recruitment model including a river-specific biological characteristic covariate of the spawners affecting the survival rate is used. The biological characteristic covariate is the proportion of the total eggs which are deposited by multi-sea-winter salmon (or large; ≥ 63 cm fork length) with the consequence that as the proportion of the total eggs from large salmon increases, the egg deposition rate from all

spawner sizes and age groups required to achieve 50% of maximum recruitment decreases. Habitat areas were wetted fluvial areas, unadjusted for habitat characteristics, type, and quality or other features. Biological characteristics data are available from a small number of rivers in the region and the biological data from sampled rivers were applied to rivers without detailed data considering proximity.

For the purposes of defining reference points for Atlantic Salmon, the biological unit is the river scale. The list of rivers is provided in DFO (2018b) and updated in this document with the proposed USRs and TRs (Appendix 6).

DERIVING USR, TR AND RR REFERENCE POINTS

Stock dynamics of Atlantic Salmon are frequently presented as spawner to recruit relationships with spawners on the horizontal axis and recruits on the vertical axis (Potter 2001; Prévost et al. 2003; Holt et al. 2009; Dionne et al. 2015; Figure 1). As fisheries target almost exclusively mature/maturing Atlantic Salmon returning to rivers, managing fisheries exploitation on mature fish returning to rivers is essentially equivalent to managing the spawners that will produce recruitment in the subsequent generation. Under this approach, potential reference points (LRP, USR) have been proposed in terms of spawners after fisheries removals (Prévost et al. 2003; Dionne et al. 2015).

The classic stock and recruitment visualization described above differs from the PA framework where stock status, or an index of total abundance, is presented on the horizontal axis and the removal rate on the vertical axis (Figure 1). Reconciling these two views simply involves transferring the recruitment axis from the stock and recruitment frame (spawners to recruitment) to the stock status axis of the PA frame (stock abundance and removal rate) (Figure 1; DFO 2015; Chaput 2015). In this way, the stock status axis of the PA diagram is interpreted as the stock abundance prior to the anthropogenic losses which are being managed and the harvest decision rule adjusts the removal rate (losses) to this abundance. When stock abundance before exploitation is at or below the defined LRP, i.e. recruitment before fisheries essentially equals spawners, the removals and removal rate must be at the lowest level possible (DFO 2009). When stock abundance before exploitation is in the healthy zone of the PA, removals can occur at a maximum rate that does not result in the abundance after exploitation (i.e. spawners) falling to or below the LRP. Removal rates in the cautious zone (when the abundance is above the LRP but below the USR) are adjusted to minimize the probability that the spawners after exploitation are less than the LRP and promotes stock rebuilding to the healthy zone (DFO 2009, 2021a).

UPPER STOCK AND TARGET REFERENCE POINTS

DFO (2009, 2015) stated that the USRs and TRs would correspond to the objectives of the users and the risk profile and risk tolerance of the management strategy but that, at a minimum, the USR must be set at a level above the LRP with a very low probability (<5%) of the spawners (after fishing) falling below the LRP when a stock that is at or above USR is exploited at the maximum removal rate. This is consistent with the Precautionary Approach for management of Atlantic Salmon fisheries adopted by the North Atlantic Conservation Organization (NASCO).

An USR has been defined as 1.5 times the LRP in terms of eggs for rivers of Newfoundland and Labrador (DFO 2018c); the basis for this choice has not been reported. The province of Quebec has identified equivalents of LRP and USR for the rivers of Quebec with USR values on average 3.8 times the LRP, with a minimum to maximum range of 1.8 to 7.5 times the LRP (Dionne et al. 2015; MFFP 2016).

Retention of Atlantic Salmon in Indigenous and recreational fisheries is desired and by default reference points defined using Maximum Sustainable Yield (MSY) concepts are presented. MSY reference points consider both the biological aspects of the resource (from the stock and recruitment relationship) and socio-economic considerations (maximizing yield from the fishery). Alternate management objectives and reference points could be considered, as described below.

Candidate USR points corresponding to possible management objectives include (DFO 2015; Chaput 2015):

- 80%R*: abundance corresponding to 80% of the recruitment that provides maximum sustainable yield. This is equivalent to the 80%Bmsy value described in DFO (2009). It is proposed as the USR for Atlantic Salmon for rivers in DFO Gulf Region.
- 80%Rmax: abundance corresponding to 80% of maximum recruitment. This would support fisheries objectives of maximizing fishing opportunities and values, as in recreational fisheries that allow the practice of catch and release and/or may be selective for size or sea age groups.

Candidate TR points include:

- R*: also referred to as Ropt, recruitment corresponding to maximum sustainable yield, expressed as the maximum difference between recruitment and spawners. This would support consumptive fisheries objectives. This is proposed as the TR for Atlantic Salmon for rivers in DFO Gulf Region.
- %Rmax: abundance corresponding to a high percentage of the estimated maximum recruitment. For the Ricker stock and recruitment function, the value could be Rmax. For the Beverton-Holt function, Rmax is a theoretical value that is realized when spawners are infinitely large and a value of 90% Rmax could be a potential TR.

MAXIMUM REMOVAL RATE IN THE HEALTHY ZONE

DFO (2009) states that the maximum removal rate in the healthy zone should not exceed the rate corresponding to Fmsy (fishing rate that results in maximum sustainable yield). As discussed above, the maximum removal rate reference (RR) is the rate corresponding to the TR. With the TR set at R*, S* as spawners that result in R*, and C* as the catch at maximum sustainable yield, the maximum removal rate (h^*) is:

$$h^* = \frac{C^*}{R^*} = \frac{R^* - S^*}{R^*}$$

APPROACHES FOR DERIVING USR, TR AND RR REFERENCE POINTS

Ideally, reference points would be derived from river-specific data and the reference points and harvest decision rules would take account of the river-specific life histories, density dependent effects in freshwater, quality and quantity of habitat that affects productivity, and marine survival. The reality is that there are very few river-specific time series of spawners and adult recruits to do these analyses and alternate approaches are required. DFO (2015) states that the USRs are best determined using full life cycle (adult to adult) data but this approach is constrained by two opposing considerations.

A long time series of contrasting abundances with which to adequately estimate life history parameters is needed. There are a limited number of reconstructed and published Atlantic Salmon adult to adult stock recruitment time series (Prévost et al. 2003; Dionne et al. 2015),

and only two rivers (Miramichi, Margaree) have such data in the DFO Gulf Region (Chaput and Jones 1992, 2006; Walters and Korman 2001; Parent and Rivot 2013).

There is a risk of directional sustained changes in the life history features, in particular survival during the density-independent phase of the life cycle, for long time series monitored. A directional and sustained change in life history parameters over time is referred to as non-stationarity, which differs from short term variation. The consequences of non-stationarity are that observations from the past may not be indicative of current and future conditions and may therefore bias our understanding of population dynamics, reference points, and expectations (DFO 2015; Malick 2020).

Time Series of Contrasting Abundance

The reconstruction of full life cycle (egg to egg) data should account for marine fisheries removals, changes in age structure, and the contributions of hatchery stocking programs.

Failure to account for removals of adult salmon in fisheries underestimates the lifetime contribution of eggs from the recruits resulting in a negative bias in the estimated productivity and carrying capacity of the stock. None of the available reconstructed adult to adult stock and recruitment data series have accounted for the removals of salmon in their second year at sea at West Greenland nor in the Faroes Islands fisheries (Prévost et al. 2003; Chaput and Jones 1992, 2006; Dionne et al. 2015). There are two main reasons for this:

- the origin of fish in the mixed stock fisheries cannot be attributed to individual rivers, and
- there is subsequent natural mortality of fish between the time of the fishery and returns to homewaters.

In recent years, putative exploitation rates by genetic/regional reporting groups have been derived (ICES 2020a) and these could be applied to the individual rivers of the region to raise the returns to account for these marine fisheries. Alternatively, the estimated exploitation rate on non-maturing one-sea-winter (1SW) salmon of North American origin, that have varied from 1.5% to 36.1% over the period 1984 to 2019 (ICES 2020a), could be applied to returns of large salmon. This would equate to raising the annual values of large salmon recruits to the river by a factor of 2% to 56% to account for those losses.

In eastern Canada, none of the reconstructed time series have considered the removals of fish in the Newfoundland and Labrador marine commercial fisheries that historically were known to intercept salmon originating in Quebec and the Maritime provinces until the closures in 1992 for Newfoundland and 1998 for Labrador (Saunders 1969; Paloheimo and Elson 1974; Marshall 1982; Bradbury et al. 2016a, 2016b).

Repeat spawners can make up important proportions, up to 25%, of the spawning stock in some Atlantic Salmon runs (O'Connell et al. 2006; Chaput and Benoît 2012; Bordeleau et al. 2019). When reconstructing recruitment time series of adult salmon, attempts are made to account for the lifetime spawning contribution of cohorts. If only recruitment of adults at the maiden spawner stage is considered, the lifetime reproductive contribution of recruits will be underestimated and this will bias downward the estimation of a number of full life cycle reference points such as R_{max} , R^* , and S^* .

In a number of rivers of eastern Canada, particularly in DFO Gulf and Maritime Regions, hatchery programs collect broodstock from returning anadromous adult salmon, spawn and incubate them in captivity, and stock juvenile salmon at relatively young ages to rivers of broodstock origin. There are active hatchery programs supported by provincial authorities and non-government organisations in DFO Gulf Region (Bliss 2017) and in many cases, the

hatchery origin juveniles, outmigrating smolts, and returning adults cannot be distinguished from wild salmon because they are not externally marked. If the contributions of hatchery fish are not excluded from the returns, the effect is to bias the productivity upwards, resulting in higher removal rate reference points and higher anticipated yield from the wild stock.

Non-Stationarity in the Population Dynamics

Variations in survival at sea have the greatest consequence on abundance of returning adults and the MSY reference values (C^* , R^* , S^*) increase as marine survival increases. There is substantial evidence of non-stationarity in the North Atlantic Ocean conditions that have affected anadromous Atlantic Salmon abundance (Chaput et al. 2005; Beaugrand and Reid 2012; Chaput 2012; Mills et al. 2013; ICES 2020b; Olmos et al. 2020). There have been reported sustained declines in sea survival in the North American and European populations of Atlantic Salmon over the past four decades with the most important declines occurring in the late 1980s and early 1990s (Chaput et al. 2005; Chaput 2012; ICES 2020b). Over the period 1971 to 2019, the abundance of anadromous Atlantic Salmon from eastern North America in the North Atlantic declined 62% overall, 36% for small salmon (< 63 cm fork length) and 82% for large salmon (\geq 63 cm fork length) with factors other than fishing considered to have contributed to the declines over the past four decades (ICES 2020a). These changes in marine dynamics, have occurred independently of production dynamics in freshwater.

Density dependent compensatory survival occurs in freshwater and this was the basis for choosing this portion of the life history for deriving the LRP for Atlantic Salmon (Chaput 2015). In an analysis of egg to smolt stock and recruitment data from fourteen rivers in eastern Canada, Chaput et al. (2015) identified a statistically significant ($p < 0.05$) temporal trend in residuals for two of the fourteen rivers. In addition to the compensatory survival considerations, there may be legacy effects from the freshwater phase that result in differences in marine survival of out-migrating smolts. Specifically sea survival has been shown to be positively associated with body size and changes in freshwater conditions could affect juvenile growth rates and body size at out-migration.

Non-stationarity in stock and recruitment data time series can be inferred from temporal trends in residuals of the stock and recruitment fits. Solutions to undesirable temporal patterns in residuals include:

- fitting separate stock and recruitment functions to different time periods;
- selecting a subset of the data for the period that corresponds to the productivity conditions that are considered more appropriate to the contemporary state; or
- ignoring the temporal trends and fitting to all available data.

DFO (2016) stated that it may be appropriate to adjust reference points to productivity changes if:

- the productivity change is known with high certainty to be due to a regime shift and there is an understanding of the mechanisms linking the environmental change with the productivity of the stock and of the life history stages that are affected by the regime shift;
- the change is not believed to be reversible in the short or medium term (e.g. is expected to last at least a decade or a generation – whichever is longer); and
- there has been a change in the capacity of the environment to support the stock.

The factors that have contributed to the reduced productivity of Atlantic Salmon in the North Atlantic are not fully known but are considered to be acting predominantly at sea and associated

with survival that is not density-dependent. The abundance of salmon at sea is too low to affect its prey but salmon are susceptible to a large number of predators even though salmon may not be an important prey for the predators (Chaput and Benoît 2012). Optimistically, the lower productivity state of the recent three decades noted for Atlantic Salmon are considered to be reversible.

Reconstructed time series of salmon abundance examined in this manuscript are contemporary with the earliest reconstruction beginning in 1961 and with most beginning with the 1971 or 1972 cohorts. We therefore considered it important to include the historical (1970s +) data for the derivation of the reference points for Atlantic Salmon that would define the abundances of salmon considered healthy and that could provide substantial fisheries benefits.

PROPOSED APPROACH FOR DEFINING REFERENCE POINTS

We analyzed reconstructed stock and recruitment data sets from two rivers in DFO Gulf Region and twelve rivers from the province of Quebec. Both Beverton-Holt and Ricker functions (Hilborn and Walters 1992) are examined to derive reference points.

The USR and TR points derived from these rivers could be transferred to other rivers in DFO Gulf Region using one of two approaches:

- Transfer the USR and TR values in terms of eggs per unit of habitat from analyzed rivers to other rivers without stock and recruitment data, as was done for the province of Quebec (Dionne et al. 2015) or for the DFO Gulf Region LRP definitions (DFO 2018b). The conservation risk of this approach is that the USR and TR points transferred do not account for changes in marine productivity through time and in some cases the reference points may be close to if not less than the defined LRP based on the egg to smolt freshwater phase model.
- Estimate the ratios of USR and TR to LRP values of the analyzed adult to adult stock and recruitment series and calculate the USR and TR for the other rivers using that ratio and the previously defined LRP values based on the egg to smolt freshwater phase model.

The following reference values and ratios are calculated:

- S^* : spawners that produce abundance at maximum sustainable yield, also referred to as S_{opt} ;
- R_{max} : maximum recruitment;
- $S_{halfR_{max}@50}$: spawners that result in a 50% chance or more that the recruitment is \geq half of R_{max} ;
- $S_{halfR_{max}@75}$: spawners that result in a 75% chance or more that the recruitment is \geq half of R_{max} . This corresponds to the LRP definition from the egg to smolt relationship (DFO 2015, 2018).
- R^* : recruitment at maximum sustainable yield, also referred to as R_{opt} ;
- $80\%R^*$: 80% of recruitment abundance at maximum sustainable yield;
- h^* : exploitation rate that results in maximum sustainable yield catch (C^* , also referred to as C_{opt}) when the stock is at R^* , also referred to as h_{opt} ;
- R^* / S^* : ratio of recruitment at maximum sustainable yield to spawners that result in maximum sustainable yield. Note that this is equivalent to $1 / (1-h^*)$.

-
- $R^* / S_{\text{halfRmax}@50}$: ratio of recruitment at maximum sustainable yield to spawners that result in 50% chance or more of recruitment being \geq half R_{max} ;
 - $R^* / S_{\text{halfRmax}@75}$: ratio of recruitment at maximum sustainable yield to spawners that result in 75% chance or more of recruitment being \geq half R_{max} .

RATIO APPROACH SIMULATION METHODS AND RESULTS

The approach based on the ratio of USR or TR to LRP is new and we review the performance of this approach using a simulated salmon population. We begin with a defined egg to smolt stock and recruitment relationship (Beverton-Holt to correspond to the model used to define the LRP for rivers of DFO Gulf Region) and apply different levels of stationary survival during the post-smolt phase to generate time series of adult spawners and returns. The simulated eggs in spawners and returns are then analyzed using Beverton-Holt and Ricker functions to estimate the various reference values of interest and to assess their association with different sea survival assumptions.

Methods

Simulated data are generated using a full life cycle model that tracks the smolt output and returning adult salmon by year-class (Appendix 1). The year class specific smolt values differ for each simulated data set because the egg depositions differ among the simulations. The contrast in spawner values has consequences on the fits of the data, in particular for estimating the slope at the origin. To generate nearly equivalent low spawner abundances, the exploitation rates on returning salmon are adjusted upwards for the scenarios with high sea survival. All the other life history and population dynamics parameters are fixed or drawn from uniform or normal distributions (on the logit scale) with similar coefficients of variation for each simulated data set; this has no directional consequence on the simulated eggs in spawners and returns.

The life cycle model requires nine years to account for the full year class returns, from egg deposition to returns of repeat alternate spawners. The life cycle model was simulated for a time series of 150 years, discarding the first 20 years to initialize the dynamic and discarding the final 20 years to ensure the year-class returns are complete. One simulated set of data was generated for each of the five post-smolt survival rate scenarios and each data set was analyzed using a Ricker and a Beverton-Holt (BH) model.

Results

Simulated data set descriptions consist of eight panels (Appendix 1 Figures A1.1-5) that include:

- time series of smolts produced by year class;
- a plot of eggs to smolts by year class and the mean predicted Beverton-Holt line;
- the simulated exploitation rate values by year;
- the simulated annual post-smolt survival in the first year at sea based on a stationary mean value;
- the abundance by simulated assessment year (not year-class) of small salmon (< 63 cm fork length) returns and small salmon spawners;
- the abundance by simulated year (not year-class) of large salmon (\geq 63 cm fork length) returns and large salmon spawners;

- the calculated eggs in the spawners and returns by year class; and
- a scatter plot of eggs in spawners and eggs in returns by year class, the data used for fitting the Beverton-Holt and Ricker stock and recruitment functions to derive reference points and ratios.

The results of fitting of the spawners and returns by year-class from the simulated time series are summarized in five panels for each of the Beverton-Holt (Appendix 1 Figures A1.6-10) and Ricker (Appendix 1 Figures A1.11-15) functions:

- panel showing the scatter plot of eggs in spawners versus eggs in returns by year-class with superimposed median and percentiles (25th to 75th percentile, 5th to 95th percentile) polygons of the predicted eggs in returns;
- boxplots of the log(residuals) from the model fits, with linear trend line and associated p-value for the slope;
- boxplots of reference values based on the fitted parameters;
- boxplots of the posterior values of the exploitation rates for select reference values, and $\log(\sigma)$; and
- boxplots of the ratios of R^* to three spawner reference values.

The derived reference values from the fitted stock and recruitment functions for the five sea survival scenarios are summarized in Figure 2a for the Beverton-Holt fits and Figure 2b for the Ricker fits.

For all five stationary simulated time series, there are no linear trends in the log residuals (Appendix 1 Figures A1.6-15). Also as expected, the estimates of S^* , R^* , and R_{max} increase monotonically with increasing simulated sea survivals (Figures 2a, 2b; Appendix 1 Figures A1.6-15). The medians of the posterior estimates of $S_{halfRmax@75}$ for the BH fits are unrelated to sea survival whereas the medians from the Ricker fit suggest a positive association with sea survivals but the ratio of highest to lowest estimated value (medians) over the simulated sea survivals was 1.67 for the Ricker fits and 4.40 for the BH fits (Figures 2a, 2b). The variations in estimates among the five survival scenarios are undoubtedly related in part to the differences in the simulated data set, in particular the differences in the contrast of spawner abundances which affect the fits of the stock and recruitment functions.

The ratios of R^* to estimates of spawner values (as S^* or $S_{halfRmax}$) are positively associated with sea survival (Figures 2a, 2b). The R^*/S^* ratios of the Ricker fits ranged from 1.55 to 3.79 compared to those of the BH fits of 2.15 to 5.20. The ratios of $R^* / S_{halfRmax@75}$ ranged from 1.47 to 8.51 for the Ricker, 1.10 to 12.81 for the BH fits.

Using the ratio of R^* to S^* or $S_{halfRmax@75}$ does not resolve the problem of reference values being associated with sea survival. Recognizing that, we are interested in the spread between LRP and USR values derived from adult to adult data as a method of defining an USR and TR when the LRP is defined from the egg to smolt life stage, as is the case for Atlantic Salmon. Although the spread between the LRP and the USR is also associated with sea survival, we propose to use this method rather than transferring directly estimates of R^* or R_{max} to define USRs for the following reasons:

For the Beverton-Holt and Ricker functions, the medians of the posterior estimate of $S_{halfRmax@75}$ from the adult to adult fits were in almost all cases similar to or greater than the $S_{halfRmax@75}$ value of the assumed egg to smolt stock and recruitment dynamic (Appendix 1 Figures A1.6-15). This is an important result to keep in mind when interpreting the estimates of reference values from fits of reconstructed adult to adult data.

For the Ricker fits the spread (ratio of maximum to minimum) of the reference values over the range of simulated sea survivals of 2% to 10% is greater for R^* (7.4 times) than it is for R^*/S^* (2.5 times) and for $R^* / S_{\text{halfRmax@75}}$ (5.8 times). This is not the case for the Beverton-Holt fits; the spread in R^* is 6.2 times, the spread for R^*/S^* is 2.4 times, and the spread for $R^* / S_{\text{halfRmax@75}}$ is 12 times.

We propose to use the ratio of R^* to $S_{\text{halfRmax@75}}$ obtained from fitting adult to adult stock and recruitment data to derive the river-specific USRs, and TRs from the defined LRPs. The ratio to use will be estimated from the analysis of available adult to adult stock and recruitment data for a suite of rivers in and proximate to DFO Gulf Region. Considering the posterior distributions of the ratios for the two stock and recruitment models, we propose using the ratio estimated from fitting the adult to adult data with a Ricker function.

STOCK AND RECRUITMENT TIME SERIES ANALYSES

We considered stock and recruitment data from two rivers in DFO Gulf Region and from twelve rivers in the province of Quebec (Table 1; Figure 3):

- adult to adult reconstructed time series for the Miramichi River (or separately for the Northwest Miramichi and the Southwest Miramichi);
- adult to adult reconstructed time series for the Margaree River;
- adult to adult reconstructed time series for twelve rivers in Quebec, published in Dionne et al. (2015). These salmon populations are geographically proximate to the DFO Gulf Region rivers and have comparable life history characteristics, especially the important contributions of multi-sea-winter fish to returns and spawners.

Details of the methods for reconstructing the time series are provided in Appendix 2 for the Miramichi River, Appendix 3 for the Margaree River and are described in Dionne et al. (2015) for the Quebec rivers (Appendix 4). The methods are summarized below.

Data Series Reconstruction

Miramichi River

The Miramichi River is the second largest watershed, after the Saint John River, in the province of New Brunswick. The Miramichi River is the only river in SFA 16 with annually published estimates of returns and spawners of Atlantic Salmon; the published time series extends from 1971 to 2019 (DFO 2020a). In 1992, the monitoring program moved to branch specific assessments from the single Miramichi River assessment conducted prior to 1992 (Courtenay et al. 1993) and estimates of returns to each of the Northwest Miramichi and Southwest Miramichi branches and to the Miramichi River overall have been provided since 1992 (DFO 2020a). Douglas et al. (in prep.¹) provide results of a modified assessment model that estimates the returns of small salmon (< 63 cm fork length) and large salmon (\geq 63 cm fork length) to each branch (Northwest Miramichi, Southwest Miramichi) of the Miramichi River for the period 1984 to 2019. In 1984, important fisheries management changes were introduced that included the closure of the commercial salmon fishery in the Maritime provinces and large

¹ Douglas, S., Underhill, K., Horsman, M., and Chaput, G. 2022. Information on Atlantic salmon (*Salmo salar*) from Salmon Fishing Area 16 (Gulf New Brunswick) of relevance to the development of a 2nd COSEWIC report. DFO Can. Sci. Advis. Sec. Res. Doc. In preparation.

portions of Quebec, and the mandatory release of large salmon in the recreational fisheries of the Maritime provinces.

Sampling of returning adult salmon has occurred every year at index trapnets operated by DFO Science since 1971. The sampling includes fork length, sex (generally external) and collection of scales for age interpretation. Combined with the estimated size – fecundity relationship published by Randall (1989), the biological characteristics of the Atlantic Salmon run to the Miramichi River can be annually described and total egg estimates in spawners and returns to the river (before homewater commercial, Indigenous, and recreational fisheries) by year of return and by year-class are provided. Details of the reconstruction of the year-class contributions of spawners and returns are provided in Appendix 2.

We examined three time series of adult spawners and returns to the Miramichi (Table 1). The first and longest time series is for the Miramichi River for the period 1971 to 2019; this series comprises the sum of the estimated returns and spawners to the Northwest Miramichi and Southwest Miramichi for the years 1984 to 2019. A subset of this data, for the period 1984 to 2019, is also considered because the returns prior to 1984 include estimates of harvests in the local commercial fisheries which have more uncertainty for numbers of fish and origin of fish.

The other two time series are the branch specific estimates of returns and spawners to the Northwest Miramichi and Southwest Miramichi for the period 1984 to 2019 (Douglas et al. *in prep.*²).

Considering the combined river and sea age structure of salmon in the Miramichi River, year-class estimates of returns are considered complete for the 1971 to 2013 cohorts.

The Miramichi River has been stocked with salmon of various juvenile stages since the beginning of the operation of a salmonid hatchery in 1873 but the extent of supplementation activities in the Miramichi has varied over time (Douglas et al. *in prep.*²). Since the late 1990s the supplementation activities have been of a scale of less than 200 adult broodstock collected annually, with juvenile stocking in the Miramichi watershed at early stages of several hundred thousand fish per year. Supplementation activities in recent years in the Miramichi River have occurred at similar or reduced levels, however, detailed broodstock collections and juvenile distributions have not been compiled in any published reports. In the years when juveniles were externally marked by ablation of the adipose fin prior to release, the proportions overall to the river of the returning adults that were identified as hatchery origin were generally very low, at less than a few percent, but the proportions of the returns comprised of hatchery origin salmon were higher in particular areas of the river with more intensive tributary specific broodstock collections and juvenile distributions (Douglas et al. *in prep.*²). Based on available information, within the Miramichi 99% or more of returning adults come from wild production (Chaput et al. 2001; Douglas et al. *in prep.*²) and no adjustment to returns was made for the stocking programs (Table 1).

Margaree River

The Margaree River in Cape Breton (NS) is the largest river in SFA 18, is used as an index river for Atlantic Salmon for this area and has published annual estimates of returns since 1984 (DFO 2020a). Between 1987 and 1996 estuarine trap nets were operated to collect biological characteristics of Atlantic Salmon and to conduct a mark and recapture study in the river (LeBlanc et al. 2005; Breau and Chaput 2012). Mark and recapture data are used to model recreational fishery catch rates raised by effort to estimate the exploitation rates. Returns are derived using the estimated annual exploitation rates applied to reported catches in volunteer angler logbooks and fishing license stub reports (Breau and Chaput 2012). For the years prior to 1987, returns were estimated from published angling catches, assuming a 30% exploitation

rate. Angling data are available starting in 1947, although there are gaps in the data for 1958 to 1960 (Claytor et al. 1987).

Atlantic Salmon stocking has taken place on the Margaree over the last century (Marshall 1982). The estimates of total returns were corrected for the proportion hatchery origin salmon to estimate total returns of wild salmon. From 1987-1994, the proportion of hatchery origin salmon in the returns was estimated from the trap net data (Leblanc et al. 2005) and therefore year-specific data are available. For all other years, a mean proportion from those years was used to adjust the returns to only wild salmon.

Spawner abundances for each year were estimated by subtracting the losses from commercial and sport fisheries from returns, including the mortalities associated with catch and release angling. Commercial harvests took place until 1984 when all commercial fisheries for Atlantic Salmon were suspended. Commercial catch data are available starting in 1947: the first three years are extracted from Marshall (1982), May and Lear (1971) report captures from 1950 to 1969, and catches from 1967-1984 are published in Claytor et al. (1987) (Appendix 3). When commercial catch data were available from multiple sources for the same year, the data from the most recent publication were used. To convert the commercial catches reported in weights to number of fish, a mean weight of 5 kg per fish was assumed (Chaput and Jones 1992). Since the commercial fishery included Atlantic Salmon from other rivers in the area, 30% of the catch from SFA 18 was assumed to come from the Margaree River (Chaput and Jones 1992). Salmon removed by sport fishing activities were taken from data published in Claytor et al. (1987) for the period 1947 to 1986, and from the SalmoNS database for 1987 onwards. Until 1978 all recreational fishing catches were considered to have been retained. Retention of large salmon ceased in 1984 (low number reported in 1985), whereas at least some small salmon were retained until 2017 even though the angling regulations stipulated a mandatory catch and release of all salmon beginning in 2015. Catch and release mortality was assumed to be 5% (Daigle 2023). Removals in the Indigenous peoples food, social, and ceremonial (FSC) fishery are not included, as available records are incomplete and FSC removals are generally low in this river (Biron and Breau 2015).

Additionally, although some adult Atlantic Salmon are removed to be used as broodstock for stocking programs every year, these removals were not included in the calculation of spawners because the contemporary numbers are small (approximately 25 pairs), and the source of broodstock in the earlier years is unknown, possibly having been sourced from the commercial fishery or from trapping in the estuary, before the recreational fishery (Marshall 1982).

The abundances of returns and spawners were converted to egg equivalents assuming 6,483 eggs per large fish and 480 eggs per small fish (DFO 2018b). Ages (freshwater and sea ages and spawning history) were estimated from data collected from trapnet samples during 1987-1994 and applied to the time series of returns and spawners to reconstruct abundance by cohorts. Years with less than on average 90% of the cohort reconstructed were excluded from the analysis. The dataset of available cohorts for spawners and returns for analysis includes the years 1947-1951, 1957, and 1961-2013. The continuous 1961-2013 dataset was retained for the Margaree River stock and recruitment analysis.

Reconstructed time series from twelve rivers of the province of Quebec

Reconstructed time series of spawners and returns to twelve rivers of the province of Quebec are provided by the Ministère des Forêts, de la Faune et des Parcs (MFFP; Dionne et al. 2015). These time series are produced for rivers with reliable information on adult return and spawner abundances, age frequency (from scale interpretation), sex ratio, average weight per age group, hatchery stocking activities, and various captures (i.e. commercial fishery, Indigenous harvests, and angling, Table 1). Data are available for the 1972 to 2005 cohorts for most of the rivers

except for the Jupiter and Chaloupe Rivers for which the time series starts in 1983 and 1984, respectively. A more detailed description of these data is provided in Dionne et al. (2015).

Stock and Recruitment Analyses

The reconstructed time series of spawners and recruits by year class (year of egg deposition) were fitted to Ricker (Eq. 1) and Beverton-Holt (Eq. 2) stock and recruitment functions (Hilborn and Walters 1992).

$$R = \alpha \cdot S \cdot e^{-\beta \cdot S} \quad (1)$$

$$R = \frac{\alpha S}{1 + \beta S} \quad (2)$$

Where R is the recruitment (expressed as the eggs in the number of returning adults), S is spawners (expressed as the eggs in the number of adult spawners), α is a measure of productivity and represents the slope at the origin, and

$1/\beta$ is the number of spawners (S_{max}) generating the maximum number of adult returns (R_{max}) for the Ricker equation (1), and

α/β is the maximum recruitment (R_{max}) for the BH equation (2).

The parameterisations of Schnute and Kronlund (1996) were used to fit these stock and recruitment functions with corresponding transition equations to derive the reference points of interest (Appendix 5). The equations of Schnute and Kronlund (1996) relate two management parameters, h^* and S^* , to α and β (Appendix 5) with h^* the equilibrium harvest rate at maximum sustainable yield and S^* the equilibrium number of spawners that allows the equilibrium catch (C^*) at maximum sustainable yield ($C^* = \frac{h^* \cdot S^*}{(1-h^*)}$).

For each year t and river i , the stock and recruitment equation (1, 2) is:

$$R_{t,i} | \mu_{t,i}, \tau_i \sim \text{LogNormal}(\text{Log}(\mu_{t,i}), \tau_i) \quad (3)$$

with

$\tau_i = 1/\sigma_i^2$ the precision, and

$$\text{Log}(\mu_{t,i}) = \text{Log}(S_{t,i}) + h_i^* - \text{Log}(1 - h_i^*) - \frac{h_i^*}{S_i^*} S_{t,i} \quad (4)$$

expressed in terms of management parameters h^* and S^* for the Ricker equation (1), and

$$\text{Log}(\mu_{t,i}) = \text{Log}(S_{t,i}) + \text{Log}\left(\frac{1}{(1-h_i^*)^2}\right) - \text{Log}\left(1 + \frac{h_i^*}{(1-h_i^*) \frac{h_i^*}{S_i^*}} S_{t,i}\right) \quad (5)$$

expressed similarly in management parameters for the BH equation (2).

Fitting was initially done independently for each river.

A hierarchical framework that combined the time series of the Miramichi River, the Margaree River and ten rivers of Quebec was also examined. The hierarchical analysis described in Dionne et al. (2015) was revisited and the following changes were made to the data series analyzed and to the hierarchical model (Appendix 4):

The units of production metric used to quantify the favorable salmon habitat available in a river by Dionne et al. (2015) was replaced with the wetted area of the river, unadjusted for habitat

type and quality, because the units of production were not available for the Miramichi and Margaree rivers.

To consider similar marine environmental conditions across the river time series, the time series of data for the Miramichi and Margaree rivers were restricted to the cohort years corresponding to the reconstructed time series of the Quebec rivers (1972 to 2005; Table 1). Two rivers with the shorter time series (Jupiter, Chaloupe) beginning in 1984-1985 were excluded from this analysis.

We only fitted the Ricker model because of difficulties in obtaining converged values for h^* with the BH model.

Some minor changes in hierarchical structure and priors from Dionne et al. (2015) were applied. Most importantly, a hierarchical structure was placed on the precision (τ_i) of the return abundances, on h_i^* , and S_i^* with the latter linked to the wetted area of each river through a linear relationship (log scale).

For the precision, $\tau_i \sim \text{Gamma}(\alpha^\tau, \beta^\tau)$

with τ_i the precision for each river,

$$\alpha^\tau = \mu^\tau \times \beta^\tau,$$

$$\mu^\tau \sim \text{Gamma}(1, 0.01) \text{ and}$$

$$\beta^\tau \sim \text{Gamma}(0.01, 0.01).$$

The hierarchical structure on h_i^* was identical to that used in Dionne et al. (2015), with the river specific exploitation rate (h_i^*) modelled on the logit scale with inverse gamma hierarchical priors for the mean and precision:

$$\text{logit}(h_i^*) = \text{logit}.h_i^*$$

with $\text{logit}.h_i^* \sim \text{Normal}(u.\text{logit}.h^*, \tau.\text{logit}.h^*)$,

$$u.\text{logit}.h^* \sim \text{Normal}(0, 0.01), \text{ and}$$

$$\tau.\text{logit}.h^* \sim \text{Gamma}(0.1, 0.1).$$

A hierarchical structure on S_i^* was implemented, linked to the wetted area of the rivers through a linear relationship (log scale). In Dionne et al. (2015) the covariate used is a metric of salmon habitat productivity (UP) which is strongly correlated with the wetted area. Since this metric was not available for the two Gulf rivers, the metric of river size used was the wetted fluvial area.

$$S_i^* | \mu_i^{S^*}, \tau^{S^*} \sim \text{LogNormal}(\text{Log}(\mu_i^{S^*}), \tau^{S^*})$$

with $\text{Log}(\mu_i^{S^*}) = \alpha \cdot \text{Log}.WA'_i + \beta$

and priors on α and β of:

$$\alpha \sim \text{Normal}(0, 0.01) \text{ and}$$

$$\beta \sim \text{Normal}(0, 0.01).$$

$\text{Log}.WA'_i$ represents the mean centered wetted area of the river:

$$\text{Log}.WA'_i = \text{Log}(WA_i) - \text{mean}(\text{Log}(WA)).$$

The stock and recruitment functions were fitted in a Bayesian framework and Monte Carlo Markov Chain (MCMC) sampling was done using JAGS 4.3.0 (Plummer 2017) called from the package R2jags in R 4.0.4 (R Core Team 2021; Su and Yajima 2020). Two chains were used

with an initial burn-in period of 10^4 iterations and followed by an additional 5×10^5 iterations from which every 100th MCMC sample was retained to reduce autocorrelation. In total 10^4 iterations were kept to generate posterior distributions. Convergence was assessed by inspecting MCMC chains visually to insure that good mixing was achieved.

Results

Independent fits

The stock and recruitment analysis results are presented in Appendix 2 for the Miramichi River, Appendix 3 for the Margaree River, and Appendix 4 for the twelve rivers of Quebec. The results are summarized in a series of five panels for each of the Beverton-Holt and Ricker fits:

- one panel showing the scatter plot of eggs in spawners versus eggs in returns by year-class with superimposed median and percentiles (25th to 75th percentile, 5th to 95th percentile) polygons of the predicted eggs in returns;
- boxplots of the log(residuals) from the model fits, with linear trend line and associated p-value for the slope;
- boxplots of reference values based on the fitted parameters,
- boxplots of the posterior values of the exploitation rates for select reference values, and $\log(\sigma)$, and
- boxplots of the ratios of R^* to three candidate LRP values.

The reference values from the independent fits of the stock and recruitment functions are summarized for the Beverton-Holt fits (Table 3a) and the Ricker fits (Table 3b).

Miramichi River

The reconstructed time series for the Miramichi River extending from the 1971 to 2013 cohorts clearly shows a non-stationary pattern of relative recruitment, with high recruitment rates at the start of the time series (1971 to 1983) and lower recruitment rates since the early 1990s (Appendix 2 Figures A2.2 and A2.3). There is a significant linear declining trend in the median of the residuals for both the BH and Ricker fits. The posterior values of the $S_{\text{halfRmax@75}}$ are substantially lower than the LRP defined for the Miramichi River (160 eggs per 100 m²) based on the egg to smolt model (Tables 3a, 4a; Appendix 2 Figures A2.2 and A2.3). As is generally the case, the estimated slope at the origin is much steeper for the BH function than the Ricker function, reflected in the much higher h^* value of 0.82 for the BH function compared to 0.51 for the Ricker function (Tables 3b, 4b). The ratio of R^* to $S_{\text{halfRmax@75}}$ for the BH fit is 13.3 in contrast to just under 3.0 for the Ricker fit (Tables 3b, 4b).

Considering the significant temporal pattern in the residuals, a second analysis using a shorter time series beginning in 1984, after the closure of the commercial fishery, was examined. The linear trend in the residual pattern remained with reference values substantially different from those of the longer time series. Specifically, $S_{\text{halfRmax@75}}$ from the BH fit (median of 142 eggs per 100 m²) and the Ricker fit (median of 120 eggs per 100 m²) are both lower than the defined LRP (160 eggs per 100 m²; Tables 2a, 3a; Appendix 2 Figures A2.4 and A2.5). The posterior values of R^* (median values of 155 and 154 eggs per 100 m² for BH and Ricker respectively) were just below the defined LRP and the ratio of R^* to $S_{\text{halfRmax@75}}$ was just over 1 for the BH fit, and 1.3 for the Ricker fit (Tables 2b, 3b).

The branch specific reconstructed time series for 1984 to 2013 also show significant linear trends in residuals, lower reference values of $S_{\text{halfRmax@75}}$ than the defined LRPs, but higher h^* values and consequently higher R^* to $S_{\text{halfRmax@75}}$ values than for the Miramichi

River overall (Tables 2, 3; Appendix 2 Figures A2.7-10). For both the Northwest Miramichi and Southwest Miramichi, the R^* values are essentially similar to the LRP defined for the rivers. In these cases, the R^* values would not be appropriate USR values defining a healthy status.

The egg to egg reconstructed time series for the Miramichi River and for each of the Northwest Miramichi and Southwest Miramichi branches indicate a stock which currently (since 1984) is of low productivity with recruitment equal to or slightly higher than the parental stock size of spawners, and this for years when spawners are varying below and above the LRP (Appendix 2 Figures A2.1 and A2.6). In the more recent years since 2007, the recruitment rate for the Southwest Miramichi has generally been below one, i.e. recruitment is less than the parental spawning stock for the cohort (Appendix 2 Figure A2.6). The pattern is less pessimistic for the Northwest Miramichi but for this river spawning escapements in the last decade have most frequently been at or below the LRP (Appendix 2 Figure A2.6).

Margaree River

The reconstructed time series for the Margaree River, extending from the 1961 to 2013 cohorts, shows low levels of spawners and adult returns during the earlier part of the time series (1961 to early 80s), followed by several years of high recruitments (1981 to 1985), with higher levels of spawners and adult returns for the remainder of the time series (1986 to 2013; Appendix 3 Figures A3.1 and A3.2). There was no significant linear trend in the median of the residuals of the BH and Ricker fits. Unlike the Miramichi River, the estimated slope for both BH and Ricker fits were similar, with h^* of 0.62 for the BH fit and 0.56 for the Ricker fit (Tables 2, 3).

The posterior distributions of $S_{\text{halfRmax@75}}$ from the BH and Ricker fits overlap the defined LRP for the Margaree River; median for $S_{\text{halfRmax@75}}$ of 167 and 157 eggs per 100 m², respectively (Tables 2a, 3a) versus the LRP value of 152 eggs per 100 m² (DFO 2018b). We could define R^* directly from these data at a value of 410 eggs per 100 m² from the BH and 589 eggs per 100 m² from the Ricker (Tables 2a, 3a). The ratios of R^* to $S_{\text{halfRmax@75}}$ are 2.45 for the BH fit and 3.74 for the Ricker fit (Tables 2b, 3b).

Twelve rivers of the province of Quebec

The reconstructed time series for the Quebec Rivers encompass the 1972 to 2005 cohorts and show a variety of patterns in both relative stock and recruitment. The reconstructed time series of most rivers show a high recruitment period at least once in the time-series and most frequently during the mid-80's (See Appendix 4 Figures for e.g. River Bonaventure, de la Trinité, York). Statistically significant declining linear trends in the median of the residuals for both the BH and Ricker model fits are noted for the Matane, Saint-Jean and de la Trinité rivers. In addition, the time series fits of most rivers show oscillating patterns in the residuals suggesting that the annual observations are not independent (i.e. autocorrelated). This raises questions on our understanding of the biological processes and population dynamics operating in these rivers that could explain these patterns, for instance cohort links during freshwater or marine migration.

For the majority of Quebec Rivers, the estimated slope at the origin is steeper for the BH function than the Ricker function, reflected in the higher h^* value for the BH function (0.75 on average) compared to the Ricker function (0.55 on average, Tables 2b, 3b). Compared to similar values of LRP as the ones used in the Gulf rivers (i.e. about 150 eggs per 100 m²), the posterior values of S_{halfRmax} are substantially lower than the LRP value (Appendix 4). The ratios of R^* to $S_{\text{halfRmax@75}}$ for the BH are extremely variable among rivers, ranging from 0.26 to 22.77 (Table 2b). The ratios from the Ricker fits are also variable but encompass a smaller range, from a low of 0.5 to a high of 6.48 (Table 3b). The Chaloupe River has a ratio less than one (i.e. R^* is lower than $S_{\text{halfRmax@75}}$) due in large part to the poor fit of the

model to the data for this particular river (Appendix 4A, Figure A4.A.3 ; Appendix 4B Figure A4.B.3).

Hierarchical modelling of similar period time series

Stock and recruitment data for the Miramichi River, Margaree River and ten of the twelve rivers of Quebec were analyzed with a hierarchical model. The time series of data for these rivers extend from the 1972 to 2004/2005 cohorts. The predicted fits (median line and Bayesian credible interval envelopes) for the twelve rivers are shown in Figure 4. The linear association (on the log scale) of S^* to wetted area is significant with a coefficient for the wetted area that encompasses a value of 1 (median = 1.11, 95% C.I. 0.86 to 1.39), indicating a direct scaling of S^* to the size of the river (Figure 5).

The shrinkage of the posterior estimates of h^* , S^* , and R^* from the hierarchical model relative to the independent model is most important for h^* and less visible for S^* and R^* (Figure 5). Whereas median estimates of h^* range from 0.49 to 0.68 for the independent model fits, the hierarchical model median estimates range from 0.58 to 0.62 (Table 5b; Figure 4). Shrinkages of the ratios of R^*/S^* , $R^*/S_{\text{halfRmax@75}}$, and $80\%R^*/S_{\text{halfRmax@75}}$ are also noted with the hierarchical model (Figure 6). The credible interval estimates for the river-specific ratio are relatively wide and overlap across the twelve rivers (Figure 6).

The estimates of R^* range between 146 and 667 eggs per 100 m² for the twelve rivers, a factor of 4.6, with the lowest value for the Madeleine River and the highest value for the Margaree River (Table 4a). The ratios of R^* to $S_{\text{halfRmax@75}}$ range from 3.84 to 5.41, a factor of 1.4, with the lowest value estimated for de la Trinite River and the highest value for the York River (Table 4b). The posterior medians of $80\%R^*/S_{\text{halfRmax@75}}$ over the twelve rivers in the hierarchical model range from 3.07 to 4.33, also a factor of 1.4 (Table 4b).

REFERENCE POINTS FOR ATLANTIC SALMON RIVERS OF DFO GULF REGION

The river-specific USR is calculated as the product of the ratio of $80\%R^*/S_{\text{halfRmax@75}}$ and the defined LRPs for the rivers of the DFO Gulf Region. This ratio of 3.78 is the mean of the values of the twelve rivers from the hierarchical model.

The TR is defined as the product of the ratio of $R^*/S_{\text{halfRmax@75}}$ and the defined LRPs for the rivers of the DFO Gulf Region. This ratio of 4.73 is the mean of the values of the twelve rivers from the hierarchical model.

The maximum removal rate in the healthy zone is set at $h^* \left(\frac{R^* - S^*}{R^*} \right)$, a similar value for all rivers. As the proposed TR (R^*) is a value corresponding to the maximum sustainable yield, the removal rate should be the value that results in maximum sustainable yield when the abundance is at R^* . From the hierarchical model fit of the twelve rivers, the mean value of $h^* = 0.60$ (Figure 5).

The PA graph with the LRP, USR, TR, and removal rate values for DFO Gulf Region rivers is shown in Figure 7. The total eggs equivalent to the LRP, USR, and TR for rivers of DFO Gulf Region are provided in Appendix 6.

For illustration, the time series of annual estimated eggs in the returns and the annual percentage of the eggs lost by fishing for the Miramichi River and for each of the Northwest Miramichi and Southwest Miramichi rivers are shown on a PA diagram with the associated LRP, USR, TR and RR reference points (Figure 8). The total eggs in returns of Atlantic Salmon to the Miramichi River were proximate to or just above the USR in two years (1974, 1977) and were below the LRP in three years (post 2014) of the assessment history 1971 to 2019 (Figure 8). The proportion of eggs lost by fishing exceeded the defined RR reference in 1971 and 1983 and

would likely be above the harvest decision rule in the cautious zone through most of the 1970s and since the 2000s. Loss rates of 1.4% to 2.9% were estimated for the three years when the point estimates of eggs in the returns before fishing were below the LRP (Figure 8).

Over the shorter history of assessment (1984 to 2019) for the Northwest Miramichi and Southwest Miramichi rivers, the abundances have never been at or above the USR, have been generally declining in the cautious zone, and were below the LRP in four years (since 2014) for the Northwest Miramichi and in two years (2014, 2019) for the Southwest Miramichi (Figure 8). The percentages of eggs lost by fishing have been higher in the Northwest Miramichi (max. of 32% in 2002) compared to the Southwest Miramichi (max. of 13.8% in 1984). The percentages of eggs lost frequently exceeded the levels prescribed by the illustrative harvest decision rule (Figure 8) in the Northwest Miramichi and less often in the Southwest Miramichi. The percentages of eggs lost when the abundance before fishing was below the LRP ranged from 1.6% to 4.9% in the Northwest Miramichi, 1.3% and 2.2% for the two years in the Southwest Miramichi.

The time series profile of abundances before fishing and eggs lost due to fishing for the Margaree River are very different from the Miramichi. Based on the eggs in total returns (wild and hatchery returns) before fishing, reconstructed for the stock and recruitment analysis, the abundances were low prior to 1986, with two years below the LRP, but increased and have been in the cautious zone or frequently in the healthy zone for the period 1985 to 2019 (Figure 9). The estimated percentages of eggs lost by fishing exceeded the RR prior to 1985, when the estimated abundances were low and in the cautious zone. The percentages of eggs lost by fishing have ranged from 1% to 5% during 1986 to 2019 (Figure 9).

UNCERTAINTIES

Uncertainties in these analyses arise from the reconstruction of time series of abundances, from incomplete accounting of fisheries activities, from the assumptions associated with model fitting, and from variations in life history characteristics and population dynamics resultant of the two environments occupied in the anadromous Atlantic Salmon life cycle.

In all the time series reconstructions, a number of simplifying assumptions were made to translate harvest weight in commercial fisheries to harvest by number, to estimate abundances by age class, and in the biological characteristics of the anadromous salmon. The most completely sampled time series of the Miramichi River contained gaps in sampling in certain years. For all rivers, no commercial fisheries samples were available. Using average values, such as the proportions at age, to estimate abundances of cohorts may result in auto-correlation in the returns and spawners data. The simplifying assumptions that the age, size, and sex ratios of the fisheries harvests and in many cases of returns were similar to average values based on available samples is a necessary compromise that would be expected to reduce the inter-annual variance of the estimated abundances.

Harvests of Atlantic Salmon in marine commercial salmon fisheries in Newfoundland and Labrador, in the historical and contemporary fisheries of Saint-Pierre and Miquelon, and at West Greenland are not accounted for. Atlantic Salmon from all rivers of DFO Gulf Region and the province of Quebec were historically exploited in these marine fisheries (Saunders 1969; Paloheimo and Elson 1974; Marshall 1982; Bradbury et al. 2016a, 2016b) and recent genetic analyses of fisheries samples from the West Greenland fishery show that salmon from the province of Quebec and rivers in DFO Gulf Region comprise important proportions (>15% each) of the sampled catches (ICES 2020a). The fish harvested at Greenland at the one-sea-winter non-maturing stage would be destined to become two-sea-winter salmon had they not been harvested and had survived the return to homewaters, a survival rate assumed to be in the

order of 72% (ICES 2020a). The exclusion of the harvests of these large salmon at Greenland and the historical catches in the Newfoundland and Labrador commercial fisheries results in an underestimation of the returns of cohorts, thus negatively biasing the estimates of R^* , R_{max} , and in turn estimates of S^* and h^* . The reference points USR and TR are underestimated and as noted from the simulation of reference points versus sea survival rates, the ratios to scale the USR from the LRP would be higher if these fisheries removals were accounted for. As the intensity of the fisheries have declined at West Greenland, and closed in Newfoundland in 1992 and in Labrador in 1998, the declining trend in productivity noted for the Miramichi and some rivers of Quebec when these fisheries harvests are ignored would be more important if the harvests had been accounted for. However, since these fisheries are now either closed or reduced in intensity, the consequences to abundance and status in recent years are of lesser concern.

Point estimates of angling catches, biological characteristics, and modelled assessments of abundance are used to reconstruct the returns and spawners time series and these are treated as true values. Ignoring uncertainties of the reconstruction steps is expected to reduce the uncertainties of the model parameters and calculated reference points. Incorporating uncertainties in all the components would require a more complex state-space life cycle modelling approach (e.g. Ohlberger et al. 2019) which we were unable to do at this time.

Spawner estimates in some cases may be overestimated because not all inriver harvests are accounted for. For the Miramichi, because of the absence of a catch reporting system for recreational fisheries in NB, assumptions were made regarding the annual recreational fisheries exploitation rate of small salmon and large salmon from a historical period 1984 to 1997 and applied these to estimate the fisheries catches for 1998 to the present. Combined with the assumption on catch and release mortality, the losses from recreational fishing are quite uncertain. This is also the case for the Margaree where although a catch reporting system is in place, the return rate of catch and effort declarations has been decreasing over time and total catches are estimated by raising the voluntarily returned reports to all licences sold (Daigle 2023). Mandatory catch and release measures of large salmon have been in effect in DFO Gulf Region since 1984 and as a result the magnitude of the loss of eggs is much less uncertain, even with an error in the catch and release mortality rate, than if retention of large salmon had been allowed. Indigenous peoples fisheries harvests are also underreported although with declines in abundance of salmon generally and corresponding Indigenous governance decisions to reduce the harvest of salmon by their communities, the overestimation of spawner abundances is considered to be small.

Broodstock collections and hatchery stocking have occurred in the Miramichi River and the Margaree River since the late 1800s. The intensity of stocking, the sources of broodstock and fish stocked, and the purposes of the programs have varied over time (Marshall 1982; Daigle 2023; Douglas et al. *in prep.*²). The broodstock collections from these two rivers over the period 1971 to 2019 have been relatively modest for the size of the river, a few hundred broodstock from the Miramichi, a few dozen pairs from the Margaree. The broodstock collections were not removed from the estimates of spawners because records of annual broodstock removals were not accessible and were considered to represent a small proportion (<5%) relative to wild spawners. Not removing the hatchery broodstock collection from the estimates of spawners results in an overestimate of the spawners in the wild, but the bias is assumed to be small.

Varying proportions of the juvenile salmon progeny are marked prior to release to the wild. Failure to account for these hatchery origin fish in the returning adults would positively bias the productivity (h^*) and the carrying capacity estimates (R^* , R_{max}) from the stock and recruitment fits. For the rivers of Quebec, adjustments for hatchery stocking were made to the data (Dionne et al. 2015). The proportions hatchery origin fish in the total returns in the Miramichi River were

low in the assessed years when hatchery origin fish could be identified by an external mark (Chaput et al. 2016). For the Margaree, the estimated total returns were adjusted for the proportion wild fish based on sampling when reconstructing the data stream for the stock and recruitment analysis. The level of stocking and the contribution of hatchery returns to total returns is considered low for the Miramichi and Margaree particularly for large salmon, the major contributor to eggs in returns (> 90% of eggs from large salmon in SW Miramichi and Margaree, >75% for NW Miramichi).

Hilborn and Walters (1992) and Walters and Korman (2001) emphasize a number of biases and pitfalls associated with stock and recruitment analyses. The two of most concern to us are the errors-in-variables bias and the time series bias. The errors in the reconstruction of spawners and returns are ignored and the poor fit may in part be attributed to errors in the assessment. The estimates of spawners and returns are not independent, with spawners being calculated directly from returns and removals. Independence of the time series of observations cannot be assumed, i.e. respecting the condition that the errors are independent and identically distributed. This absence of independence is in part the result of the reconstruction of the data, the age lag used to attribute fish to their year-class, and the non-independent processes in nature acting on several cohorts of fish at similar times. In their own example analysis, Walters and Korman (2001) comment that it is more appropriate to think of the Margaree stock and recruitment data as having only three rather than 38 observations, an early period with moderate or high spawning stock, a middle period with mainly low spawning stocks, and a late period with high spawning stocks. The false assumption of independence leads to more confident assessments than the data would justify (Walters and Korman 2001).

In at least four rivers in the hierarchical analysis, the temporal trends in residuals can be interpreted as evidence of a change in productivity, which is considered to be occurring in the marine environment. This interpretation is supported by evidence from monitored rivers of declines in return rates from smolts to adults (ICES 2020a). The change in productivity has been noted in a relatively short time series of a few decades (1971 to 2004), has been assessed as occurring rapidly over a few years (Chaput et al. 2005; Olmos et al. 2020), and we are loathe to subset the time series into smaller units of possibly homogeneous productivity conditions given the challenge of fitting these stock and recruitment models to data sets with little contrast in abundance. Including periods of high productivity and low productivity in a joint analysis results in parameter estimates that are averaged over these productivity states, neither high nor low. This may not be an acceptable compromise if the perceived trend in productivity was from a low to a high condition since the derived parameters would underestimate key reference values to protect the population (LRP) and to benefit fisheries (R^* , R_{max} , h^*). For Atlantic Salmon in eastern Canada, it is the opposite situation with productivity declining. As a result the estimated reference values are higher than those which we would calculate using only the more contemporary data from the recent time period of low productivity. If only the more contemporary data were used, we would risk underestimating the LRP and unduly increase the risk to the population. We have not concluded that the factors acting after the smolt stage that are considered to be driving the reduced productivity of salmon at sea are irreversible and we prefer to set the fisheries benefits indicators (USR, TR) by including data from the higher productivity period with the expectation that the overall abundance of salmon has the potential to increase from current low levels. This approach is consistent with reviews and conclusions of DFO (2013, 2016) that reference points should not be changed due to changes in productivity but rather to adapt robust control rules for the changed conditions.

CONCLUSIONS

The analyses presented in this paper, with those of DFO (2018b), complete the first component of the PA framework that require defining reference points to delineate critical, cautious and healthy zones. DFO (2018b) provides the river-specific LRPs for the Atlantic Salmon rivers of DFO Gulf Region. A ratio approach of USR or TR to LRP references derived from adult to adult stock and recruitment data analyses is proposed to define the USR, TR references. The ratio approach is proposed because the LRPs are defined using the life stage and dynamics restricted to the freshwater phase of the anadromous life cycle, the phase where density dependent compensatory survival is expressed (DFO 2015), whereas USR and TR references are intended to identify desired states of abundance of the adult components with associated fisheries benefits. The calculated ratios represent the spread between the LRP and the USR or TR obtained from adult to adult stock and recruitment data which are then applied to the defined LRP based on the freshwater stage.

The LRP, USR, and TR reference points are defined for each river known or assumed to have an anadromous salmon run. The reference points are expressed in units of eggs contributed by all anadromous sea age and size groups. Scaling the total eggs in the returns and spawners as well as the reference points by the size of the rivers, defined as the total wetted fluvial area used by salmon, is a convenient way to compare the status of different sized rivers and salmon populations.

Using ratios of USR or TR to LRP estimated from analyses of adult data does not eliminate the problem that reference points scale to marine survival conditions in anadromous Atlantic Salmon. Marine survival is considered to be density independent and the main determinant of anadromous adult abundance once the freshwater output is set (Hansen and Quinn 1998). The ratios are estimated using stock and recruitment data considered to be representative of anadromous salmon populations in DFO Gulf Region. We collectively analyzed data from two rivers in the Gulf and ten rivers from the province of Quebec that are geographically proximate and have similar biological characteristics to the Gulf rivers, primarily the high proportion of total eggs contributed by large salmon. The hierarchical Bayesian analysis of these twelve rivers provides relatively similar ratios of USR and TR to LRP among the rivers and we use the average of the values over the twelve rivers to derive the USR and TR for the DFO Gulf rivers.

The USR to LRP ratio has an average 3.78 while the TR to LRP ratio has an average of 4.73. The boundary of the cautious / healthy zones is approximately four times higher than the boundary of the critical and cautious zones. This spread should provide ample time for management response to reduce exploitation rate when stock abundance declines and take action to move the stock toward the healthy zone (DFO 2009).

The removal rate equivalent to h^* , that results in maximum sustained yield (MSY) when the recruitment is at MSY, is very similar among the rivers, with a mean value of 0.60. This is proposed as the RR reference for all the rivers.

At those reference values, the Miramichi River anadromous salmon returns may have been at or just above the USR in only 2 of 49 years during the period of 1971 to 2019, and below the LRP (point estimate) in two of those years. The estimated total eggs in the returns to the Miramichi River have declined 57% over the 1971 to 2019 period, whereas the estimated eggs in spawners have declined less, 16% over the same period. The closure of the commercial fishery and the introduction of mandatory catch and release measures for large salmon in the recreational fishery in 1984, combined with more restrictive management measures in the last decades have reduced the losses of spawners, but the decline persists. Under the current low productivity conditions in both freshwater and in the marine phase, the recruitment before fishing is approximately sufficient to replace the spawners but there is limited to no opportunity

for rebuilding. Without several very good recruitment events and improved marine survival rates, the Miramichi River and its two main branches are not expected to attain abundances that would surpass the USR in the near future.

The status of the Margaree River relative to the reference values is quite different from the Miramichi and its tributaries. With the exception of the 1970s to early 1980s, the recruitment is estimated to have increased substantially and in most years post 1985, the abundance is situated in the cautious and healthy zones.

When assessing status of the rivers relative to these reference values, guidance from DFO (2021a, 2021b) is relevant. DFO (2021a) considers the LRP and USR to be threshold reference points that are intended to be exceeded greater than 50% of the time. This contrasts with the TR which is considered a target and intended to be met on average, or 50% of the time (DFO 2021a).

DFO (2021a) re-emphasizes the role and consequence of being below the LRP:

“A stock that persists near a LRP is more likely to lead to a situation that triggers the need for a rebuilding plan, ... possibly also incurring irreversible or only slowly-reversible serious harm. At the very least, stock biomass near a LRP may represent a loss of maneuvering room for decision-makers, loss of benefits to resource users, and potential risks to both ecosystem function and fisheries on coincident stocks.”

Subsequently, DFO (2021b) emphasized:

“the LRP represents a biological threshold to possible serious harm, below which rebuilding prospects are uncertain, and as such declines of the stock to or below its LRP should be avoided”.

In DFO (2009), the LRP was considered to be a threshold to be avoided and since the LRP defines a point below which there is an increasing chance of serious and irreversible harm, it could be interpreted as a point to be avoided with high probability, as for example 95% chance of being above the LRP. DFO (2021a) states that science guidelines should establish consistency in the way that stock status is determined and reported relative to the LRP but does not specify a probability level. In turn, DFO (2021b) states:

“Unless otherwise defined in stock-specific precautionary approach frameworks, as general guidance, the LRP should be considered breached if the terminal year stock status indicator is estimated to be at or below the LRP with a greater than 50% probability or if the projected stock status indicator falls below the LRP with a greater than 50% probability under a zero catch scenario in a one year projection.”

In previous stock status reports of Atlantic Salmon in eastern Canada, the status has generally been reported as being above or below the LRP (DFO 2020a, 2020b) and more recently as above or below the USR for stocks of Newfoundland and Labrador (DFO 2020c). These assessments of status were made based on the midpoint of the estimated abundance. DFO (2020a) provides a table for the Miramichi River that quantifies the estimates (median with 5th to 95th percentile range) of the eggs in returns before fishing, eggs in spawners, and the probability of the eggs in spawners being below the LRP. A companion figure for the Miramichi summarizes the time series of assessments using shaded symbols to distinguish when the 5th percentile of the estimated eggs exceeded the LRP or was below the LRP. A similar summary is presented in Figure 10 for the estimates of eggs in returns and eggs in spawners for the Northwest and Southwest Miramichi rivers, 1984 to 2019. Whether such a presentation of

status relative to the LRP is useful for management and decision makers is unknown, but as a minimum such summary figures can be produced for the assessments where uncertainty has been quantified and this would address the advice in DFO (2021a, 2021b).

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TABLES

Table 1. Description of rivers and reconstructed time series of Atlantic Salmon spawners and returns used in the development of reference points for DFO Gulf Region rivers.

Province	River	Reconstructed year-classes	Wetted area (1000 m ²)	Accounting for			
				Marine fisheries removals (Greenland, Newfoundland, Labrador, SPM)	Local coastal commercial fishery harvests	Indigenous and recreational fisheries	Hatchery stocking
Nova Scotia	Margaree	1961 to 2013	2,798	No	Yes	Yes	Yes
New Brunswick	Miramichi	1971 to 2013	53,433	No	Yes	Yes	No
	Northwest Miramichi	1984 to 2013	16,779	No	NA	Yes	No
	Southwest Miramichi	1984 to 2013	36,654	No	NA	Yes	No
Quebec	York	1972-2004	2,591	No	NA	Yes (2003 - 2012)	Yes (2003 - 2012)
	Dartmouth	1972-2004	1,758	No	NA	Yes (2009-2012)	Yes (2009-2012)
	Bonaventure	1972-2004	4,361	No	Yes (1976)	NA	NA
	Cascapedia	1972-2003	4,797	No	Yes (1973 - 1976)	Yes (1972 - 2008)	Yes (1972 - 2008)
	Grande-Riviere	1972-2004	1,144	No	NA	NA	NA
	Sainte-Anne	1973-2005	1,331	No	NA	NA	NA
	Madeleine	1972-2005	2,814	No	NA	NA	NA

Province	River	Reconstructed year-classes	Wetted area (1000 m ²)	Accounting for			
				Marine fisheries removals (Greenland, Newfoundland, Labrador, SPM)	Local coastal commercial fishery harvests	Indigenous and recreational fisheries	Hatchery stocking
	Matane	1972-2005	3,357	No	NA	NA	NA
	Jupiter	1983-2005	2,303	No	NA	NA	NA
	Chaloupe	1984-2005	546	No	NA	NA	NA
	Saint-Jean	1972-2005	2,251	No	NA	NA	NA
	de la Trinite	1976-2005	1,916	No	Yes (1976-1992)	NA	NA

Table 2a. Summary (median with 25th to 75th percentiles range) of the abundance reference values (eggs per 100 m²) from independently fitting the Beverton-Holt function to the reconstructed egg to egg time series by river.

River (time period)	Abundance reference values (eggs per 100 m ²)						
	C*	R*	Rmax	Srep	S*	S_halfRmax @50	S_halfRmax @75
Gulf Region rivers							
Margaree River (1961 – 2013)	253 (239 - 268)	410 (393 - 430)	666 (627 - 708)	567 (541 - 597)	157 (146 - 170)	98 (83 - 115)	167 (142 - 199)
Miramichi River (1971 – 2013)	185 (160– 211)	227 (213 – 241)	280 (266 – 296)	268 (258 – 280)	41 (28 – 55)	10 (4 – 19)	17 (7 – 34)
Miramichi River (1984 – 2013)	73 (51 – 103)	155 (140 – 171)	323 (276 – 393)	232 (220 – 244)	79 (66 – 89)	91 (44 – 161)	142 (70 – 250)
Northwest Miramichi River (1984 – 2013)	94 (72 – 122)	165 (151 – 180)	284 (255 – 328)	232 (221 – 244)	68 (55 – 81)	52 (25 – 92)	83 (40 – 147)
Southwest Miramichi River (1984 – 2013)	98 (71 – 132)	165 (148 – 182)	272 (247 – 314)	227 (217 – 238)	64 (49 – 77)	44 (19 – 86)	69 (29 – 137)
Quebec rivers							
York 1972 - 2004	228 (209 - 249)	285 (276 - 295)	353 (338 - 371)	339 (330 - 351)	55 (42 - 69)	14 (7 - 23)	18 (9 - 30)
Dartmouth 1972 - 2004	160 (140 - 183)	202 (192 - 214)	254 (240 - 272)	243 (233 - 254)	41 (27 - 54)	11 (5 - 20)	17 (7 - 33)
Bonaventure 1972 - 2004	168 (149 - 186)	197 (187 - 208)	233 (223 - 246)	227 (218 - 237)	29 (20 - 40)	5 (2 - 11)	9 (4 - 18)
Cascapedia 1972 - 2003	273 (242 - 305)	331 (316 - 346)	399 (381 - 423)	387 (373 - 402)	56 (37 - 75)	11 (5 - 23)	16 (7 - 34)
Grande- Riviere 1972 - 2004	124 (110 - 140)	158 (150 - 167)	201 (189 - 216)	191 (183 - 201)	34 (24 - 40)	10 (4 - 17)	16 (8 - 29)
Sainte-Anne 1973 - 2005	155 (139 - 173)	189 (178 - 201)	230 (216 - 247)	222 (210 - 235)	33 (23 - 43)	8 (4 - 14)	14 (7 - 28)
Madeleine 1972 - 2005	84 (72 - 98)	120 (113 - 127)	168 (156 - 185)	154 (147 - 161)	35 (26 - 43)	15 (7 - 26)	24 (12 - 42)

Abundance reference values (eggs per 100 m²)

River (time period)	C*	R*	Rmax	Srep	S*	S_halfRmax @50	S_halfRmax @75
Matane 1972 - 2005	169 (153 - 189)	241 (233 - 250)	335 (312 - 365)	307 (294 - 323)	69 (54 - 82)	28 (16 - 44)	39 (22 - 61)
Jupiter 1983 - 2005	42 (34 - 52)	72 (67 - 78)	122 (110 - 139)	101 (96 - 107)	29 (24 - 34)	21 (11 - 35)	34 (18 - 57)
Chaloupe 1984 - 2005	62 (41 - 88)	107 (87 - 129)	187 (158 - 228)	149 (127 - 173)	42 (32 - 52)	35 (15 - 66)	343 (124 - 1435)
Saint-Jean 1972 - 2005	154 (134 - 174)	188 (177 - 199)	229 (218 - 243)	221 (212 - 231)	33 (23 - 44)	8 (3 - 15)	24 (12 - 75)
de la Trinite 1976 - 2005	107 (87 - 130)	152 (138 - 168)	210 (188 - 243)	192 (176 - 212)	42 (29 - 56)	17 (7 - 36)	52 (20 - 116)

Table 2b. Summary (median with 25th to 75th percentiles range) of the ratios of the reference values from independently fitting the Beverton-Holt function to the reconstructed egg to egg time series by river.

River (time period)	Ratio reference values			
	h*	R* / S*	R* / S_halfRmax@50	R* / S_halfRmax@75
Gulf Region rivers				
Margaree River (1961 – 2013)	0.62 (0.59 – 0.64)	2.61 (2.47 – 2.77)	4.17 (3.61 – 4.88)	2.45 (2.09 – 2.87)
Miramichi River (1971 – 2013)	0.82 (0.75 – 0.88)	5.50 (3.95 – 8.43)	23.42 (11.34 – 55.92)	13.30 (6.31 – 32.84)
Miramichi River (1984 – 2013)	0.47 (0.36 – 0.60)	1.89 (1.56 – 2.50)	1.68 (0.89 – 3.72)	1.07 (0.56 – 2.35)
Northwest Miramichi River (1984 – 2013)	0.57 (0.47 – 0.69)	2.33 (1.87 – 3.18)	3.06 (1.63 – 6.81)	1.91 (1.01 – 4.29)
Southwest Miramichi River (1984 – 2013)	0.60 (0.48 – 0.73)	2.51 (1.91 – 3.76)	3.74 (1.74 – 10.19)	2.36 (1.11 – 6.42)
Quebec rivers				
York 1972 - 2004	0.80 (0.75 – 0.86)	5.10 (4.05 – 6.91)	20.63 (12.29 – 39.91)	15.88 (9.35 – 30.87)
Dartmouth 1972 - 2004	0.80 (0.72 – 0.87)	4.93 (3.62 – 7.59)	18.91 (9.37 – 46.90)	11.96 (5.87 – 30.55)
Bonaventure 1972 - 2004	0.85 (0.79 – 0.90)	6.70 (4.79 – 10.42)	37.43 (17.93 – 92.80)	22.77 (10.60 – 57.25)
Cascapedia 1972 - 2003	0.83 (0.76 – 0.89)	5.89 (4.23 – 9.09)	28.54 (13.63 – 72.16)	19.87 (9.46 – 50.87)
Grande-Riviere 1972 - 2004	0.79 (0.72 – 0.85)	4.68 (3.60 – 6.63)	16.40 (9.12 – 34.10)	9.65 (5.30 – 20.58)
Sainte-Anne 1973 - 2005	0.82 (0.76 – 0.88)	5.64 (4.23 – 8.32)	24.83 (13.30 – 53.63)	12.86 (6.69 – 28.82)
Madeleine 1972 - 2005	0.71 (0.63 – 0.79)	3.40 (2.68 – 4.69)	8.05 (4.49 – 16.94)	4.95 (2.76 – 10.49)
Matane 1972 - 2005	0.71 (0.65 – 0.77)	3.44 (2.87 – 4.44)	8.33 (5.33 – 15.14)	6.09 (3.86 – 11.01)
Jupiter 1983 - 2005	0.58 (0.45 – 0.71)	2.40 (1.99 – 3.14)	3.33 (1.95 – 6.60)	2.06 (1.19 – 4.10)

River (time period)	Ratio reference values			
	h*	R* / S*	R* / S_halfRmax@50	R* / S_halfRmax@75
Chaloupe 1984 - 2005	0.58 (0.45 – 0.71)	2.35 (1.81 – 3.44)	3.10 (1.44 – 7.86)	0.26 (0.04 – 0.92)
Saint-Jean 1972 - 2005	0.82 (0.75 – 0.88)	5.62 (4.07 – 8.63)	25.17 (12.33 – 61.38)	15.32 (7.34 – 37.96)
de la Trinite 1976 - 2005	0.72 (0.61 – 0.81)	3.53 (2.56 – 5.39)	8.78 (3.98 – 22.85)	2.82 (1.23 – 7.78)

Table 3a. Summary (median with 25th to 75th percentiles range) of the abundance reference values (eggs per 100 m²) from independently fitting the Ricker function to the reconstructed egg to egg time series by river. In the table, ND means the value was not determined for the range of egg depositions used in the simulations.

River (time period)	Abundance reference values (eggs per 100 m ²)						
	C*	R*	Rmax	Srep	S*	S_halfRmax @50	S_halfRmax @75
Gulf Region rivers							
Margaree River (1961 – 2013)	327 (305 - 350)	589 (563 - 615)	679 (655 - 705)	641 (620 - 664)	260 (252 - 270)	109 (104 - 116)	157 (148 - 168)
Miramichi River (1971 – 2013)	122 (106 – 140)	241 (225 – 258)	293 (281 – 306)	283 (273 – 294)	118 (113 – 123)	54 (49 – 61)	81 (73 – 92)
Miramichi River (1984 – 2013)	43 (32 – 56)	154 (140 – 169)	267 (251 – 291)	239 (225 – 253)	109 (103 – 115)	91 (76 – 112)	120 (100 – 146)
Northwest Miramichi River (1984 – 2013)	27 (22 – 32)	77 (71 – 84)	117 (112 – 125)	112 (107 – 118)	50 (48 – 53)	34 (30 – 40)	46 (40 – 54)
Southwest Miramichi River (1984 – 2013)	48 (37 – 61)	157 (142 – 172)	256 (243 – 274)	237 (223 – 250)	107 (102 – 113)	82 (70 – 98)	109 (93 – 130)
Quebec rivers							
York 1972 - 2004	193 (182 - 204)	312 (303 - 322)	345 (336 - 354)	303 (293 - 314)	118 (113 - 124)	44 (41 - 48)	54 (49 - 59)
Dartmouth 1972 - 2004	126 (114 - 139)	221 (210 - 233)	253 (243 - 263)	232 (224 - 243)	93 (89 - 99)	38 (35 - 43)	51 (46 - 57)
Bonaventure 1972 - 2004	158 (141 - 177)	235 (220 - 251)	252 (240 - 266)	203 (197 - 210)	76 (72 - 80)	26 (24 - 29)	36 (33 - 40)
Cascapedia 1972 - 2003	227 (207 - 247)	359 (344 - 375)	395 (382 - 408)	338 (326 - 353)	131 (124 - 139)	48 (44 - 54)	60 (55 - 68)
Grande-Riviere 1972 - 2004	111 (100 - 123)	187 (176 - 198)	210 (200 - 220)	189 (182 - 197)	75 (71 - 79)	30 (27 - 32)	42 (38 - 46)
Sainte-Anne 1973 - 2005	148 (131 - 165)	232 (216 - 250)	254 (240 - 270)	216 (206 - 228)	83 (79 - 89)	31 (28 - 35)	49 (44 - 55)
Madeleine 1972 - 2005	65 (57 - 73)	133 (125 - 140)	163 (156 - 171)	159 (152 - 168)	67 (63 - 71)	32 (28 - 37)	44 (39 - 51)
Matane 1972 - 2005	145 (136 - 154)	269 (260 - 279)	315 (304 - 326)	300 (288 - 314)	123 (117 - 130)	53 (49 - 58)	66 (60 - 72)
Jupiter 1983 - 2005	26 (21 - 32)	78 (70 - 85)	119 (111 - 128)	113 (105 - 121)	51 (47 - 54)	35 (30 - 41)	49 (43 - 58)

Abundance reference values (eggs per 100 m²)

River (time period)	C*	R*	Rmax	Srep	S*	S_halfRmax @50	S_halfRmax @75
Chaloupe 1984 - 2005	39 (22 - 62)	133 (100 - 171)	227 (198 - 262)	203 (162 - 242)	92 (76 - 108)	73 (62 - 88)	225 (172 - ND)
Saint-Jean 1972 - 2005	131 (117 - 145)	213 (201 - 226)	237 (227 - 247)	209 (203 - 216)	82 (78 - 86)	31 (29 - 36)	44 (40 - 49)
de la Trinite 1976 - 2005	104 (86 - 124)	178 (160 - 196)	202 (186 - 219)	178 (167 - 194)	71 (65 - 79)	29 (26 - 37)	52 (44 - 65)

Table 3b. Summary (median with 25th to 75th percentiles range) of the ratios of the reference values from independently fitting the Ricker function to the reconstructed egg to egg time series by river. In the table, ND means the value was not determined for the range of egg depositions used in the simulations.

River (time period)	Ratio reference values			
	h*	R* / S*	R* / S_halfRmax@50	R* / S_halfRmax@75
Gulf Region rivers				
Margaree River (1961 – 2013)	0.56 (0.54 - 0.57)	2.25 (2.17 – 2.35)	5.36 (4.99 – 5.75)	3.74 (3.45 – 4.03)
Miramichi River (1971 – 2013)	0.51 (0.47 – 0.55)	2.03 (1.87 – 2.21)	4.41 (3.73 – 5.17)	2.96 (2.50 – 3.46)
Miramichi River (1984 – 2013)	0.28 (0.23 – 0.33)	1.39 (1.30 – 1.50)	1.67 (1.27 – 2.14)	1.28 (0.96 – 1.63)
Northwest Miramichi River (1984 – 2013)	0.34 (0.29 – 0.38)	1.51 (1.41 – 1.62)	2.17 (1.75 – 2.67)	1.63 (1.30 – 2.00)
Southwest Miramichi River (1984 – 2013)	0.31 (0.26 – 0.36)	1.44 (1.34 – 1.56)	1.90 (1.47 – 2.39)	1.43 (1.10 – 1.79)
Quebec rivers				
York 1972 - 2004	0.62 (0.60 – 0.64)	2.63 (2.48 – 2.78)	6.99 (6.34 – 7.66)	5.80 (5.24 – 6.36)
Dartmouth 1972 - 2004	0.57 (0.54 – 0.61)	2.34 (2.17 – 2.54)	5.75 (5.02 – 6.58)	4.29 (3.72 – 4.93)
Bonaventure 1972 - 2004	0.67 (0.64 – 0.71)	3.07 (2.79 – 3.40)	8.89 (7.69 – 10.31)	6.48 (5.54 – 7.51)
Cascapedia 1972 - 2003	0.63 (0.60 – 0.66)	2.73 (2.51 – 2.97)	7.43 (6.48 – 8.47)	5.91 (5.13 – 6.74)
Grande-Riviere 1972 - 2004	0.60 (0.57 – 0.63)	2.48 (2.30 – 2.68)	6.31 (5.54 – 7.13)	4.44 (3.88 – 5.05)
Sainte-Anne 1973 - 2005	0.64 (0.60 – 0.67)	2.76 (2.51 – 3.03)	7.50 (6.46 – 8.63)	4.75 (4.03 – 5.51)
Madeleine 1972 - 2005	0.49 (0.45 – 0.53)	1.96 (1.82 – 2.11)	4.11 (3.52 – 4.78)	2.97 (2.53 – 3.47)
Matane 1972 - 2005	0.54 (0.52 – 0.56)	2.17 (2.06 – 2.29)	5.05 (4.58 – 5.53)	4.08 (3.69 – 4.49)
Jupiter 1983 - 2005	0.34 (0.29 – 0.38)	1.52 (1.41 – 1.62)	2.21 (1.77 – 2.65)	1.58 (1.26 – 1.91)

River (time period)	Ratio reference values			
	h*	R* / S*	R* / S_halfRmax@50	R* / S_halfRmax@75
Chaloupe 1984 - 2005	0.30 (0.22 – 0.37)	1.42 (1.28 – 1.58)	1.78 (1.19 – 2.48)	0.5 (ND – 0.83)
Saint-Jean 1972 - 2005	0.61 (0.58 – 0.65)	2.59 (2.38 – 2.82)	6.60 (5.75 – 7.56)	4.89 (4.22 – 5.60)
de la Trinite 1976 - 2005	0.59 (0.53 – 0.64)	2.44 (2.11 – 2.81)	5.93 (4.60 – 7.41)	3.31 (2.50 – 4.18)

Table 4a. Summary (median with 25th to 75th percentiles range) of the abundance reference values (eggs per 100 m²) from hierarchical fitting of the Ricker function to the reconstructed egg to egg time series by river.

River (time period)	Abundance reference values (eggs per 100 m ²)						
	C*	R*	Rmax	Srep	S*	S_halfRmax @50	S_halfRmax @75
Gulf Region rivers							
Margaree River (1972 – 2005)	408 (386 - 432)	667 (642 - 693)	739 (715 - 763)	656 (638 - 674)	257 (250 - 265)	98 (95 - 102)	129 (123 - 134)
Miramichi River (1972 – 2005)	169 (156 – 181)	287 (274 – 301)	324 (313 – 336)	298 (288 – 307)	119 (115 – 123)	47 (44 – 50)	66 (62 – 70)
Quebec rivers							
York 1972 - 2004	188 (179 - 197)	309 (300 - 319)	343 (334 - 353)	306 (296 - 317)	120 (116 - 125)	46 (43 - 49)	57 (53 - 61)
Dartmouth 1972 - 2004	134 (126 - 142)	225 (217 - 234)	253 (244 - 262)	229 (222 - 238)	91 (87 - 95)	36 (34 - 38)	47 (44 - 51)
Bonaventure 1972 - 2004	133 (124 - 143)	216 (206 - 226)	238 (229 - 248)	209 (202 - 217)	82 (78 - 85)	31 (29 - 33)	42 (39 - 46)
Cascapedia 1972 - 2003	213 (202 - 226)	349 (337 - 362)	387 (376 - 400)	344 (332 - 356)	135 (129 - 141)	51 (48 - 55)	65 (61 - 70)
Grande-Riviere 1972 - 2004	113 (106 - 120)	188 (180 - 196)	210 (202 - 218)	189 (183 - 196)	75 (72 - 78)	29 (28 - 31)	41 (38 - 44)
Sainte-Anne 1973 - 2005	137 (127 - 147)	223 (211 - 236)	247 (236 - 260)	219 (210 - 230)	86 (82 - 91)	33 (31 - 35)	50 (47 - 55)
Madeleine 1972 - 2005	84 (77 - 91)	146 (139 - 153)	167 (161 - 173)	155 (150 - 161)	62 (60 - 65)	25 (24 - 28)	35 (33 - 38)
Matane 1972-2005	159 (150 - 168)	275 (266 - 284)	311 (302 - 321)	287 (278 - 298)	115 (110 - 120)	46 (43 - 50)	58 (54 - 63)
Saint - Jean 1972 - 2005	127 (120 - 136)	211 (202 - 219)	235 (227 - 243)	210 (204 - 217)	83 (80 - 86)	32 (30 - 34)	43 (40 - 46)
de la Trinite 1976 - 2005	107 (99 - 116)	178 (168 - 190)	199 (188 - 212)	179 (170 - 190)	71 (67 - 75)	28 (26 - 30)	46 (42 - 51)

Table 4b. Summary (median with 25th to 75th percentiles range) of the ratios of the reference values from the hierarchical fitting of the Ricker function to the reconstructed egg to egg time series for the period 1971-1972 to 2004-2005.

River (time period)	Ratio reference values			
	h*	R* / S*	R* / S_halfRmax@50	0.8 R* / S_halfRmax@75
Gulf Region rivers				
Margaree River (1972 – 2005)	0.61 (0.60 – 0.63)	2.58 (2.50 – 2.68)	5.17 (4.86 – 5.50)	3.52 (3.19 – 3.80)
Miramichi River (1972 – 2005)	0.59 (0.57 – 0.61)	2.43 (2.30 – 2.54)	4.40 (3.98 – 4.75)	4.14 (3.89 – 4.40)
Quebec rivers				
York 1972 - 2004	0.61 (0.59 – 0.62)	2.55 (2.46 – 2.66)	5.41 (5.05 – 5.81)	4.33 (4.04 – 4.65)
Dartmouth 1972 - 2004	0.60 (0.58 – 0.61)	2.48 (2.37 – 2.58)	4.75 (4.40 – 5.09)	3.80 (3.52 – 4.07)
Bonaventure 1972 - 2004	0.62 (0.60 – 0.64)	2.61 (2.49 – 2.78)	5.04 (4.63 – 5.61)	4.03 (3.70 – 4.49)
Cascapedia 1972 - 2003	0.61 (0.59 – 0.63)	2.57 (2.46 – 2.70)	5.30 (4.91 – 5.77)	4.24 (3.93 – 4.61)
Grande-Riviere 1972 - 2004	0.60 (0.58 – 0.62)	2.50 (2.40 – 2.61)	4.60 (4.26 – 4.95)	3.68 (3.41 – 3.96)
Sainte-Anne 1973 - 2005	0.61 (0.59 – 0.63)	2.57 (2.47 – 2.70)	4.41 (4.04 – 4.82)	3.52 (3.23 – 3.86)
Madeleine 1972 - 2005	0.58 (0.55 – 0.60)	2.36 (2.20 – 2.48)	4.21 (3.76 – 4.60)	3.37 (3.01 – 3.68)
Matane 1972 - 2005	0.58 (0.56 – 0.60)	2.39 (2.27 – 2.49)	4.74 (4.36 – 5.09)	3.79 (3.49 – 4.08)
Saint-Jean 1972 - 2005	0.60 (0.59 – 0.62)	2.53 (2.43 – 2.64)	4.85 (4.51 – 5.24)	3.88 (3.61 – 4.20)
de la Trinite 1976 - 2005	0.60 (0.58 – 0.62)	2.51 (2.39 – 2.62)	3.84 (3.47 – 4.19)	3.07 (2.77 – 3.35)

FIGURES

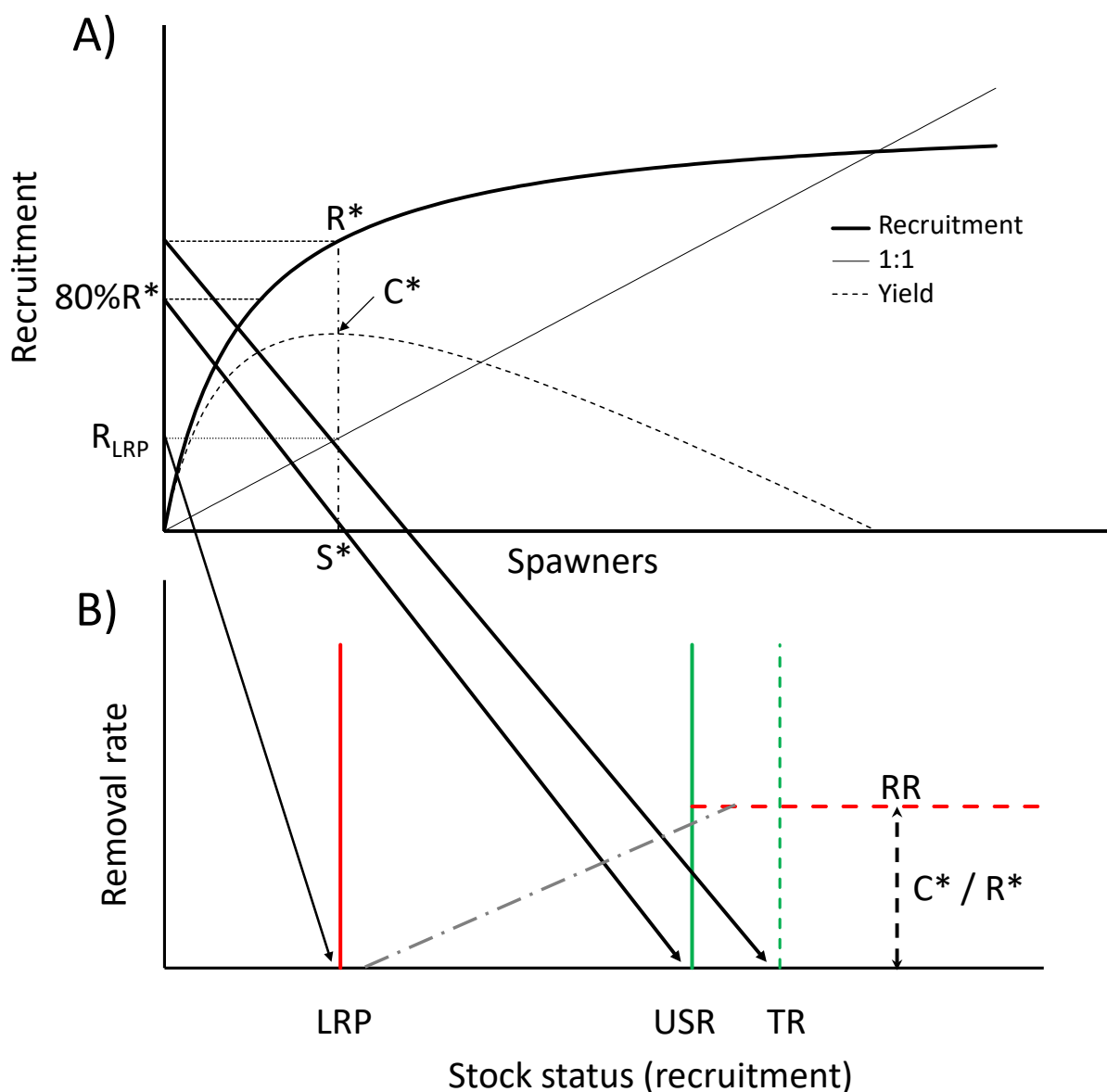


Figure 1. Transposing a spawning stock to recruitment relationship (upper panel A) to the removal rate and stock status axes (lower panel B) of the PA framework. The example is for an upper stock reference (USR) corresponding to $80\%R^*$ (R_{msy}), a target reference (TR) corresponding to R^* (R_{msy}), a limit reference point (LRP) equal to S^* (S_{msy}), and a maximum removal rate (RR) corresponding to F_{msy} . The exploitation rate in the cautious zone (grey hatched line) would be defined on the basis of a risk analysis of the chance that abundance after exploitation would be less than the LRP. Figure is redrawn from DFO (2015).

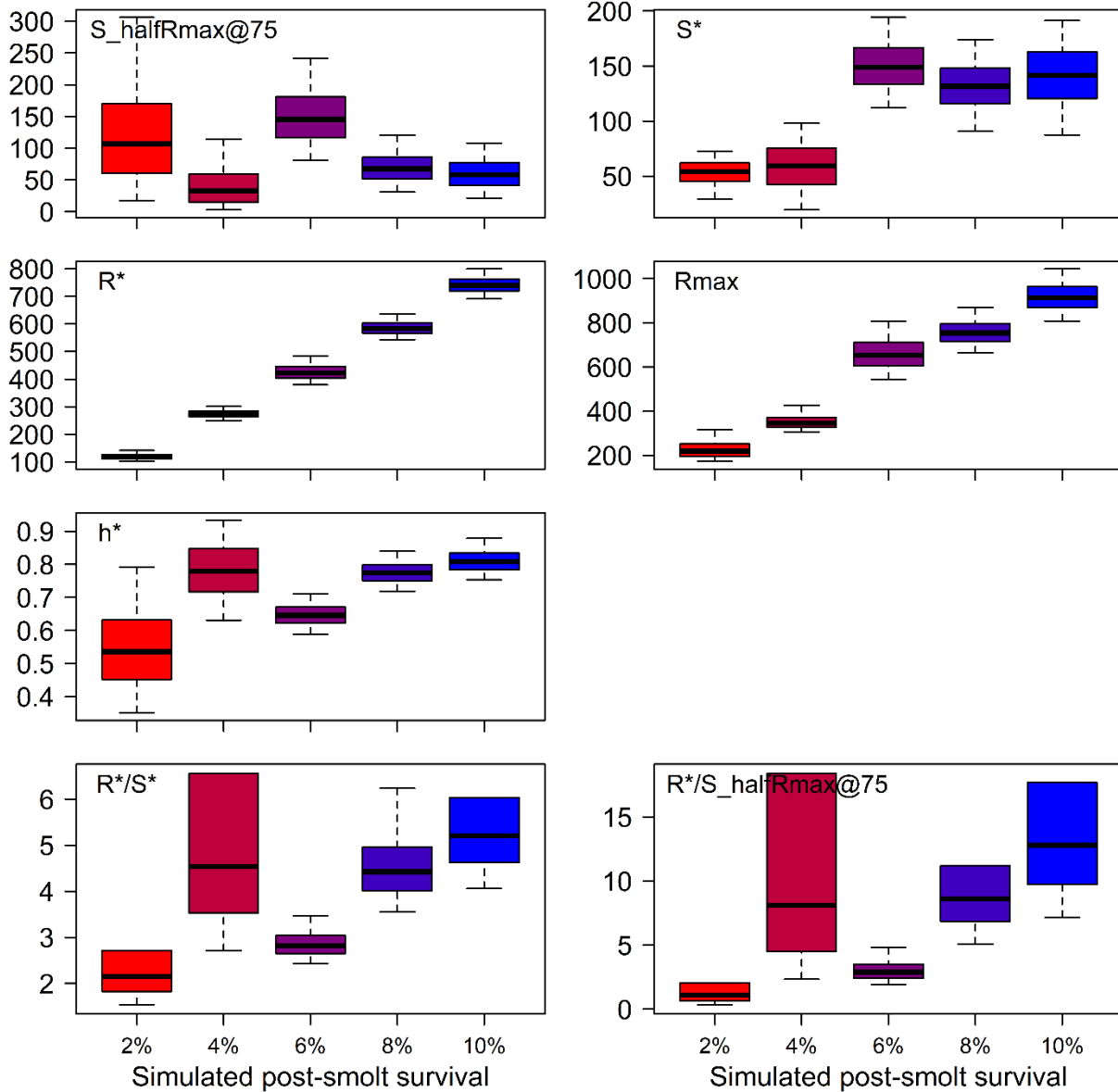


Figure 2a. Posterior distributions of select reference values from fitting a Beverton-Holt stock and recruitment function to simulated time series of spawners and returns generated using five levels of stationary post-smolt survival at sea. The boxplots show the 5th to 95th percentile range as whiskers, the 25th to 75th percentile range as the boxes and the median as the horizontal line in each box. The data simulation method, the simulated data, and fits are provided in Appendix 1.

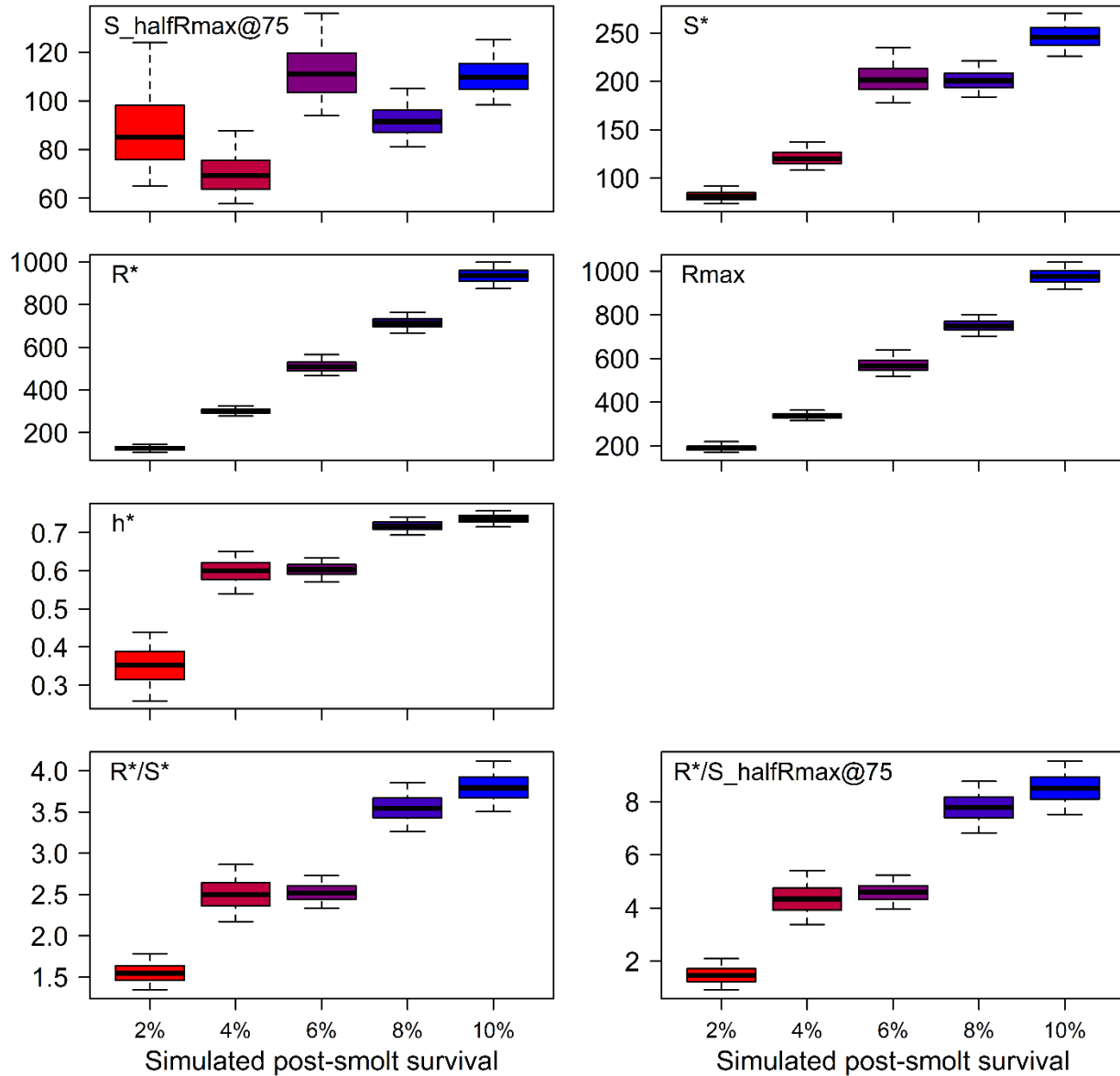


Figure 2b. Posterior distributions of select reference values from fitting a Ricker stock and recruitment function to simulated time series of spawners and returns generated using five levels of stationary post-smolt survival at sea. The boxplots show the 5th to 95th percentile range as whiskers, the 25th to 75th percentile range as boxes and the median as the horizontal line in each box. The data simulation method, the simulated data, and fits are provided in Appendix 1.

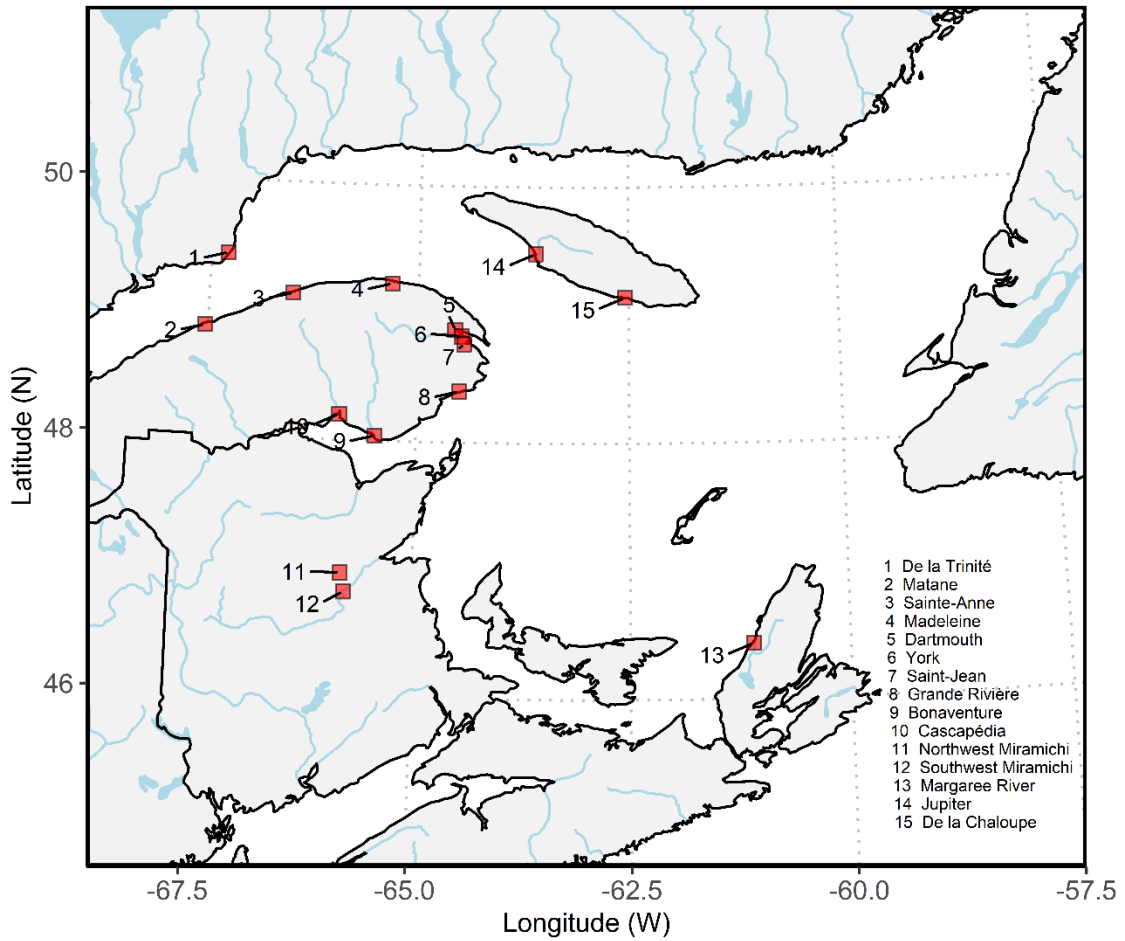


Figure 3. Geographic location of rivers with reconstructed adult to adult stock and recruitment data analyzed in this study. The Northwest Miramichi and Southwest Miramichi rivers have a common confluence in tidal waters and become the Miramichi River, referenced in the paper.

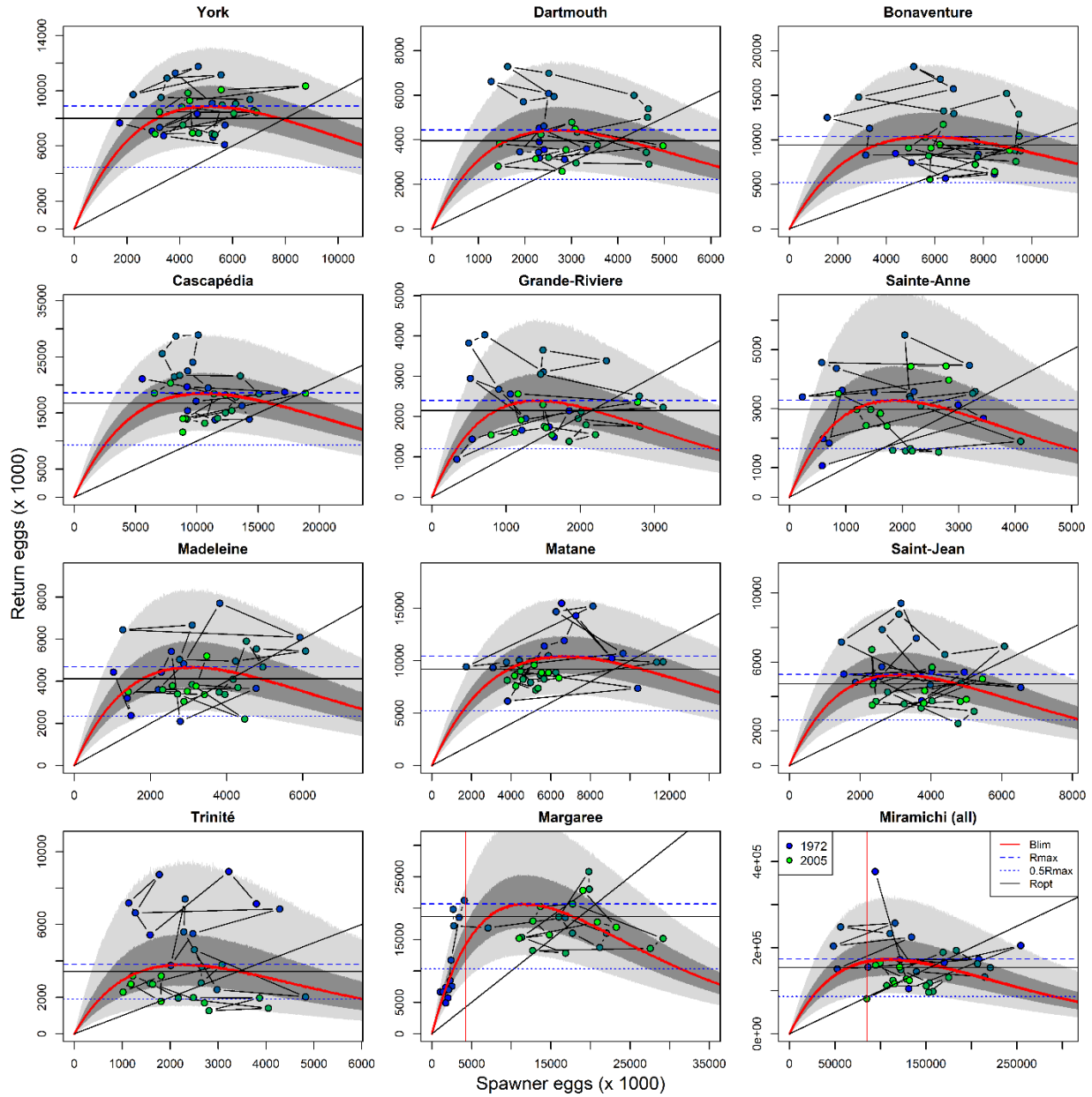


Figure 4. Ricker (hierarchical) stock and recruitment function fits to the egg to egg time series for the ten Quebec rivers and two DFO Gulf Region rivers, 1972 (dark blue) to 2015 (bright green) cohorts (see Table 4 for river-specific cohorts). The total eggs in spawners (horizontal axis) and in returns (vertical axis) by cohort are expressed as thousands of eggs. The thick red curve indicates the median Ricker stock and recruitment relationship, the dark and light grey areas indicate 25th-75th and 2.5th-97.5th interquartile envelopes, respectively. The black diagonal line is the 1:1 line, the black horizontal line indicates R^* , and the dashed and dotted blue horizontal lines indicate R_{max} and $0.5R_{max}$, respectively. The vertical red line indicates the LRP when available.

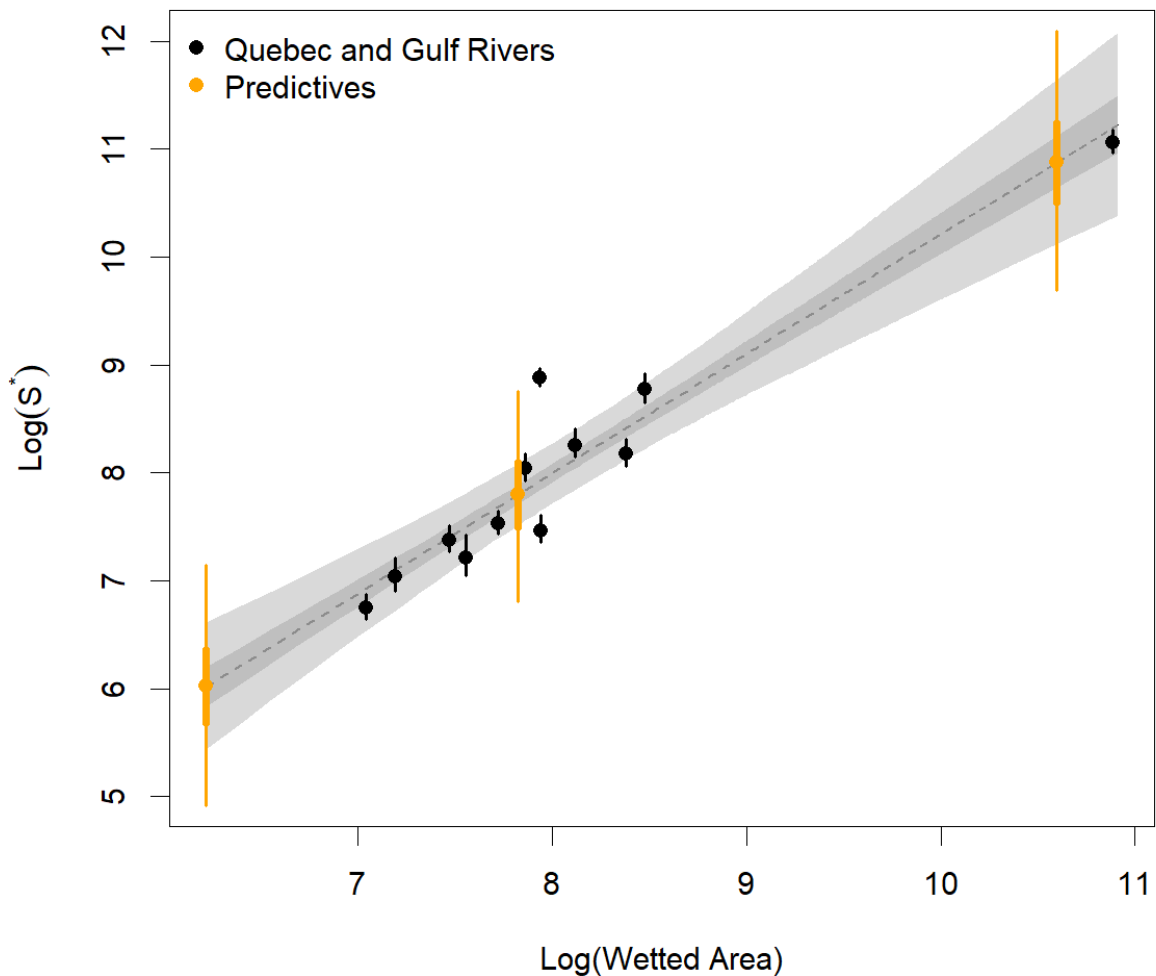


Figure 5. Linear relationship between $\text{Log}(S^*)$ and $\text{Log}(\text{Wetted area})$ from the hierarchical analysis of twelve rivers from DFO Gulf Region and Quebec (see Figures 3 and 4). The dashed line, dark, and light grey shaded areas indicate the median, the 25th-75th percentiles range, and the 2.5th-97.5th percentiles range, respectively. Black dots and segments indicate the median and 2.5th-97.5th percentile range of the posterior distribution of S^* for the individual rivers. The orange dots and segments indicate the median, the 25th -75th percentiles range, and the 2.5th-97.5th percentiles range of the posterior predictive distribution of S^* for three rivers with wetted areas of 500, 2500 and 40000 m².

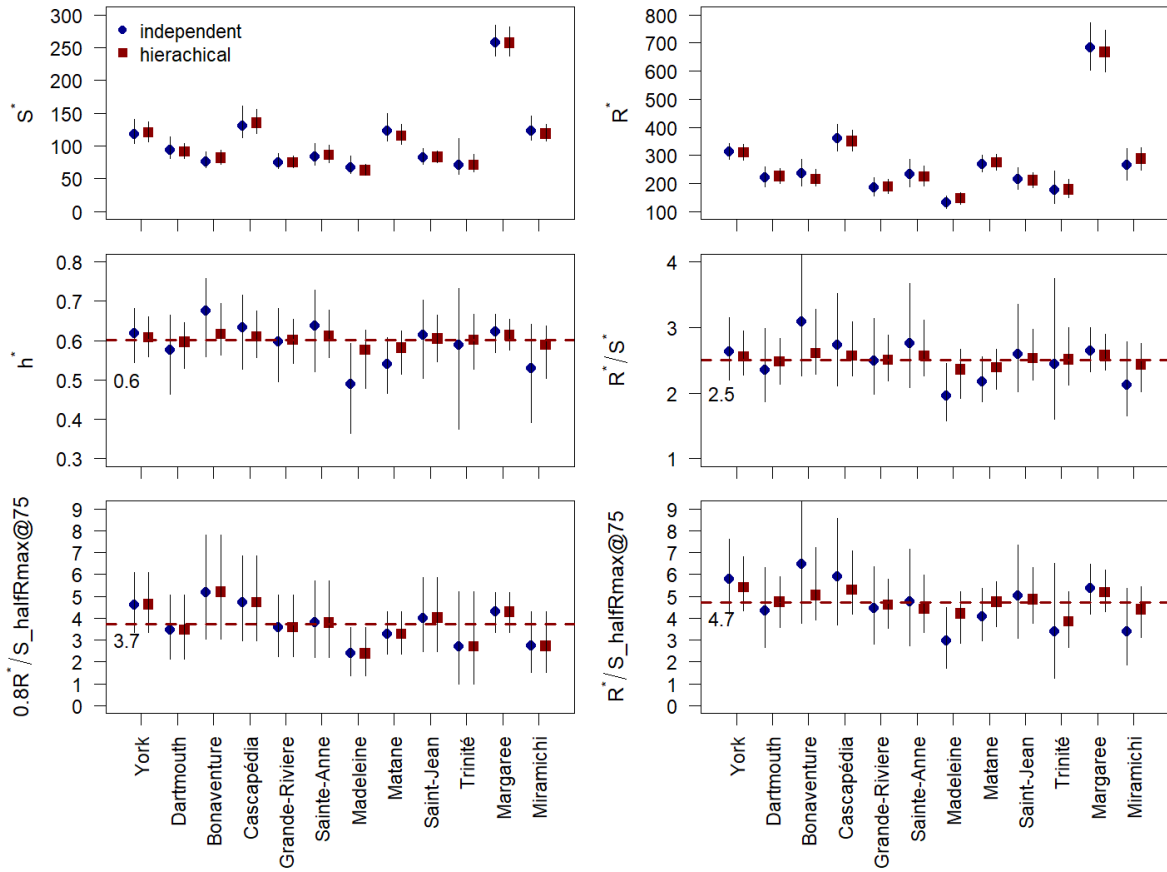


Figure 6. Posterior summaries (median as symbol, 2.5th to 97.5th percentile range as vertical bars) of S^* and R^* (eggs per 100 m²), h^* , and different ratios from the independent and hierachical model fits to the Ricker stock and recruitment function for ten rivers in Quebec and two Gulf rivers (Margaree and Miramichi) for the 1972 to 2015 cohorts. The horizontal red dashed lines and the numbers correspond to the mean values across rivers from the hierachical fit.

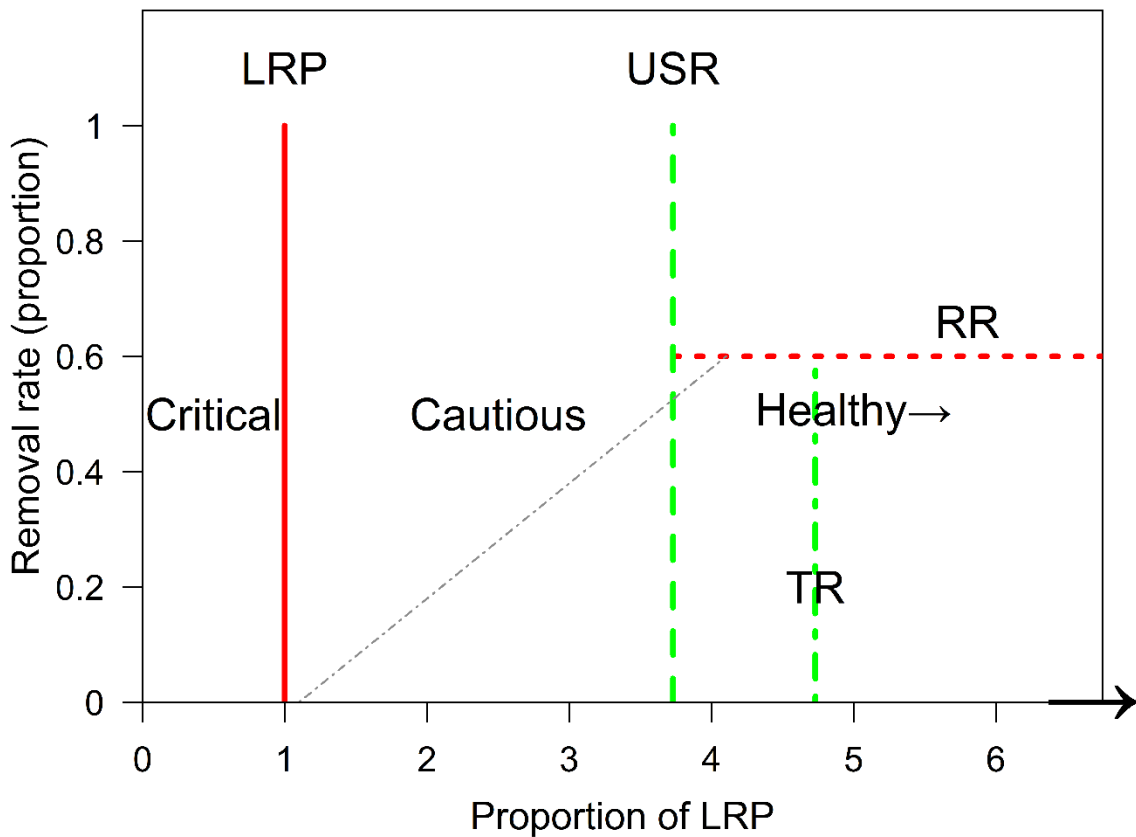


Figure 7. PA plot of reference points and the three status zones for Atlantic Salmon of DFO Gulf Region rivers. The acronyms in the plot are: LRP = Limit Reference Point, USR = Upper Stock Reference ($3.78 \times \text{LRP}$), TR = Target Reference ($4.73 \times \text{LRP}$), and RR = Removal Rate reference (0.60). The stock status axis is shown as a proportion of the LRP. The light grey diagonal dash dotted line illustrates a candidate harvest decision rule with a linear decline anchored by two Operational Control Points that are offset from LRP and USR to account for uncertainties in the estimated abundances before fishing.

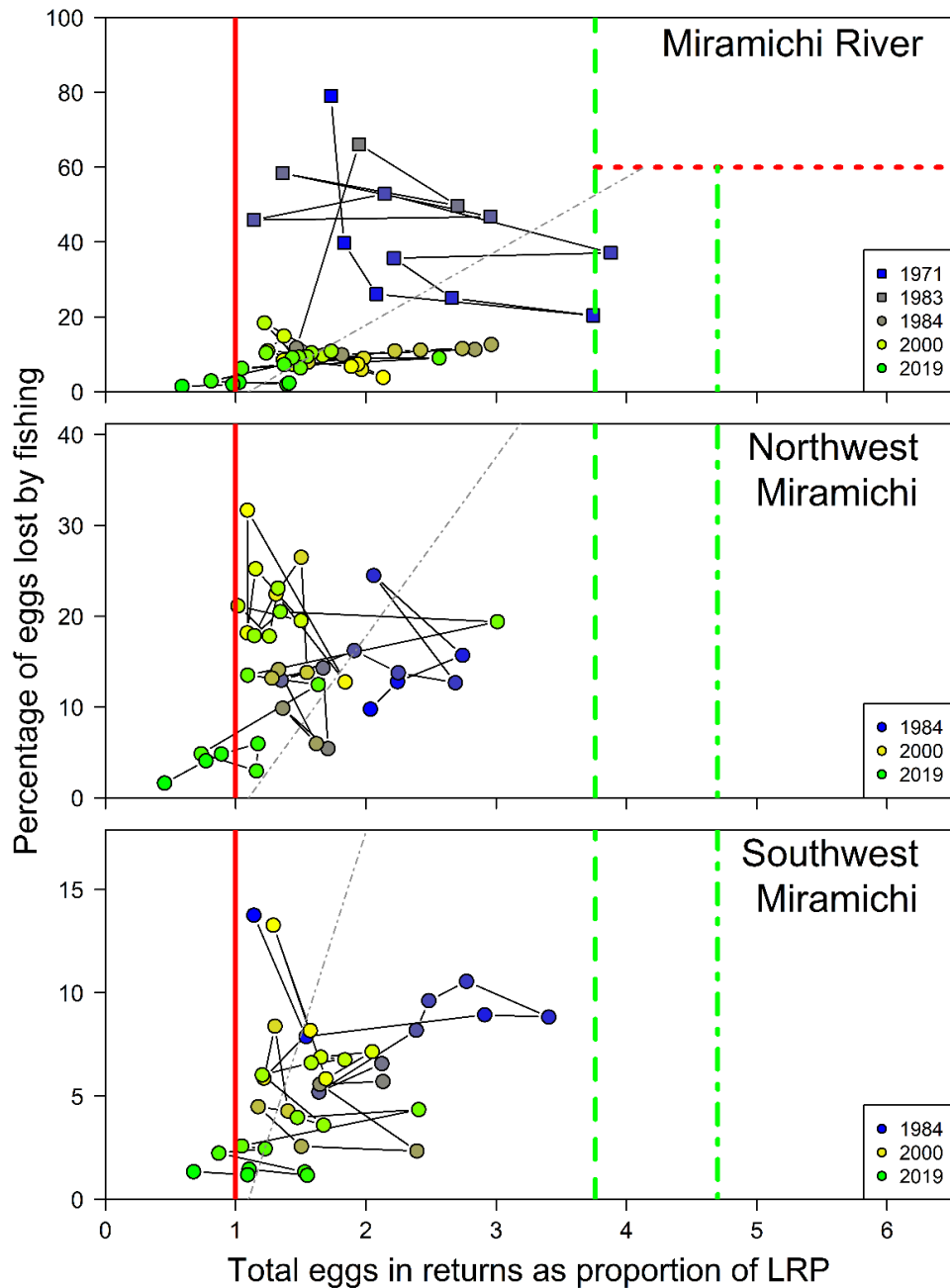


Figure 8. Percentages of eggs lost due to fishing and point estimates of eggs in total returns (before fishing) for the Miramichi River overall (top; 1971 to 2019), the Northwest Miramichi (middle; 1984 to 2019), and the Southwest Miramichi (bottom; 1984 to 2019). The total eggs in returns are shown as a proportion of the river-specific LRP. The vertical solid red line is the LRP, the vertical dashed green line is the UR and the vertical dotted green line is the TR. The maximum removal rate (RR) reference of 60% is shown in the top panel as a horizontal dashed red line but it is offscale in the middle and bottom panels. For illustration, the light grey diagonal dash dotted line in each panel is an example harvest decision rule with a linear decline anchored by two Operational Control Points that are offset by 10% from the LRP and UR to account for uncertainties in the estimated abundances before fishing.

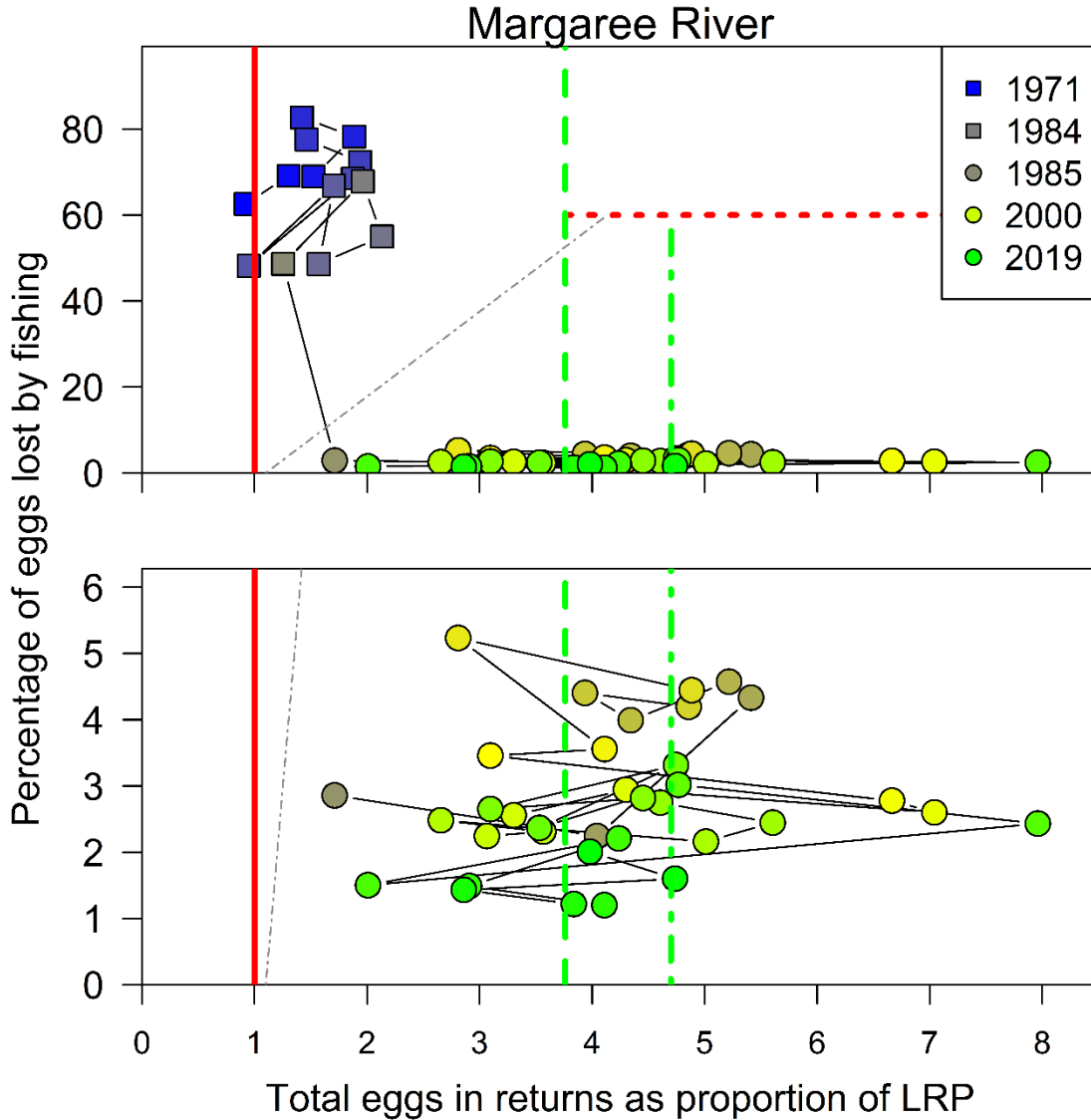


Figure 9. Percentages of eggs lost due to fishing and point estimates of eggs in total returns (before fishing) for the Margaree River, 1971 to 2019 (upper panel) and 1985 to 2019 (lower panel). The total eggs in returns are shown as a proportion of the LRP of the Margaree River. The vertical solid red line is the LRP, the vertical dashed green line is the USA and the vertical dash-dot green line is the TR. The maximum removal rate (RR) reference of 60% is shown in the top panel as a horizontal dashed red line but it is offscale in the bottom panel. For illustration, the light grey diagonal dash-dotted line in each panel is an example harvest decision rule with a linear decline anchored by two Operational Control Points that are offset by 10% from the LRP and USA to account for uncertainties in the estimated abundances before fishing.

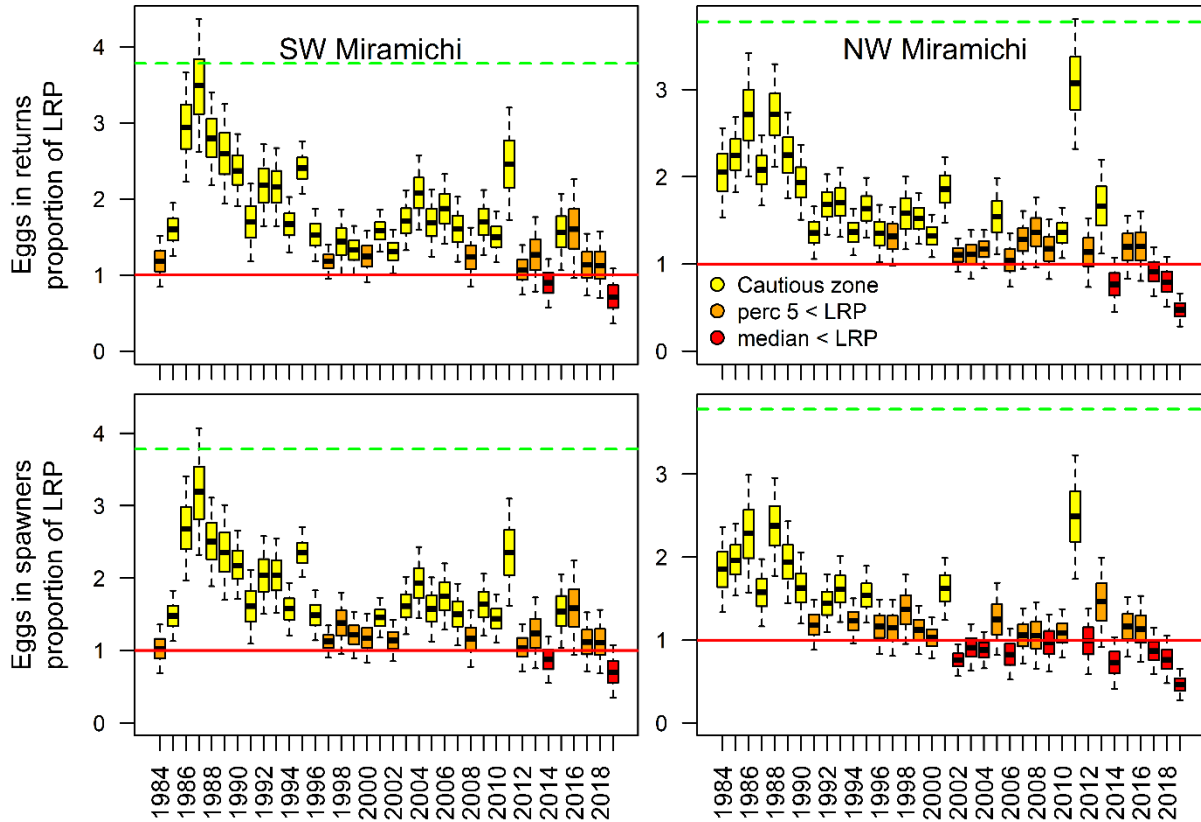


Figure 10. Time series of the posterior distributions of estimated eggs in returns (top row) and eggs in spawners (bottom row) as a proportion of the river-specific LRP for the Southwest Miramichi (left column) and the Northwest Miramichi (right column), 1984 to 2019. The boxplots show the 5th to 95th percentile range as whiskers, the 25th to 75th percentile range as boxes and the median as the horizontal line in each box. The boxplots are shaded to correspond to the probability of the estimated eggs being below the LRP as: yellow is the cautious zone (5th percentile > LRP and median < USR, orange indicates the 5th percentile of the estimate is less than the LRP, and red indicates that the median is less than the LRP. The red horizontal line is the LRP, the dashed horizontal green line is the USR. The TR is offscale in all panels.

APPENDICES

APPENDIX 1. SIMULATION TO ASSESS THE RATIO METHOD TO TRANSLATE THE LRP TO THE USR

The life cycle of Atlantic Salmon was simulated beginning with an egg to smolt relationship to model the density dependent stage in freshwater followed by the marine phase and returning mature fish to the river. Five data sets of eggs in spawners and eggs in returns by year-class were generated, assuming different survival rate values in the first year at sea for each simulated data set. The resulting egg to egg data sets were fitted to Beverton-Holt and Ricker stock recruitment functions and reference points were calculated from the parameter estimates of each as described in text.

Freshwater phase

The density dependent egg to smolt dynamic was modelled using a Beverton-Holt stock and recruitment function. A single annual value of smolts (per 100 m²) produced per year class, is drawn from a lognormal distribution:

$$Smolts_t \sim rlnorm(1, \log . u_t, \sigma)$$

with

$$\log . u_t = \log(\alpha) + \log(Eggs_t) - \log\left(1 + \frac{\alpha}{R_{max}} Eggs_t\right) \text{ and}$$

$Eggs_t$ in units of eggs per 100 m².

The parameter values of the Beverton-Holt relationship were taken from Chaput et al. (2015) assuming no lacustrine habitat for smolt production ($R_{max} = 3.9$ smolts per 100 m²), α the slope at the origin corresponding to a salmon population with 90% of the eggs contributed by large salmon ($\alpha = 0.088$), and σ as the standard deviation (log scale) (median = 0.317).

Smolts from an egg deposition year were attributed to a smolt migration year based on a fixed proportion smoltifying at ages 2, 3, and 4 years and raised to smolt migration from the river by the habitat area of the river in the simulation.

$$Sm_{t+a+1} = Smolt_t * p_Sm_a * habitat_area$$

with Sm_{t+a+1} the number of smolts of age a migrating in year t+a+1,

a the smolt age at migration (2,3,4),

p_Sm_a the proportion of a year class smoltifying at age a, and

habitat area the wetted area of the river taken as the number of units (100 m²) of habitat in the Northwest Miramichi River (167,877 units).

The proportion of smolts at age from a year class was fixed at 0.40, 0.55, and 0.05 for age 2 to 4, respectively.

Marine phase

The marine phase includes returns as maiden salmon for two sea ages (1SW, 2SW) and one repeat spawning event.

$$N.1SW_{t+a+2} = Sm_{t+a+1} * S_{postSmolt_{t+a+1}} * p_mat1SW$$

$$N.2SW_{t+a+3} = Sm_{t+a+1} * S_{postSmolt_{t+a+1}} * (1 - p_mat1SW) * S_2SW$$

with $N.1SW_{t+a+2}$; $N.2SW_{t+a+3}$ the return of maiden 1SW salmon in year t+a+2 and maiden 2SW salmon in year t+a+3, respectively,

$S_{postSmolt_{t+a+1}}$ the survival rate of a post-smolt in its first year at sea in year t+a+1 (year of smolt migration) and similar regardless of maturation schedule,

p_{mat1SW} is the proportion of smolts maturing after one year at sea, and

S_{2SW} the survival of 1SW nonmaturing salmon in the second year at sea.

Five series of stationary post smolt survival rates were considered, with mean values of 2%, 4%, 6%, 8%, and 10%. Variability in the annual sea survivals was simulated using a normal distribution on the logit scale with a coefficient of variation of 0.10.

In all cases, S_{2SW} was fixed at 72% and p_{mat1SW} was fixed at 0.6.

One repeat spawning event is included for each maiden sea age group, as either a consecutive (C) or alternate (A) spawner.

$$N.1SW_{t+a+3}^C = N.1SW_{t+a+2} * (1 - ER_{t+a+2}^{Small}) * S_{rep1SW} * p_{cons1SW}$$

$$N.1SW_{t+a+4}^A = N.1SW_{t+a+2} * (1 - ER_{t+a+2}^{Small}) * S_{rep1SW} * (1 - p_{cons1SW}) * S_{repAlt}$$

$$N.2SW_{t+a+4}^C = N.2SW_{t+a+3} * (1 - ER_{t+a+3}^{Large}) * S_{rep2SW} * p_{cons2SW}$$

$$N.2SW_{t+a+5}^A = N.2SW_{t+a+3} * (1 - ER_{t+a+3}^{Large}) * S_{rep2SW} * (1 - p_{cons2SW}) * S_{repAlt}$$

with

$N.1SW_{t+a+3}^C$ and $N.2SW_{t+a+4}^C$ the returns of consecutive repeat 1SW and 2SW salmon, respectively;

$N.1SW_{t+a+4}^A$ and $N.2SW_{t+a+5}^A$ the returns of alternate repeat 1SW and 2SW salmon, respectively;

$N.1SW_{t+a+2}$ and $N.2SW_{t+a+3}$ as above;

ER_{t+a+2}^{Small} and ER_{t+a+2}^{Large} the exploitation rate (removal rate) in the inriver fisheries for small (< 63 cm fork length) salmon and large (>= 63 cm fork length) salmon, respectively;

S_{rep1SW} and S_{rep2SW} the survival rate of post-spawned salmon in the initial period at sea (0.10 and 0.30, respectively);

S_{repAlt} the survival rate of alternate spawners in the full year of reconditioning at sea (0.6); and

$p_{cons1SW}$ and $p_{cons2SW}$ the proportion of post-spawned salmon that mature as consecutive repeat spawners, fixed at 0.7 for both sea age groups.

Exploitation on returning salmon was included to generate contrasts in spawner abundances. Size group specific exploitation rates can be simulated but in this analysis, the exploitation rates were the same for small salmon and large salmon. The exploitation rate was adjusted as a function of effort and catchability parameters, with a raising factor on effort for each sea survival scenario:

$$ER_{x,t} = 1 - e^{-q * E_t * E_{scale_x}} \text{ with}$$

$ER_{x,t}$ = the exploitation rate [0, 1] for sea survival scenario x and year t of the simulation;

q = catchability per unit of effort fixed at 0.10;

E_t = units of effort, drawn from uniform distributions for three time periods (50 years each) with min to max ranges of 3 to 5, 5 to 7, 1 to 3; and

$Escale_x$ = raising factor to adjust the effort to the sea survival scenario (0.2, 1.5, 2.25, 2.75, 3).

Maiden 1SW salmon and 1SW repeat consecutive salmon were assumed to be in the small salmon size group. Maiden 2SW salmon, 1SW repeat alternate, and both repeat spawning stages of 2SW salmon were assumed to be in the large salmon size group.

Returns of small and large salmon, by cohort (Ret_y^{sm} , Ret_y^{lg}), were calculated as:

$$Ret_y^{sm} = \left(\sum_{a=2}^4 N \cdot 1SW_{t+a+2} + \sum_{a=2}^4 N \cdot 1SW_{t+a+3}^C \right)$$

$$Ret_y^{lg} = \left(\sum_{a=2}^4 N \cdot 2SW_{t+a+3} + \sum_{a=2}^4 N \cdot 1SW_{t+a+4}^A + \sum_{a=2}^4 N \cdot 2SW_{t+a+4}^C + \sum_{a=2}^4 N \cdot 2SW_{t+a+5}^A \right)$$

Spawners were estimated from the returning salmon as fish that survived the fisheries. There is no catch and release in these scenarios. Spawners of small and large salmon, by cohort (Sp_y^{sm} , Sp_y^{lg}), were calculated as:

$$Sp_y^{sm} = \left(\sum_{a=2}^4 N \cdot 1SW_{y,a} + \sum_{a=2}^4 N \cdot 1SW_{y,a}^C \right) * (1 - ER_y)$$

$$Sp_y^{lg} = \left(\sum_{a=2}^4 N \cdot 2SW_{y,a} + \sum_{a=2}^4 N \cdot 1SW_{y,a}^A + \sum_{a=2}^4 N \cdot 2SW_{y,a}^C + \sum_{a=2}^4 N \cdot 2SW_{y,a}^A \right) * (1 - ER_y)$$

Eggs in returns ($Eggs.ret_y$) and spawners ($Eggs.sp_y$) by cohort class were calculated using the mean number of eggs per fish, 867 and 6,016 eggs per fish for small salmon and large salmon size groups, respectively, corresponding to characteristics of salmon from the Northwest Miramichi River (DFO 2018b).

$$Eggs.ret_y = Ret_y^{sm} * Eggs_{Small} + Ret_y^{lg} * Eggs_{Large}$$

$$Eggs.sp_y = Sp_y^{sm} * Eggs_{Small} + Sp_y^{lg} * Eggs_{Large}$$

Appendix 1. Results

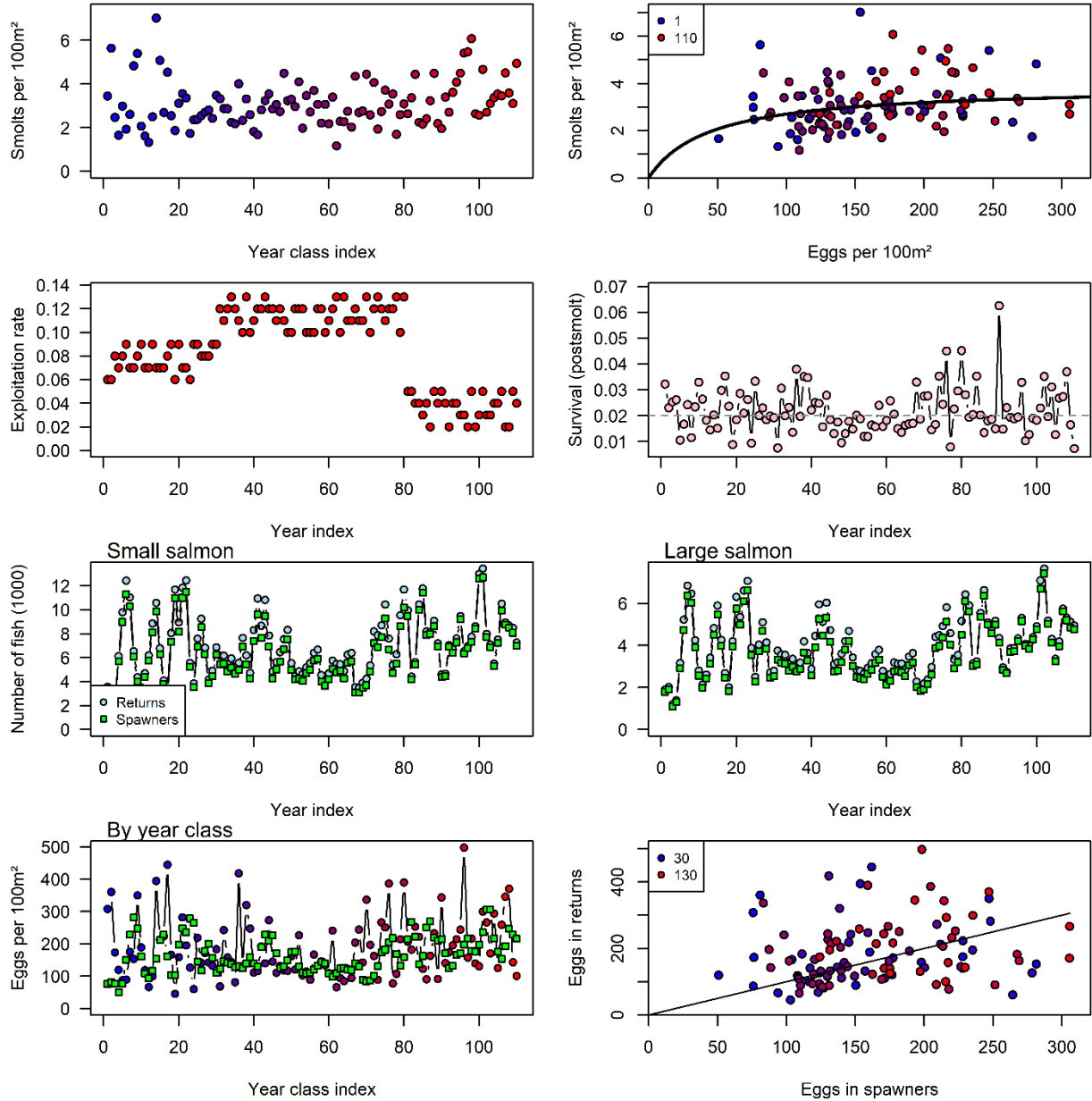


Figure A1.1. Simulated data series for mean stationary post-smolt survival rate of 2%.

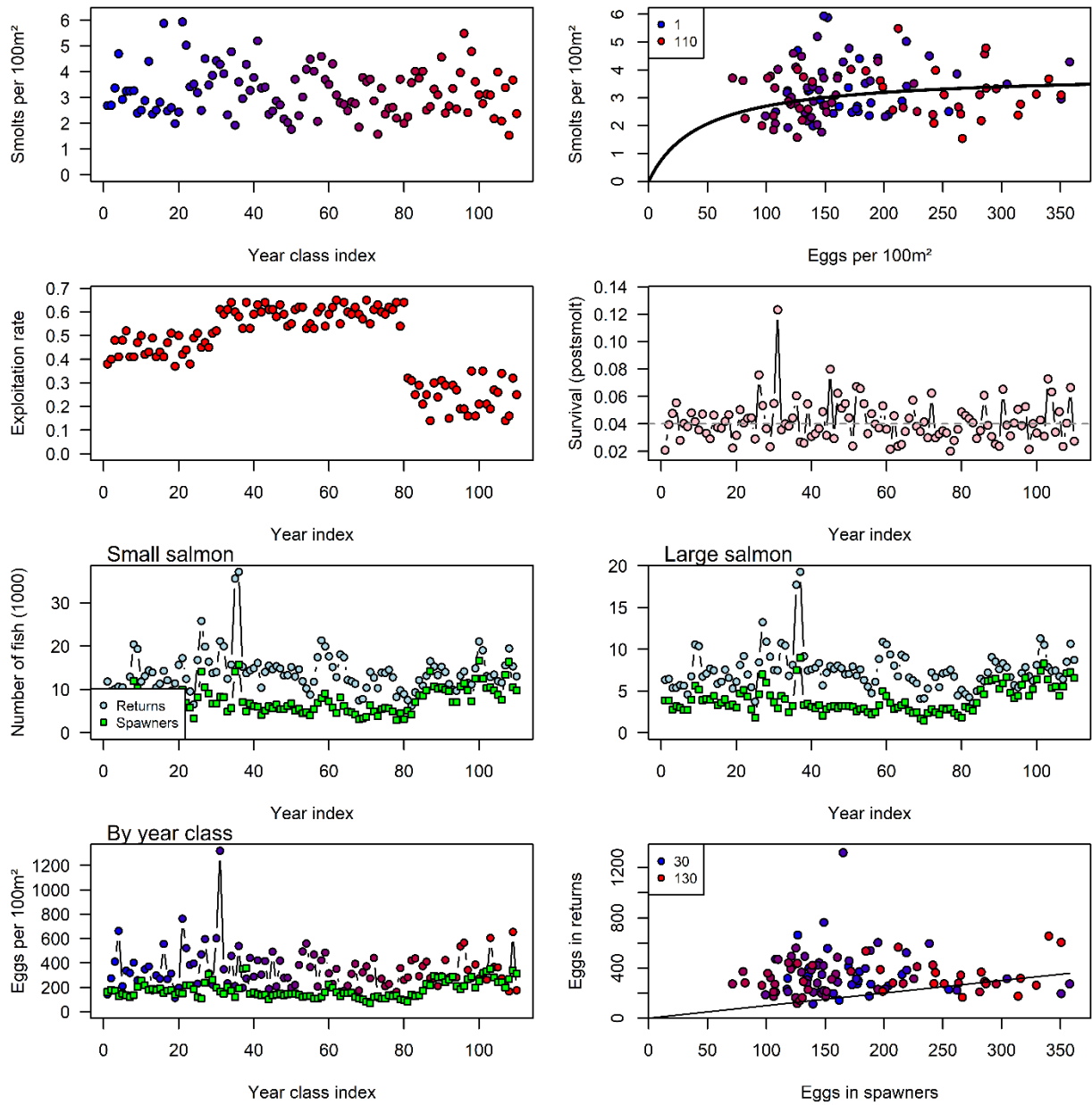


Figure A1.2. Simulated data series for a mean stationary post-smolt survival of 4%.

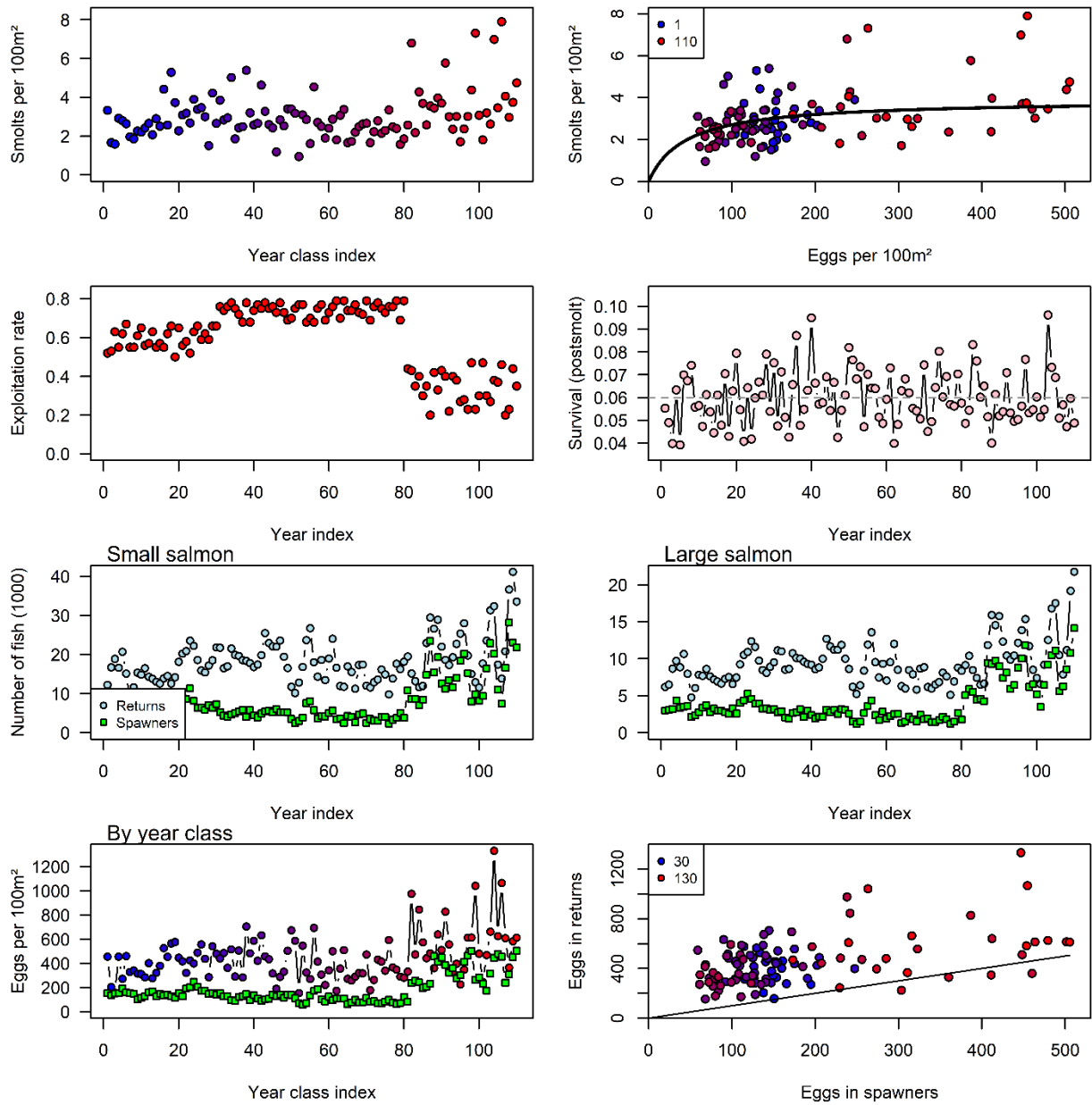


Figure A1.3. Simulated data series for a mean stationary post-smolt survival rate of 6%.

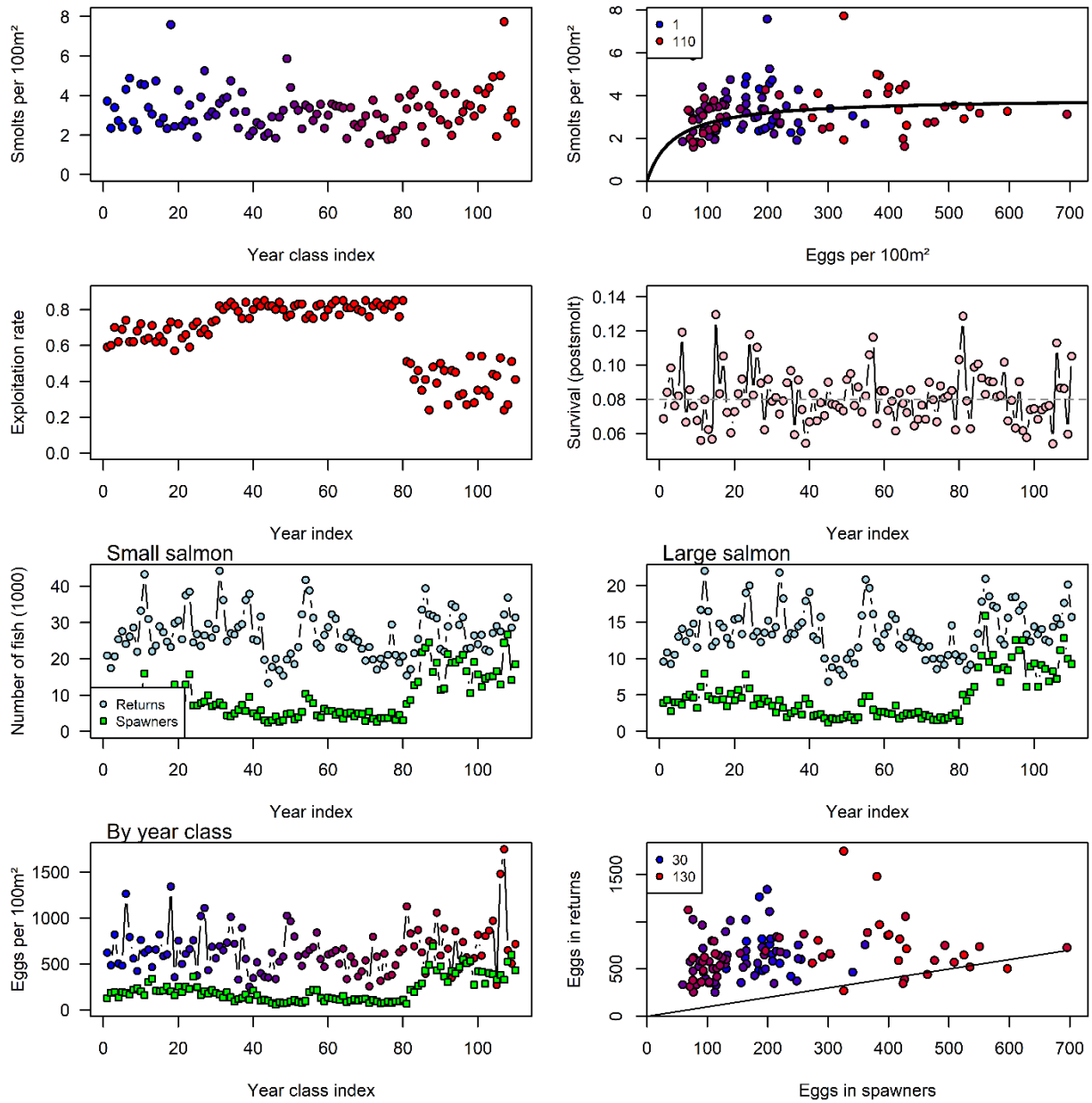


Figure A1.4. Simulated data series for a mean stationary post-smolt survival rate of 8%.

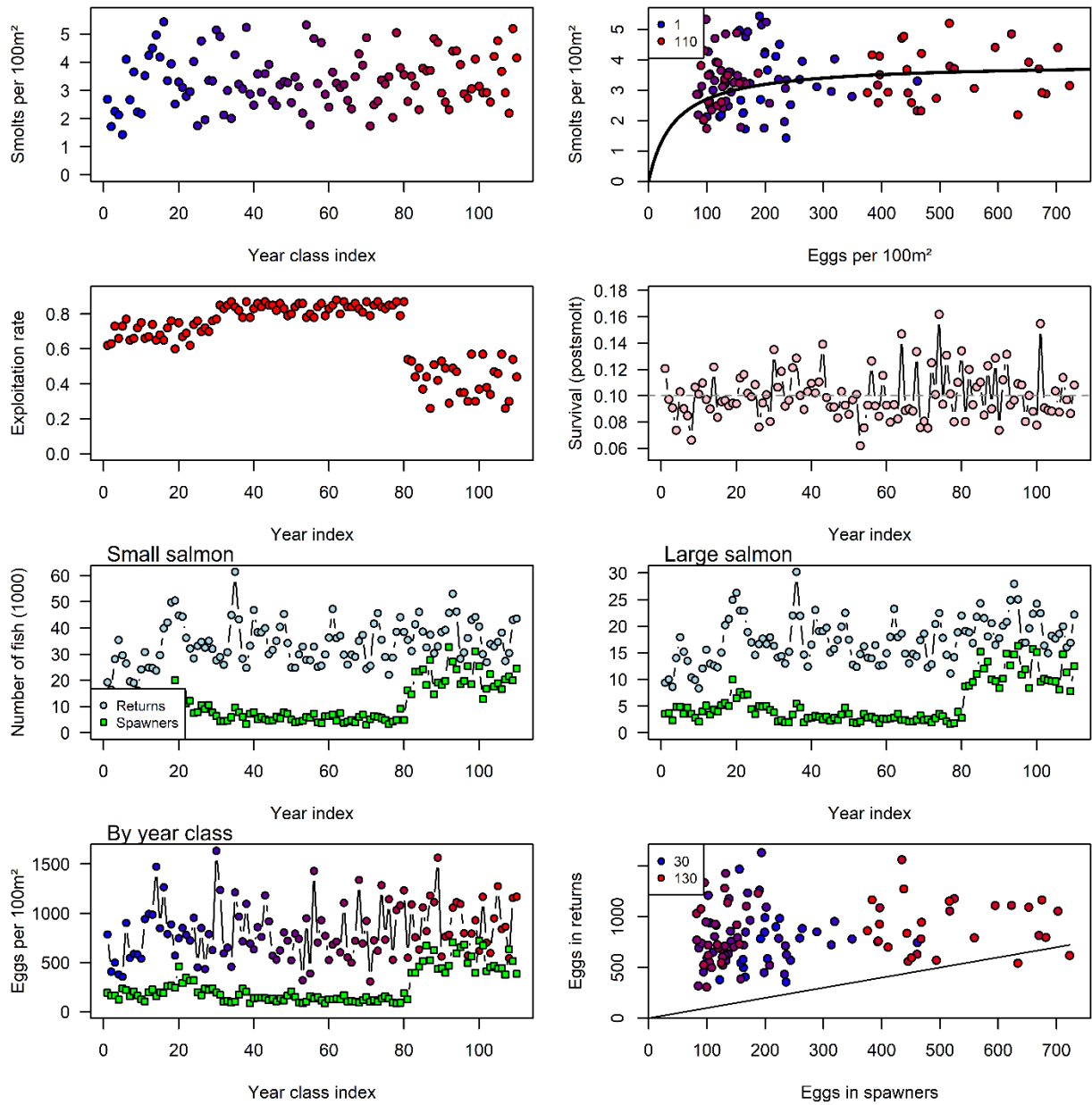


Figure A1.5. Simulated data series for a mean stationary post-smolt survival rate of 10%.

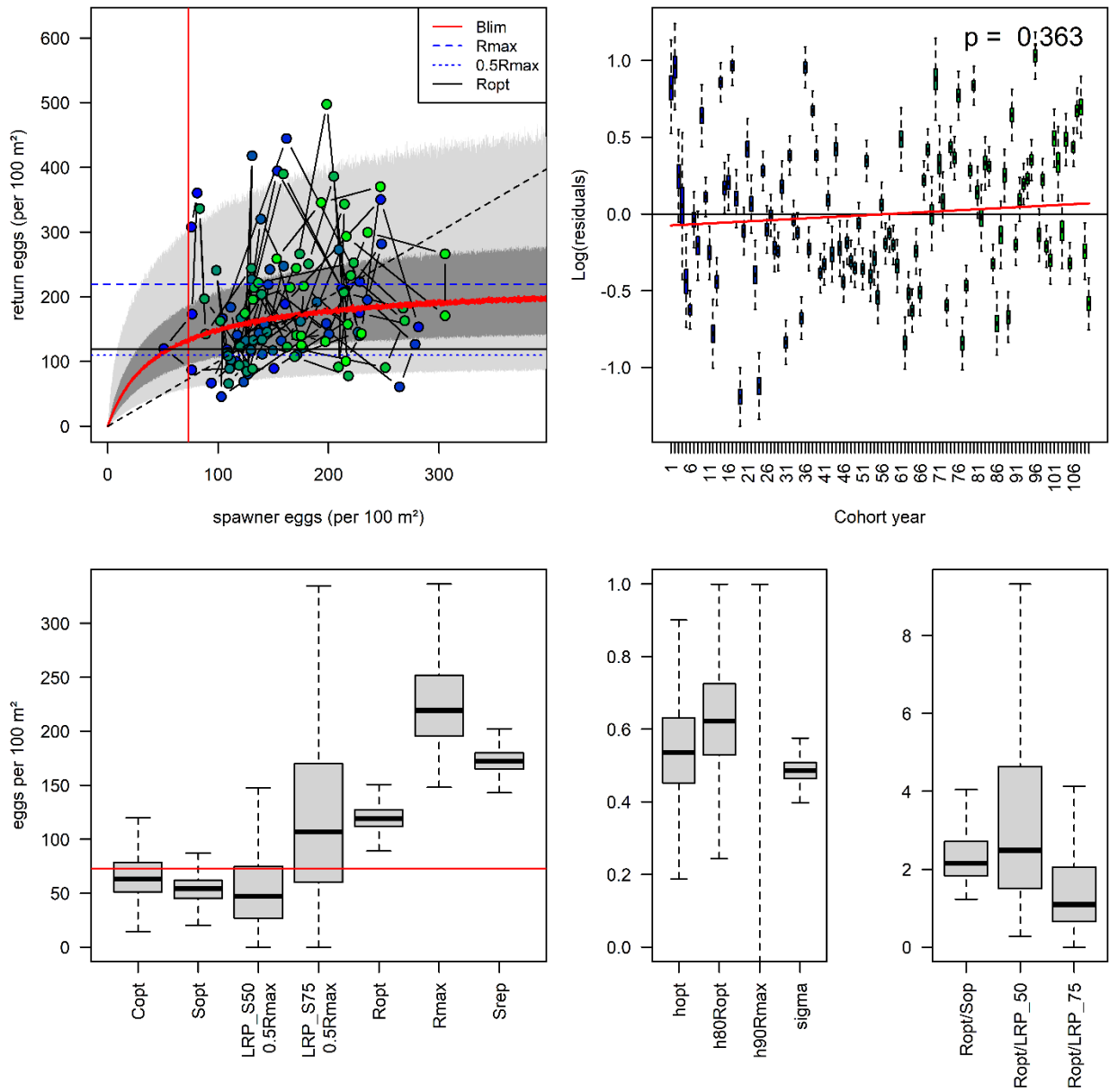


Figure A1.6. Diagnostics and reference values of fitting the Beverton-Holt stock and recruitment function to the simulated egg to egg time series for a mean stationary post-smolt survival rate of 2%.

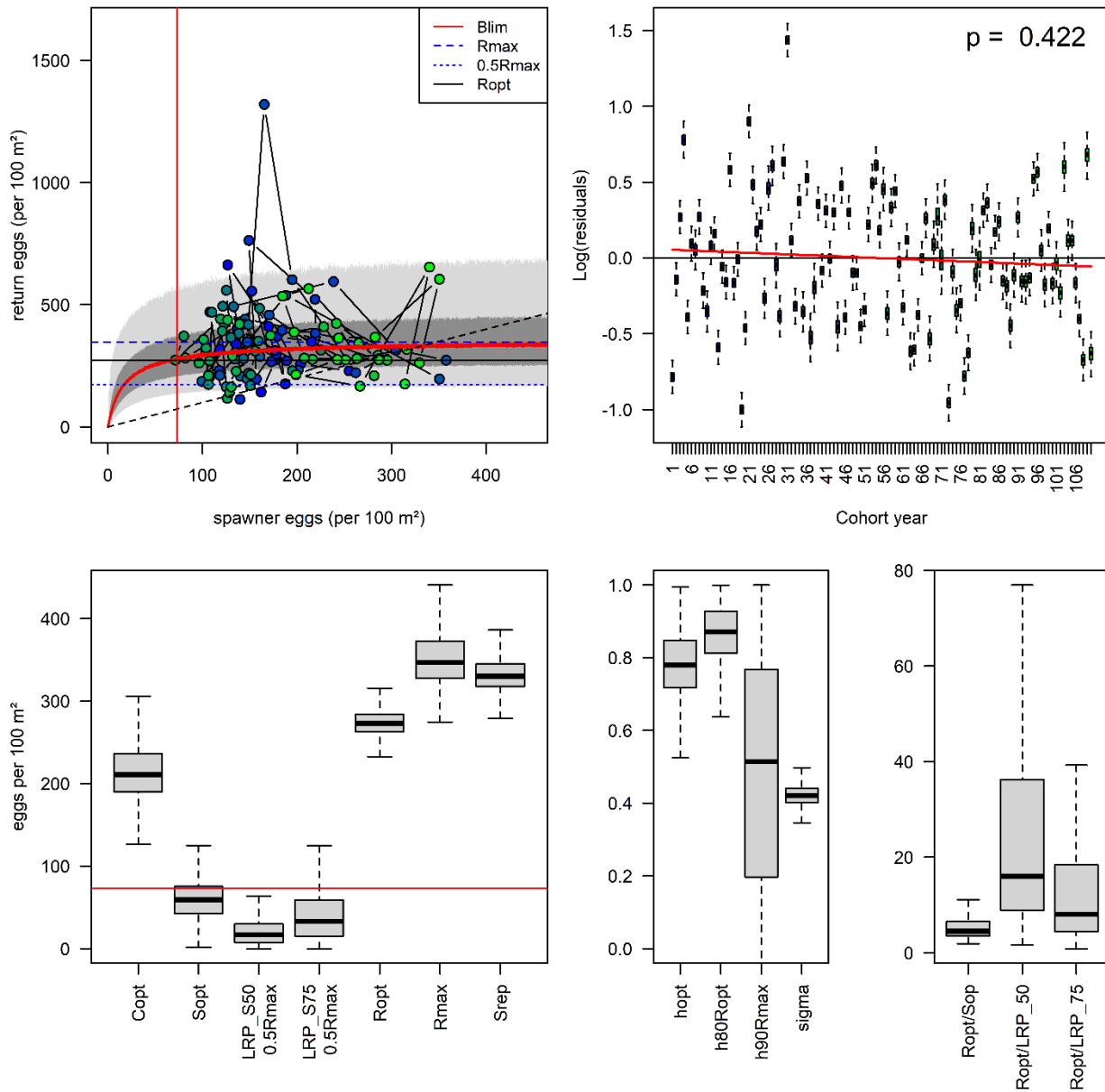


Figure A1.7. Diagnostics and reference values of fitting the Beverton-Holt stock and recruitment function to the simulated egg to egg time series for a mean stationary post-smolt survival rate of 4%.

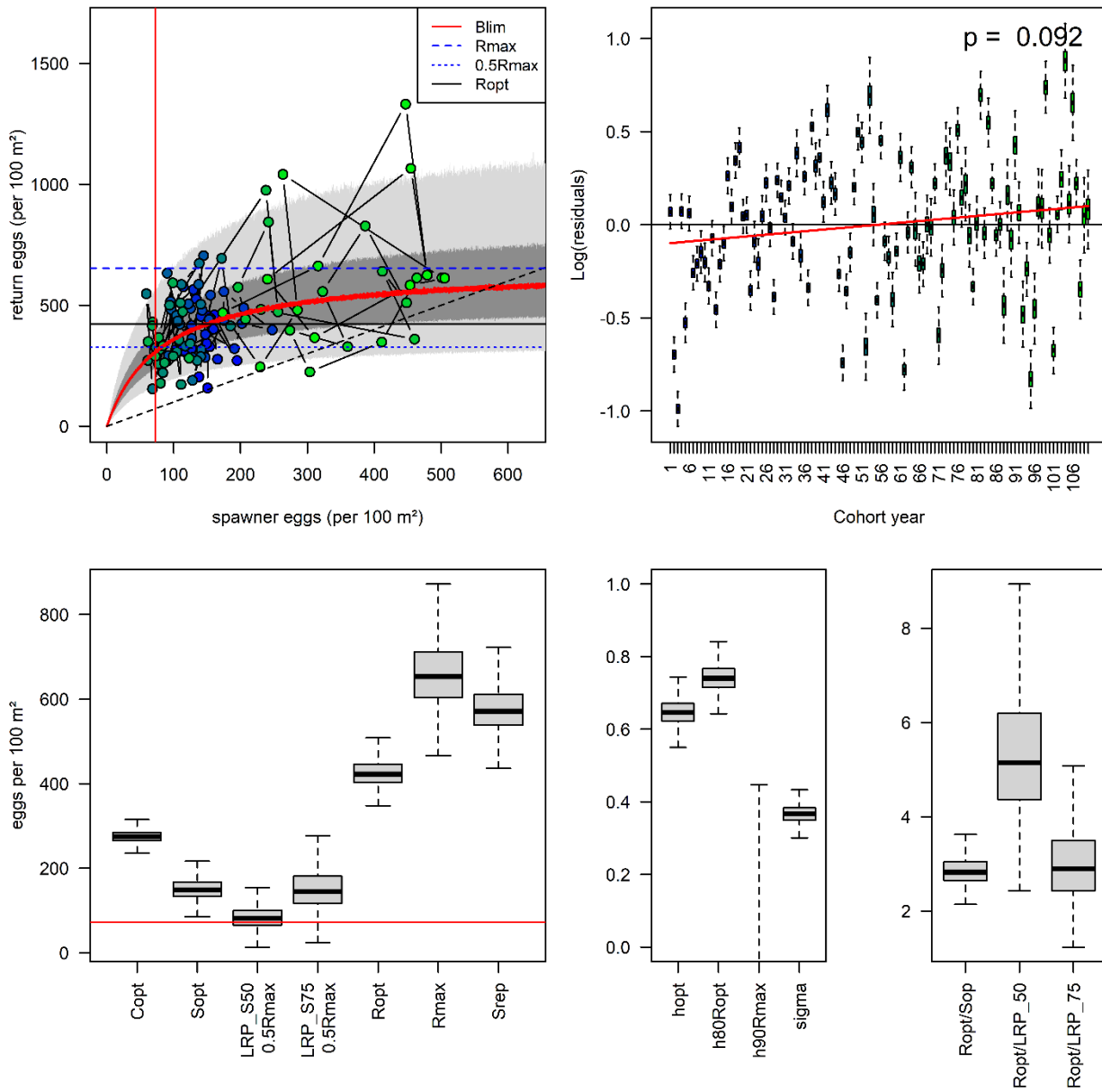


Figure A1.8. Diagnostics and reference values of fitting the Beverton-Holt stock and recruitment function to the simulated egg to egg time series for a mean stationary post-smolt survival rate of 6%.

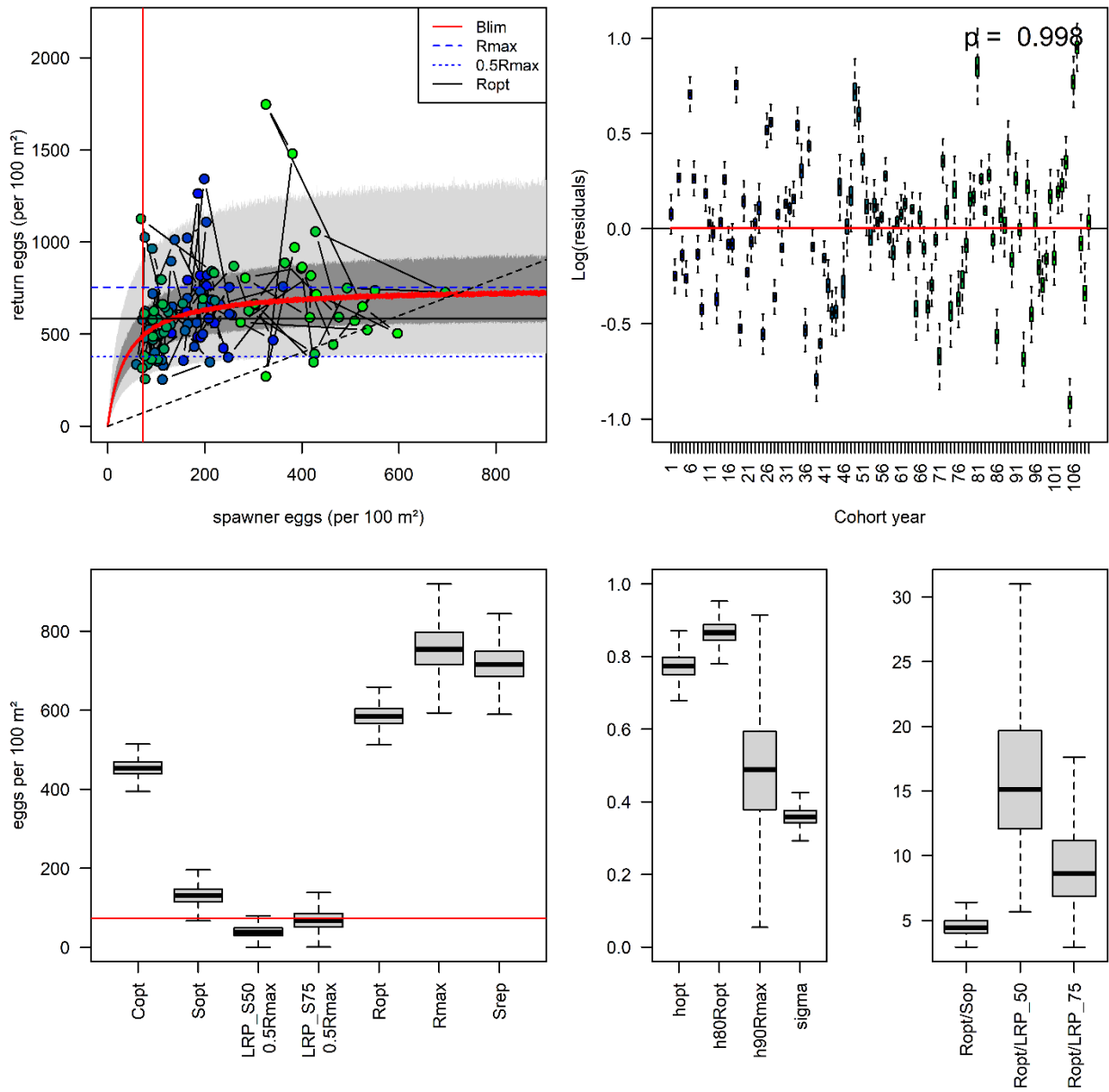


Figure A1.9. Diagnostics and reference values of fitting the Beverton-Holt stock and recruitment function to the simulated egg to egg time series for a mean stationary post-smolt survival rate of 8%.

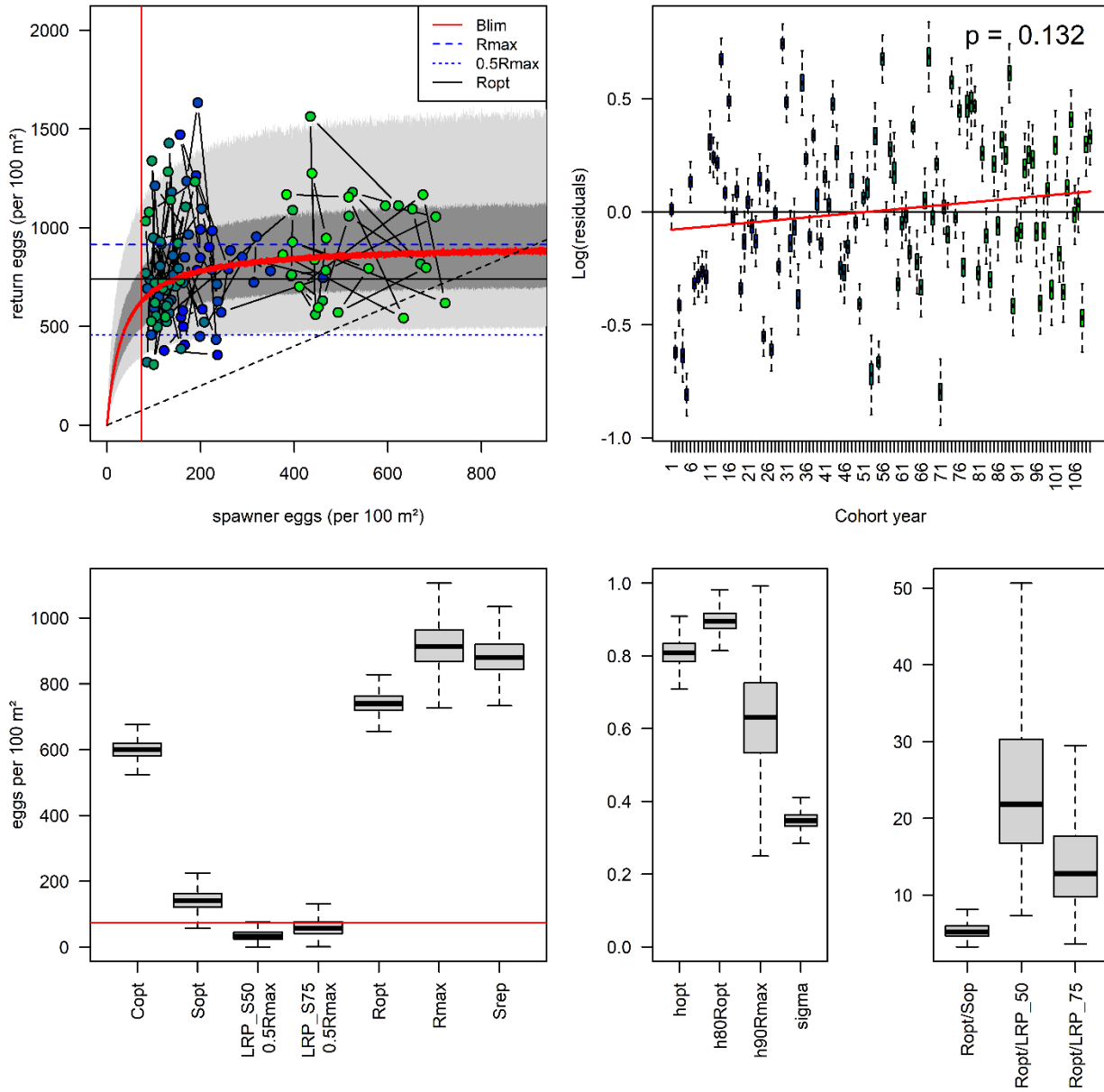


Figure A1.10. Diagnostics and reference values of fitting the Beverton-Holt stock and recruitment function to the simulated egg to egg time series for a mean stationary post-smolt survival rate of 10%.

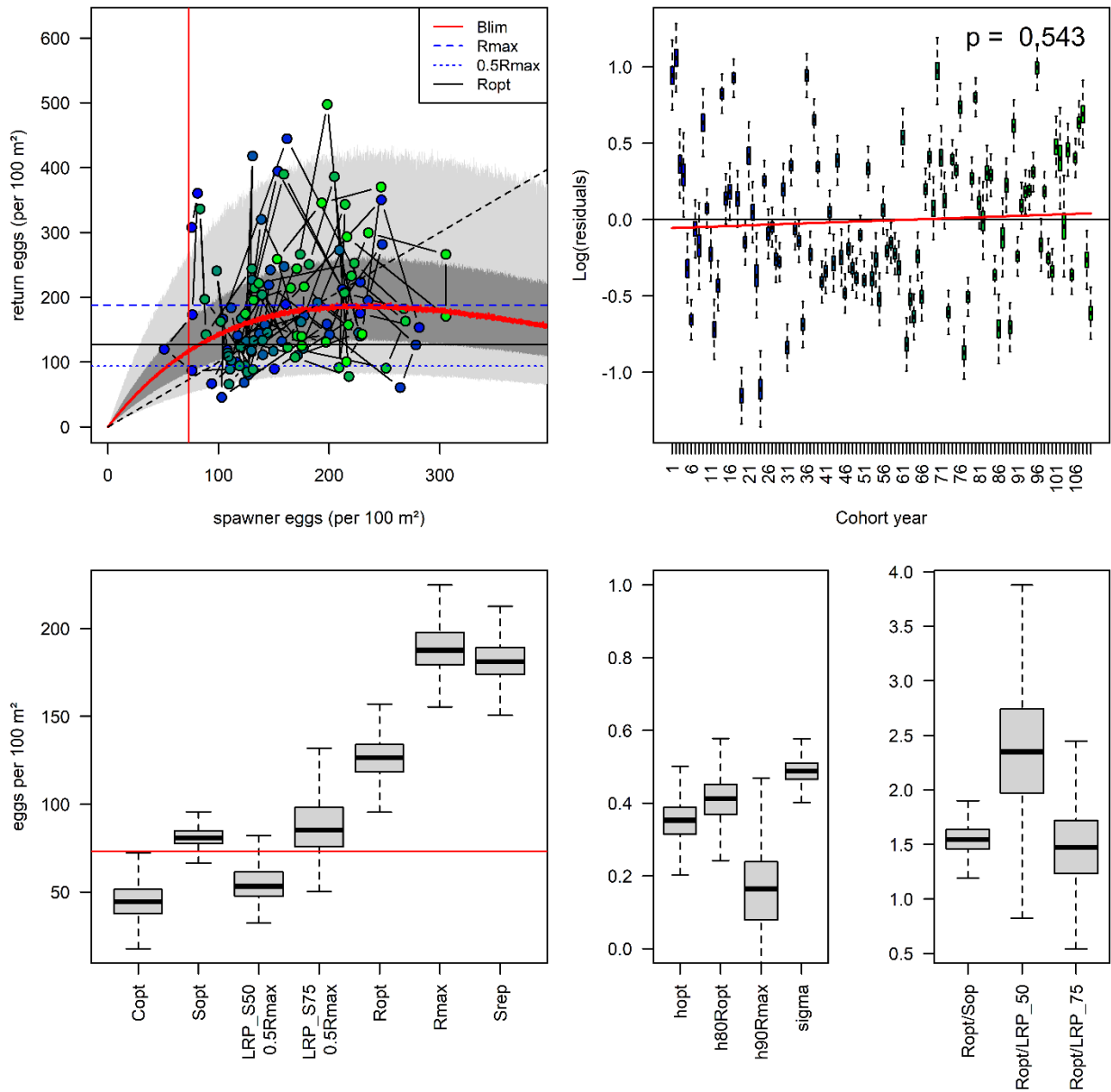


Figure A1.11. Diagnostics and reference values of fitting the Ricker stock and recruitment function to the simulated egg to egg time series for a mean stationary post-smolt survival rate of 2%.

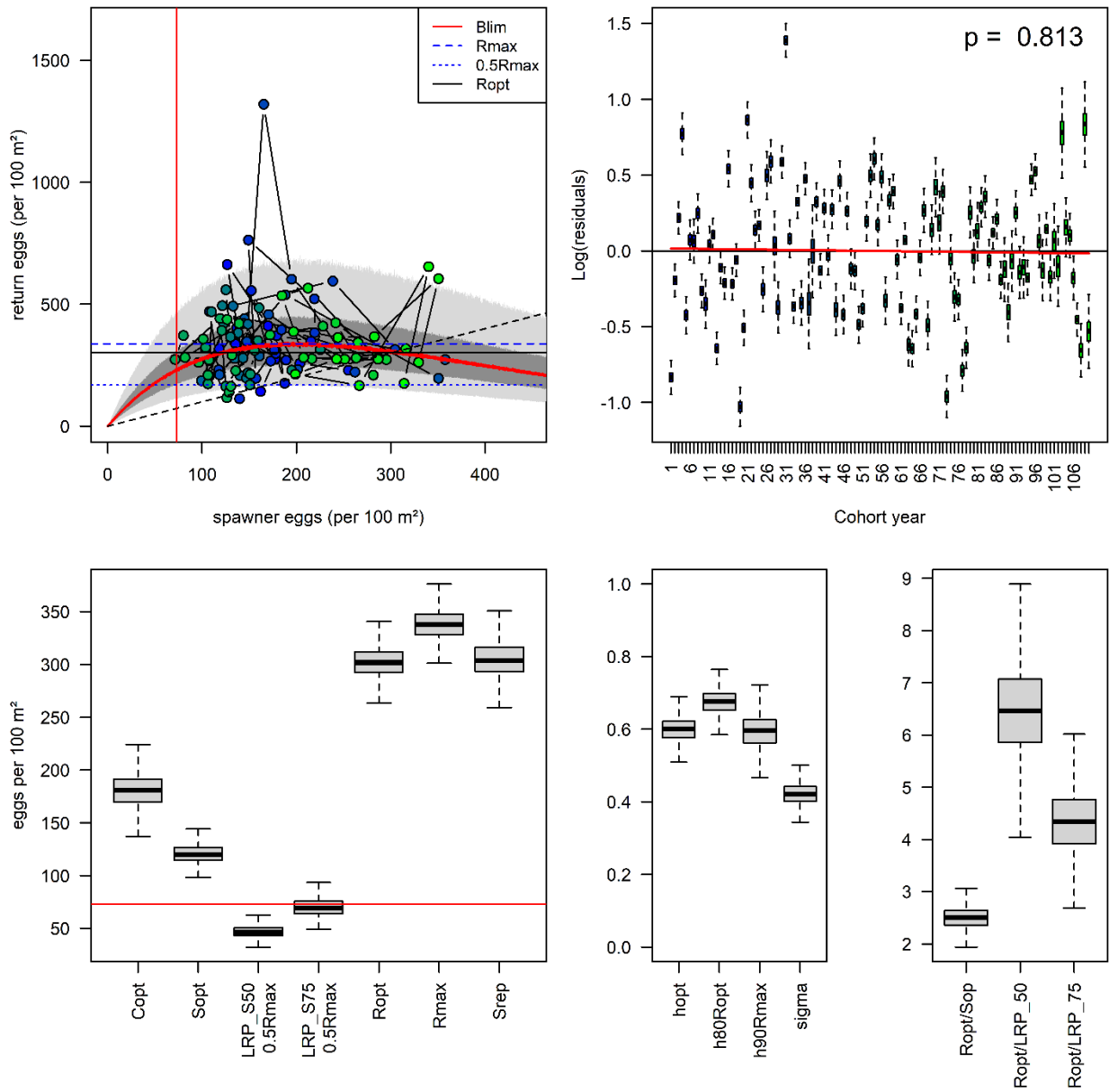


Figure A1.12. Diagnostics and reference values of fitting the Ricker stock and recruitment function to the simulated egg to egg time series for a mean stationary post-smolt survival rate of 4%.

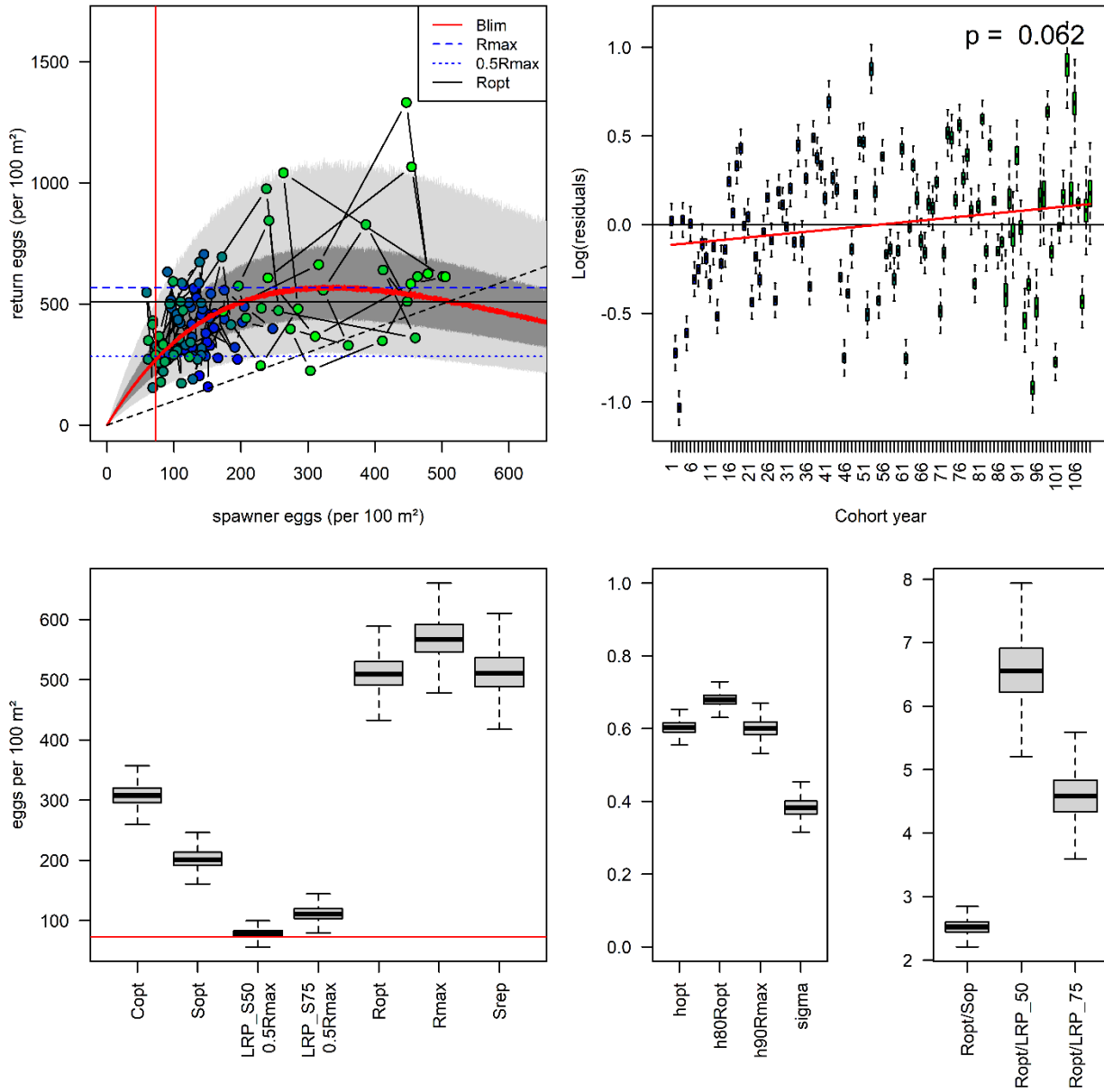


Figure A1.13. Diagnostics and reference values of fitting the Ricker stock and recruitment function to the simulated egg to egg time series for a mean stationary post-smolt survival rate of 6%.

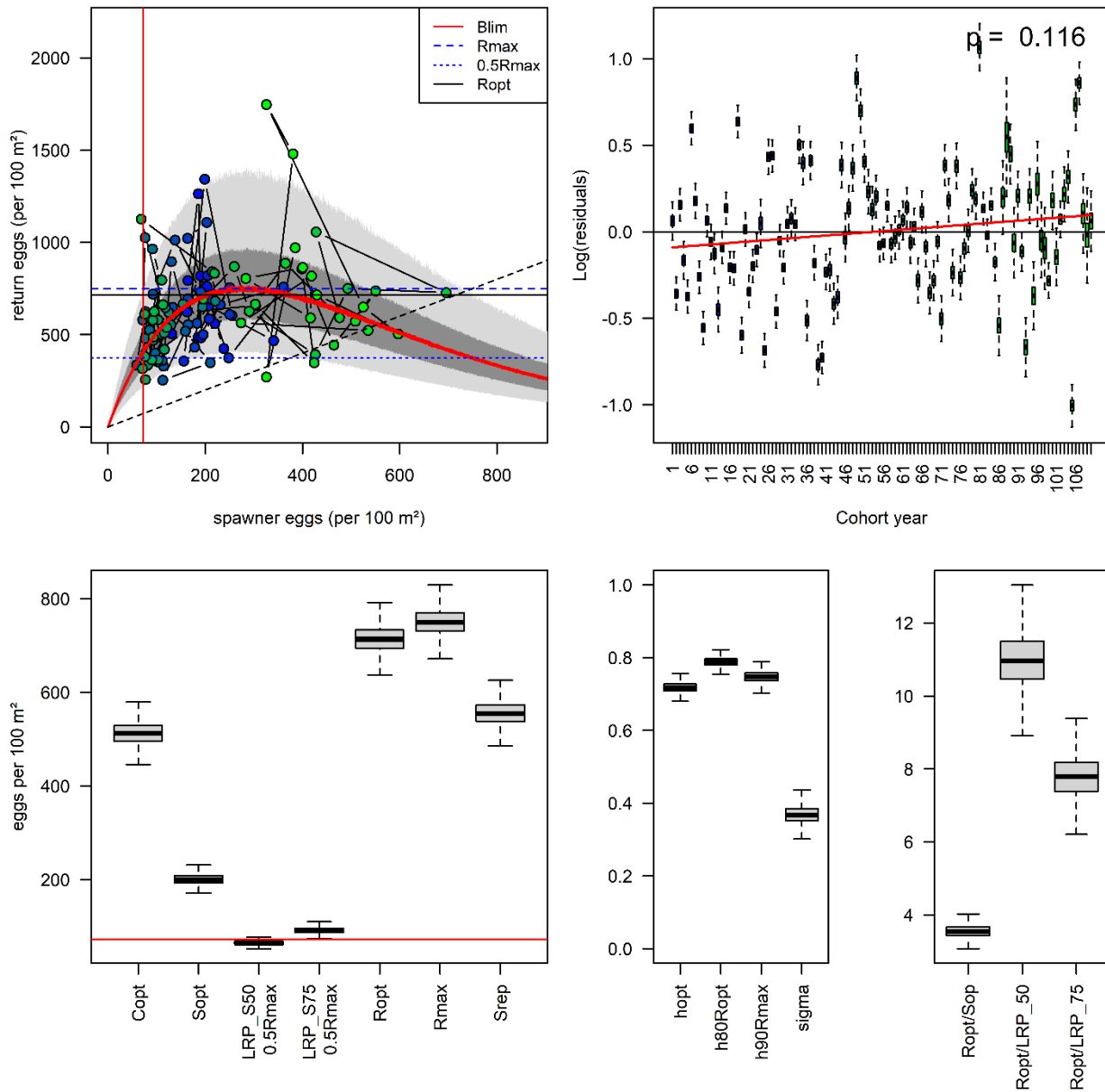


Figure A1.14. Diagnostics and reference values of fitting the Ricker stock and recruitment function to the simulated egg to egg time series for a mean stationary post-smolt survival rate of 8%.

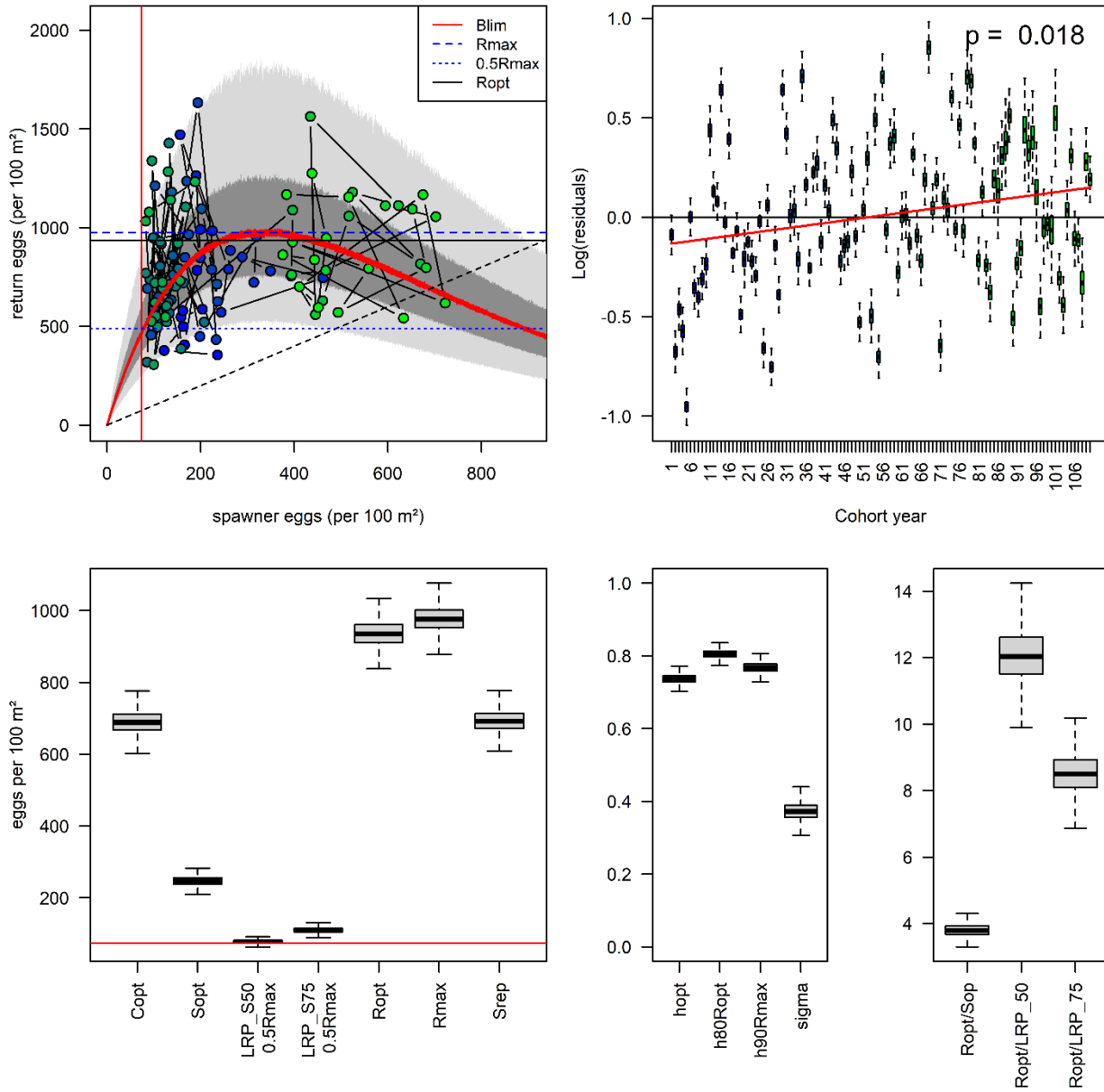


Figure A1.15. Diagnostics and reference values of fitting the Ricker stock and recruitment function to the simulated egg to egg time series for a mean stationary post-smolt survival rate of 10%.

APPENDIX 2. MIRAMICHI RIVER AND BRANCH SPECIFIC RECONSTRUCTION OF EGGS BY YEAR-CLASS AND RESULTS OF THE STOCK AND RECRUITMENT FITS

The Miramichi River is comprised of a network of six rivers whose outflows enter in tidal waters of an extended estuarine zone referred to as the Miramichi River (DFO 2018b; Douglas et al. *in prep.*²). Annual published estimates of returns and spawners of Atlantic Salmon are available for the Miramichi River for the period 1971 to 2019 (DFO 2020a; Douglas et al. *in prep.*²) and specific estimates for the Southwest Miramichi system (comprised of the Barnaby River, Renous River, Southwest Miramichi River) and the Northwest Miramichi system (comprised of the Northwest Millstream, Little Southwest Miramichi River, Northwest Miramichi River) are available for the period 1984 to 2019 (Douglas et al. *in prep.*²). The estimates of returns are obtained from catches at index trapnets in the estuary of the Northwest and Southwest Miramichi rivers combined with mark and recapture data to estimate the proportions of the returns intercepted at the trapnets, augmented with indicators of abundance from three headwater barriers and catches at Crown Reserve waters of the Northwest Miramichi system (Douglas et al. *in prep.*²). For the period 1984 to 2019, a Bayesian hierarchical model is used to estimate annual returns of small salmon (< 63 cm fork length) and large salmon (>= 63 cm fork length) to each of the Northwest Miramichi and Southwest Miramichi systems with returns to the Miramichi River the sum of the branch estimates. Estimates of returns for the period 1971 to 1983 are taken from published values in Courtenay et al. (1993).

Spawners are estimated by subtracting from the returns the estimates of commercial fisheries harvests in the Miramichi Bay commercial fishery (1971 to 1983), Indigenous peoples Food, Social and Ceremonial (FSC) fisheries harvests in the Miramichi River and Bay, and recreational fisheries catches and harvests. In 1984, important fisheries management changes were introduced that included the closure of the commercial salmon fishery in the Maritime provinces and large portions of Quebec, and the mandatory release of large salmon in the recreational fisheries of the Maritime provinces. Recreational fisheries catches and harvest from the Northwest Miramichi system and the Southwest Miramichi system are available for the period 1971 to 1995 and 1997 (Moore et al. 1995; Chaput et al. 1998), but catch and harvest estimates are not available for 1996 and 1998 to 2019. Recreational fishery catches and harvests were estimated for the years without values by applying the derived exploitation rates from the model based on the years with angling statistics to the return estimates by size group of salmon for the years 1996, 1998 to 2019. Since 1984, no retention of large salmon has been allowed in the recreational fishery therefore all large salmon catch is considered to be released. Since 2015, mandatory catch and release measures were introduced for small salmon and for those years, all the estimated catches are considered released. A 3% catch and release mortality is assumed and applied to the released portion of the catches for small salmon and large salmon (Randall et al. 1986).

Sampling of adult returning salmon has occurred every year at index trapnets operated by DFO Science. The sampling includes fork length, sex (generally external) and collection of scales for age interpretation (Hayward 2001; Hayward et al. 2014).

No branch specific (Northwest, Southwest) sampling data are available for the years 1984 to 1991 but overall Miramichi River samples were collected from the Millbank trapnet located in the main stem of the Miramichi River below the confluence of the two branches. For those years, the biological characteristics (fork length, proportion female, age structure) from the Miramichi River sampling were assumed for the two branches.

Branch specific age interpretations from scales are not available for all years over the period 1984 to 2019 of the branch assessments. For the period 1971 to 1991, samples and age interpretations from scale samples collected annually from the Millbank trapnet were assumed

to apply to the Miramichi River overall and to each of the branches. For the period 1992 to 2019, sampling occurred at upriver trapnets in each branch although scale interpretations for age were not available in all years for each branch. The following infilling procedure was used for the years with missing data:

- Northwest Miramichi 1994 to 1997: no age samples for small salmon and large salmon. The average proportions at age for small salmon and large salmon separately from samples in 1992, 1993, 1998 and 1999 from the Northwest Miramichi were used to fill in the missing data.
- Small salmon age interpretations are not available for the years 2014 to 2019 in both the Northwest Miramichi and the Southwest Miramichi. The average age proportions of small salmon from the previous five years (2009 to 2013), by branch, were used to fill in in the age structure.
- Large salmon age interpretations are not available for 2018 and 2019 for the Southwest Miramichi. The average proportions from the previous five years (2013 to 2017) are used to fill in the age structure.
- Large salmon age interpretations are not available for 2019 for the Northwest Miramichi. The average proportions from the previous five years (2014 to 2018) are used to fill in the age structure.

Freshwater ages of outmigrating salmon smolts are predominantly ages 2 and 3 years with low proportions of age 4 and age 5 years (Douglas et al. *in prep.*²). The sea age of salmon is very diverse with 52 unique maiden and repeat spawning histories interpreted from scales of salmon from the Miramichi (Douglas et al. *in prep.*²). One-sea-winter (1SW) and two-sea-winter (2SW), with a low proportion of three-sea-winter (3SW) maiden salmon returns are the most common. There is a large variety of consecutive and alternate repeat spawner age categories with the maximum sea age recorded to date of nine years (Douglas et al. *in prep.*²). Reconstruction of the returns of a year-class included the maiden and repeat spawner strategies, adjusted to their originating year of egg deposition based on the estimated total age (plus one for the year of egg deposition). Considering the combined river and sea age structure of salmon in the Miramichi River, year-class estimates of returns are considered complete for the 1971 to 2013 cohorts.

Proportion female and fecundity of female salmon were estimated for small salmon and large salmon size groups separately. Generally, the small salmon category is comprised of maiden 1SW salmon and some consecutive repeat spawning 1SW fish whereas the large salmon category includes 2SW and 3SW salmon and all other categories of repeat spawners. The size – fecundity relationship of Randall (1989) for small salmon and large salmon is used to estimate annually the eggs per female in each size group based on the mean size of sampled fish per size group.

Run reconstructed results for the Miramichi River for the period 1971 to 2019 are summarized in Appendix 2 Figure A2.1 and run reconstructed results for Northwest Miramichi and Southwest Miramichi for the period 1984 to 2019 are summarised in Appendix 2 Figure A2.6.

We examined three time series of adult spawners and returns to the Miramichi (Table 1). The first and longest time series is for the Miramichi River for the period 1971 to 2019; this series includes the sum of the estimated returns and spawners to the Northwest Miramichi and Southwest Miramichi for the years 1984 to 2019. A subset of this data for the period 1984 to 2019 is also considered because the returns prior to 1984 include estimates of harvests in the local commercial fisheries which have more uncertainty for numbers of fish, and origin of fish.

The other two time series are the branch specific estimates of returns and spawners to the Northwest Miramichi and Southwest Miramichi for the period 1984 to 2019 (Douglas et al. *in prep.*²).

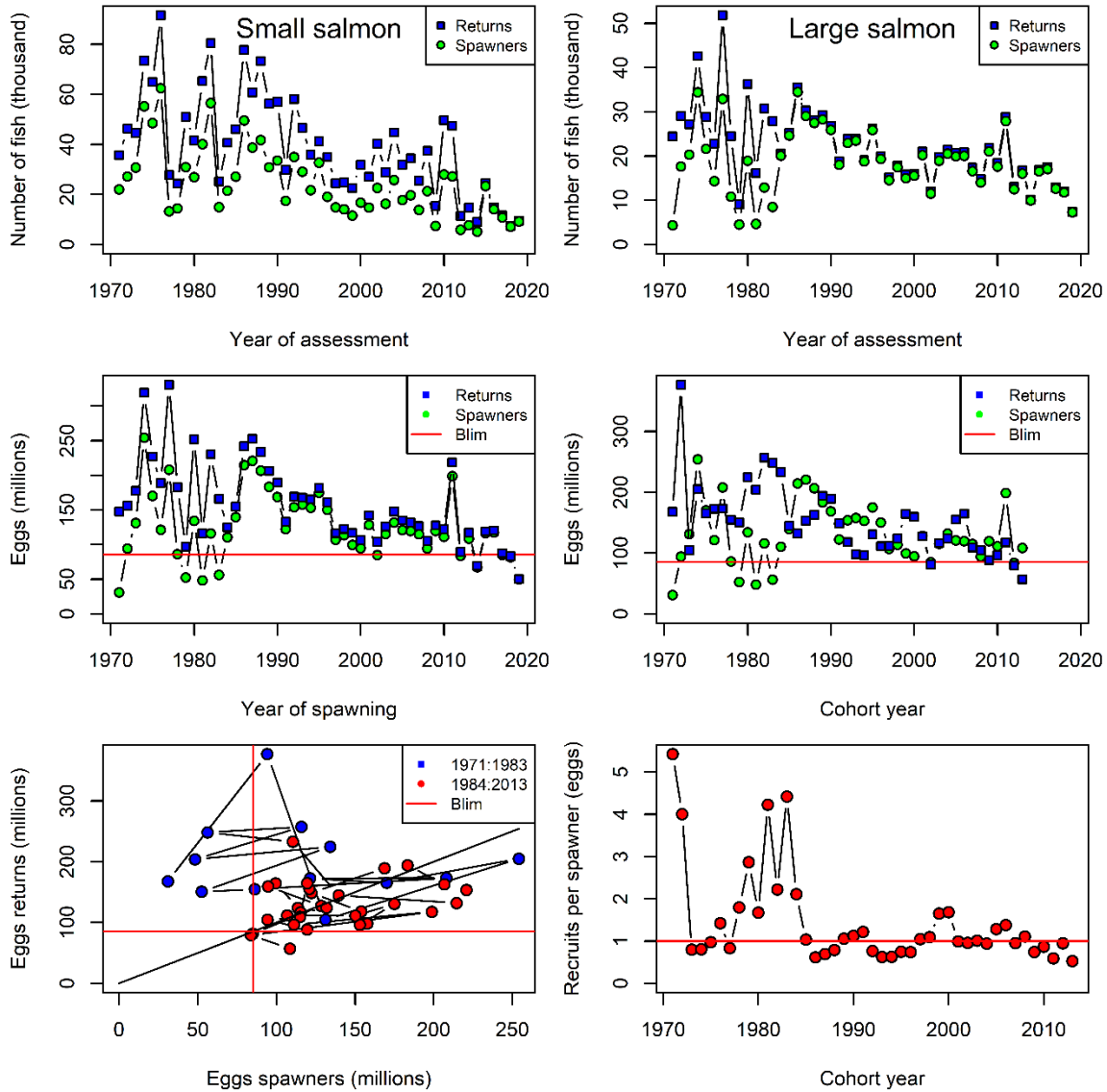


Figure A2.1. Miramichi River assessments of returns and spawners of small salmon (top row left panel), and large salmon (top row right panel). Run reconstructed values of eggs (millions) in spawners and eggs in returns by year of assessment and by cohort year, 1917 to 2103 are shown in the middle row. The two panels in the bottom row show the scatter plot of eggs in spawners and eggs in returns by cohort year (left panel) and the recruits per spawner (eggs) by cohort year (right panel). The horizontal red line in the two upper panels and the bottom left panel is the total egg equivalent for the LRP for the Miramichi River (DFO 2018b).

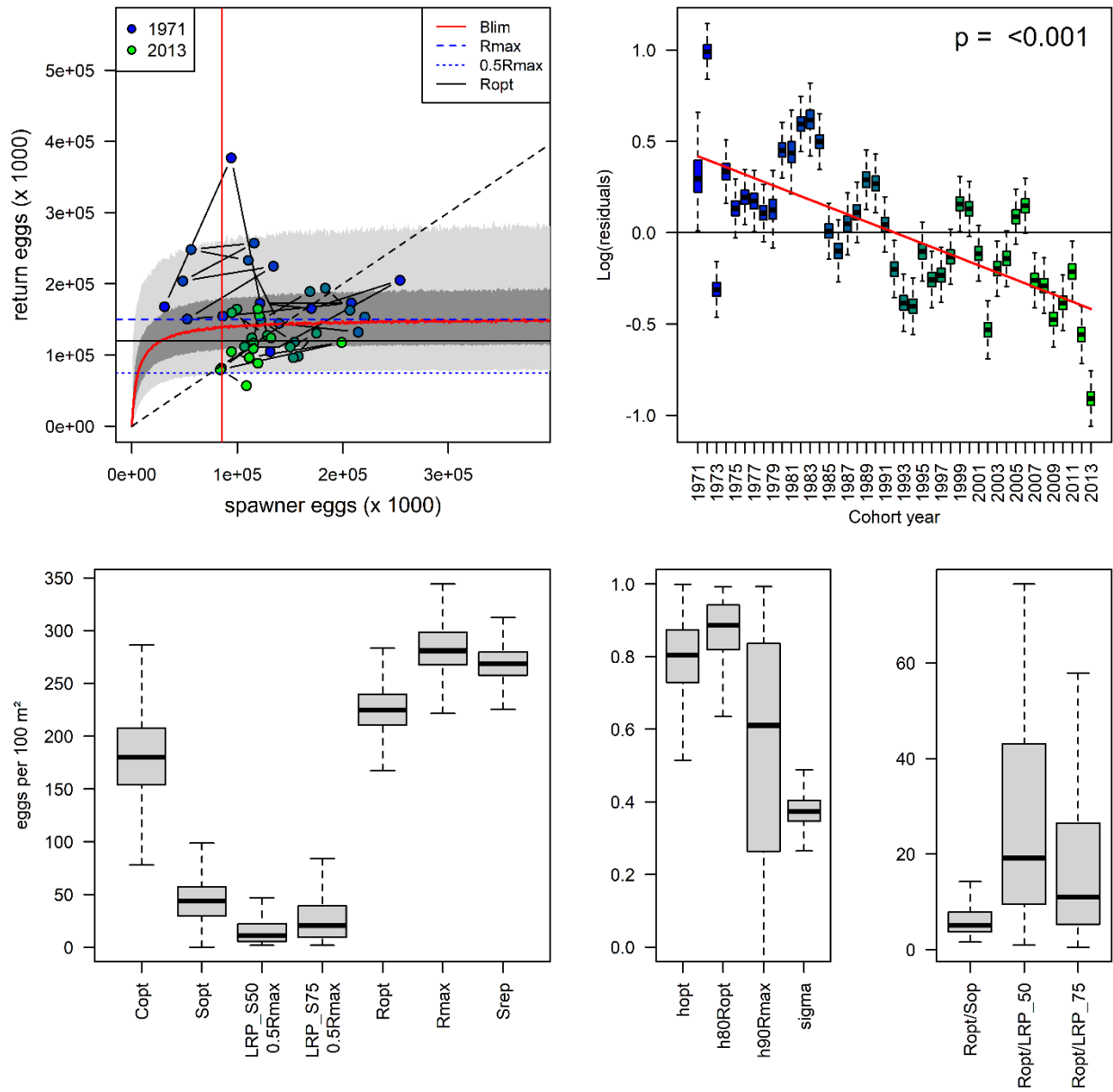


Figure A2.2. Diagnostics and reference values of fitting the Beverton-Holt stock and recruitment function to the egg to egg (eggs in 1000s) time series for the Miramichi River, 1971 to 2013 cohorts. Habitat area of the Miramichi is 53.433 million m².

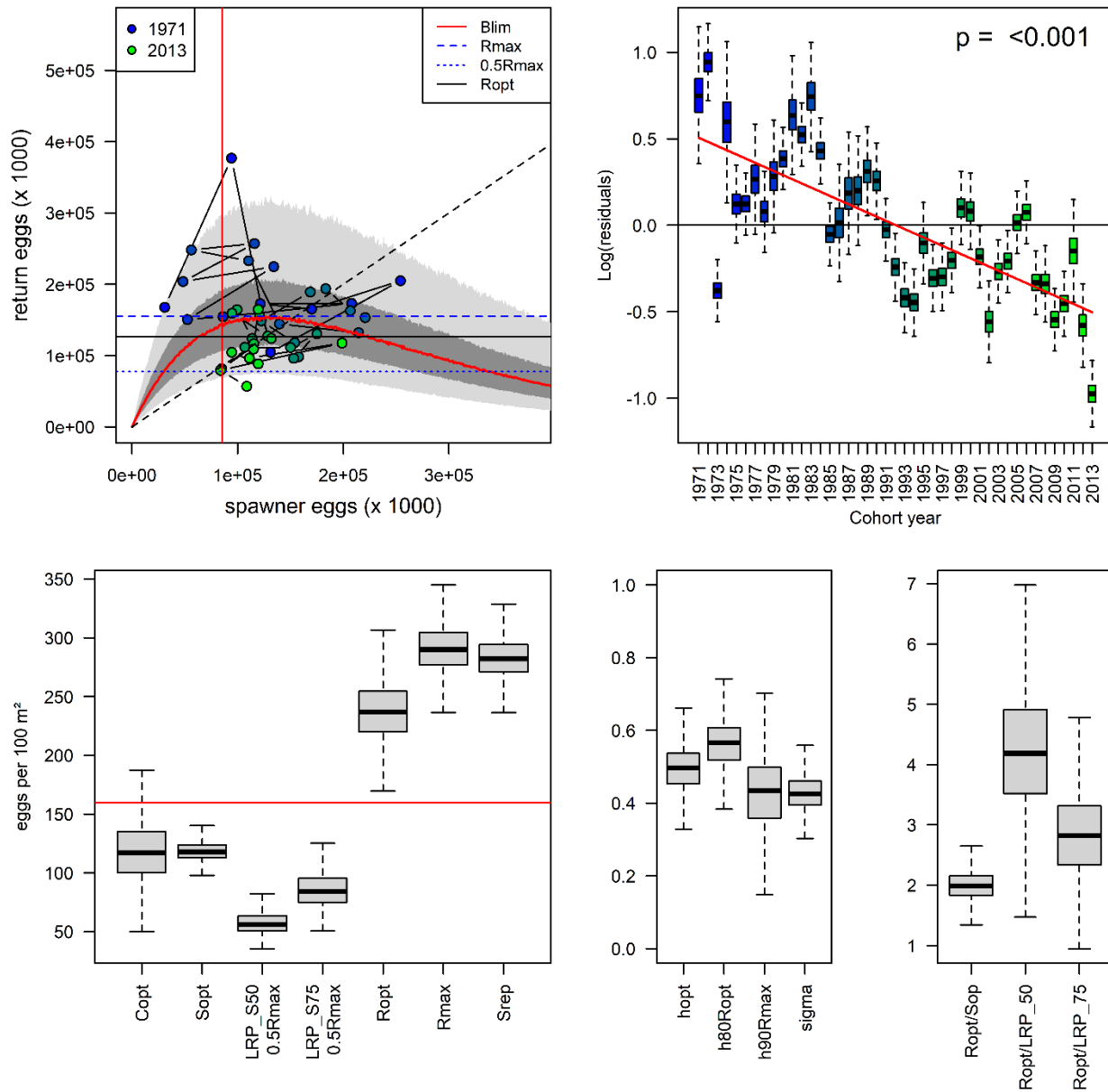


Figure A2.3. Diagnostics and reference values of fitting the Ricker stock and recruitment function to the egg to egg (eggs in 1000s) time series for the Miramichi River, 1971 to 2013 cohorts. Habitat area of the Miramichi is 53.433 million m².

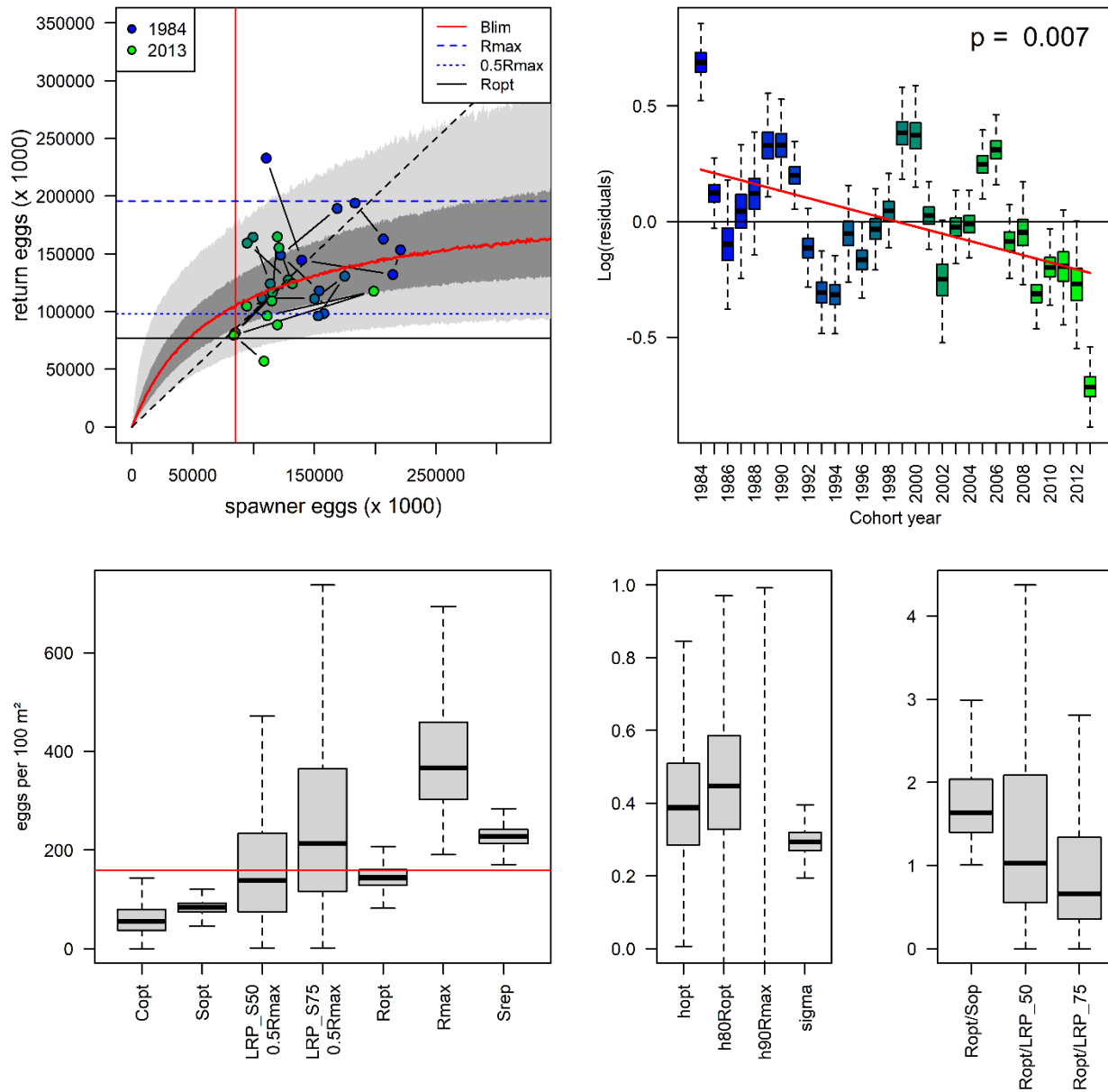


Figure A2.4. Diagnostics and reference values of fitting the Beverton-Holt stock and recruitment function to the egg to egg (eggs in 1000s) time series for the Miramichi River, 1984 to 2013 cohorts. Habitat area of the Miramichi is 53.433 million m².

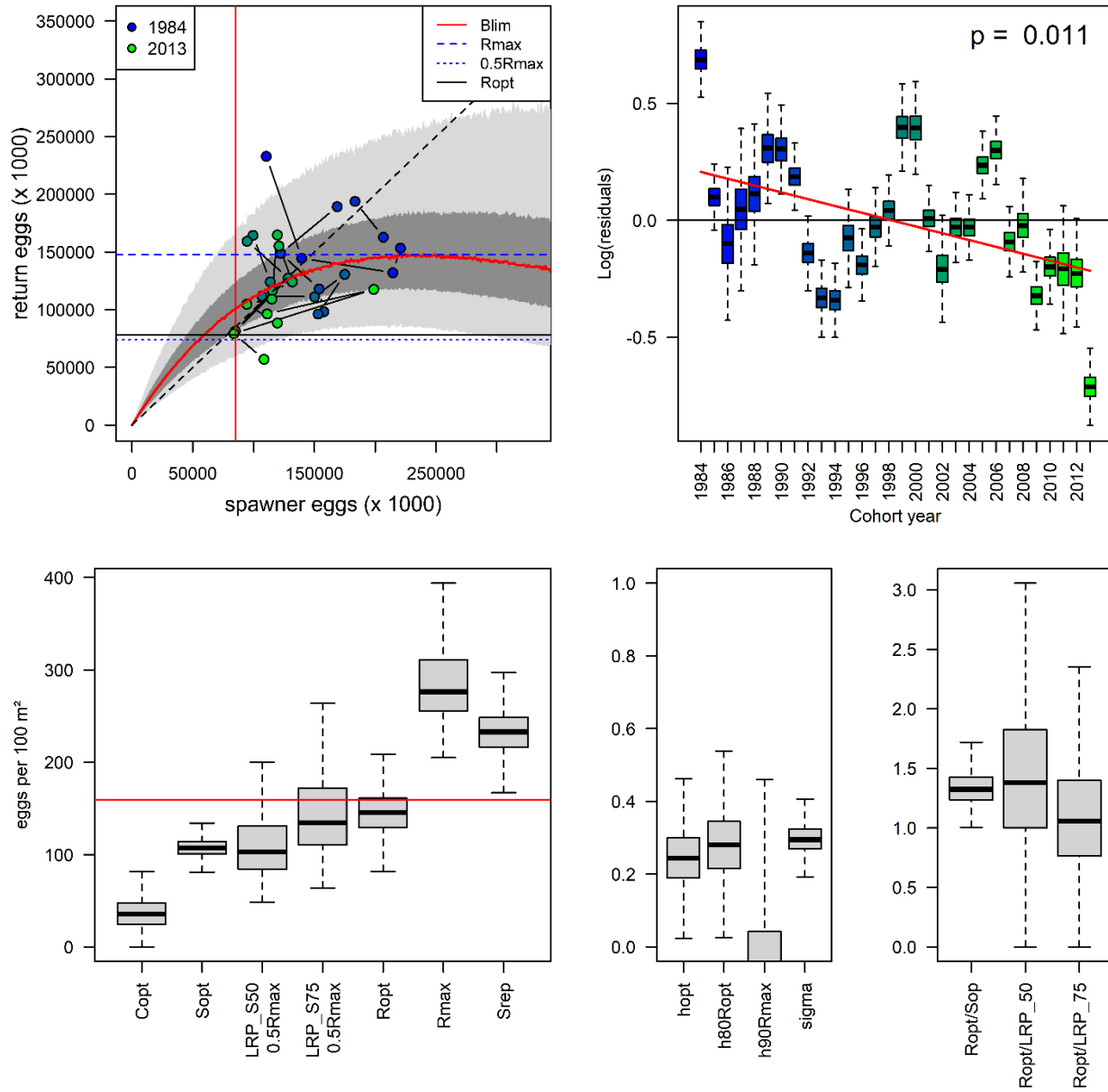


Figure A2.5. Diagnostics and reference values of fitting the Ricker stock and recruitment function to the egg to egg (eggs in 1000s) time series for the Miramichi River, 1984 to 2013 cohorts. Habitat area of the Miramichi is 53.433 million m².

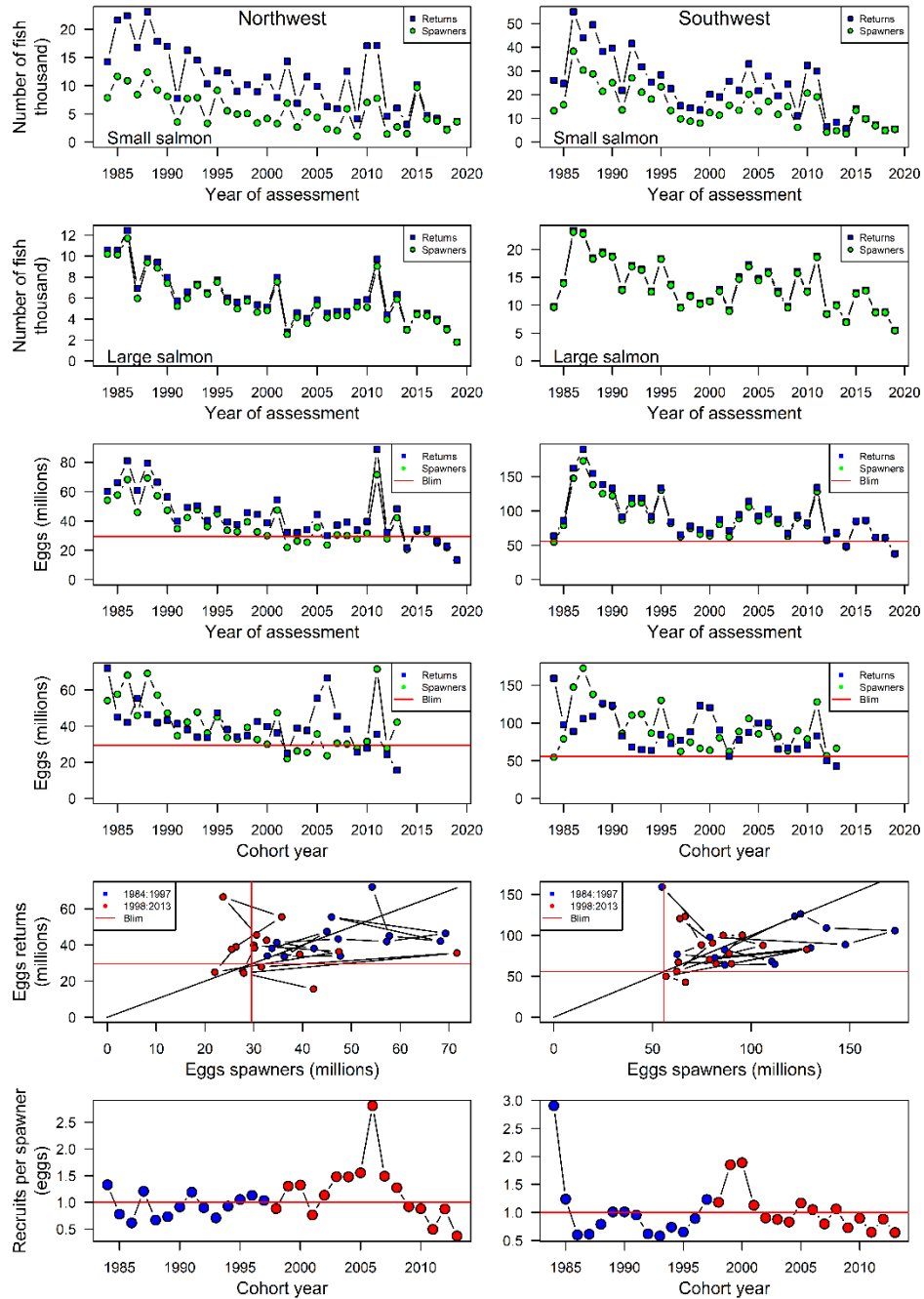


Figure A2.6. Northwest Miramichi (left column) and Southwest Miramichi (right column) assessments of returns and spawners of small salmon (top row), and large salmon (second row), run reconstructed values of eggs (millions) in spawners and eggs in returns by year of assessment 1984 to 2019 (third row) and by cohort year 1984 to 2013 (fourth row). The fifth row shows the scatter plot of eggs in spawners and eggs in returns by cohort year and the bottom row shows the recruits per spawner (eggs) by cohort year. The horizontal (and vertical) red line in the panels of the third to fifth rows is the total egg equivalent for the LRP for the each branch (DFO 2018b).

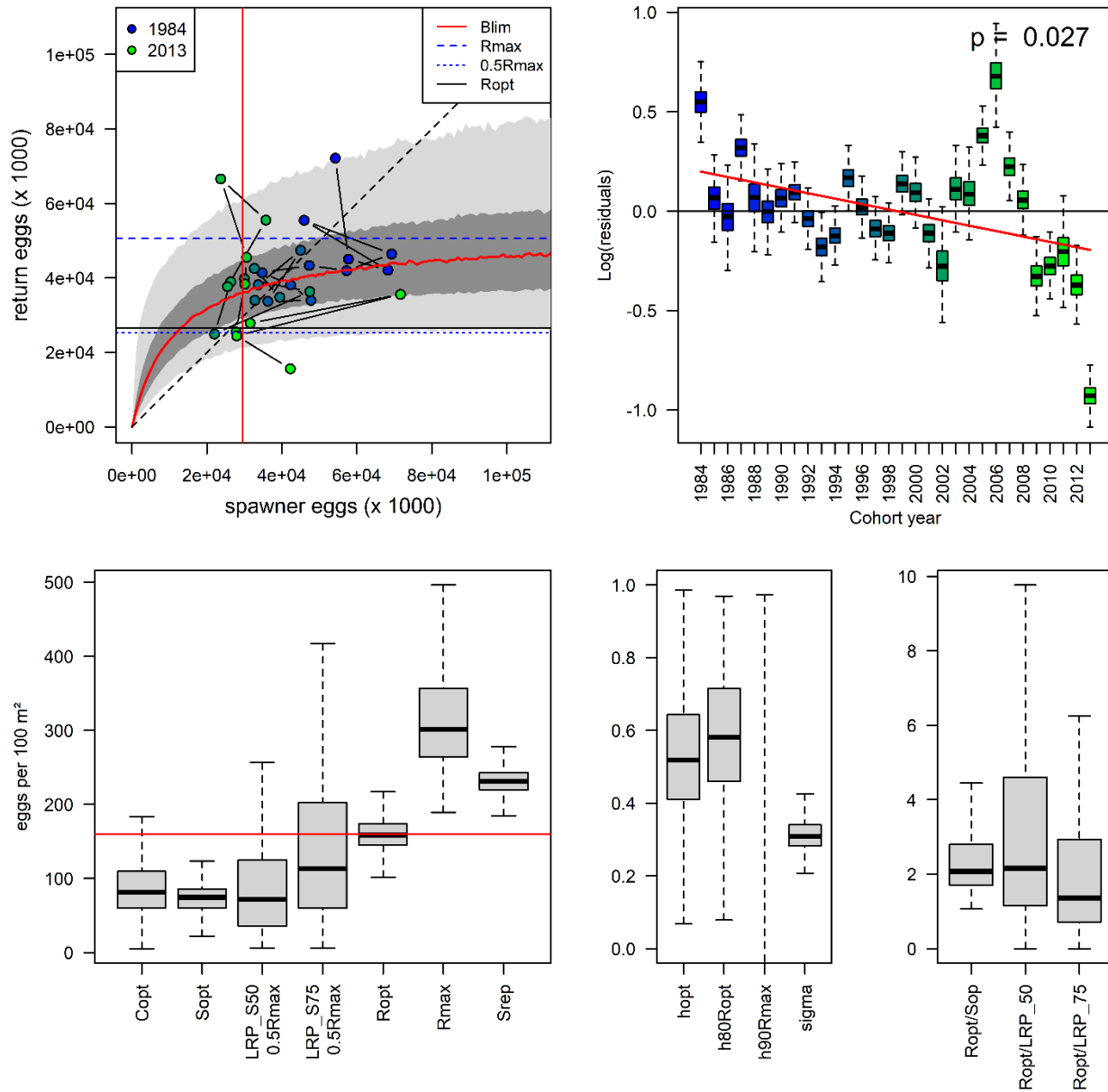


Figure A2.7. Diagnostics and reference values of fitting the Beverton-Holt stock and recruitment function fit to the egg to egg (eggs per 100 m² of habitat area for the river) time series for the Northwest River, 1984 to 2013 cohorts.

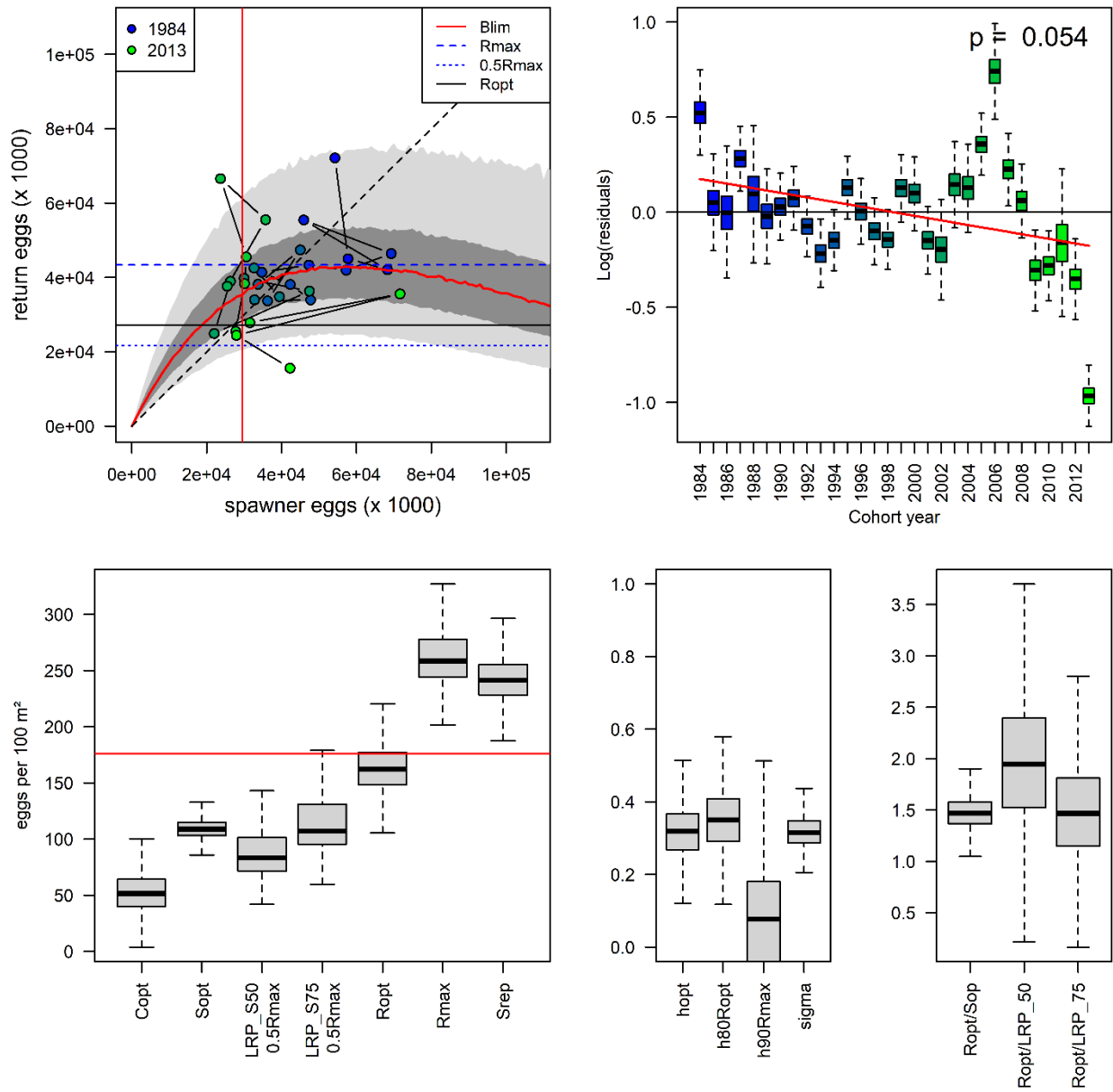


Figure A2.8. Diagnostics and reference values of fitting the Ricker stock and recruitment function fit to the egg to egg (eggs per 100 m² of habitat area for the river) time series for the Northwest River, 1984 to 2013 cohorts.

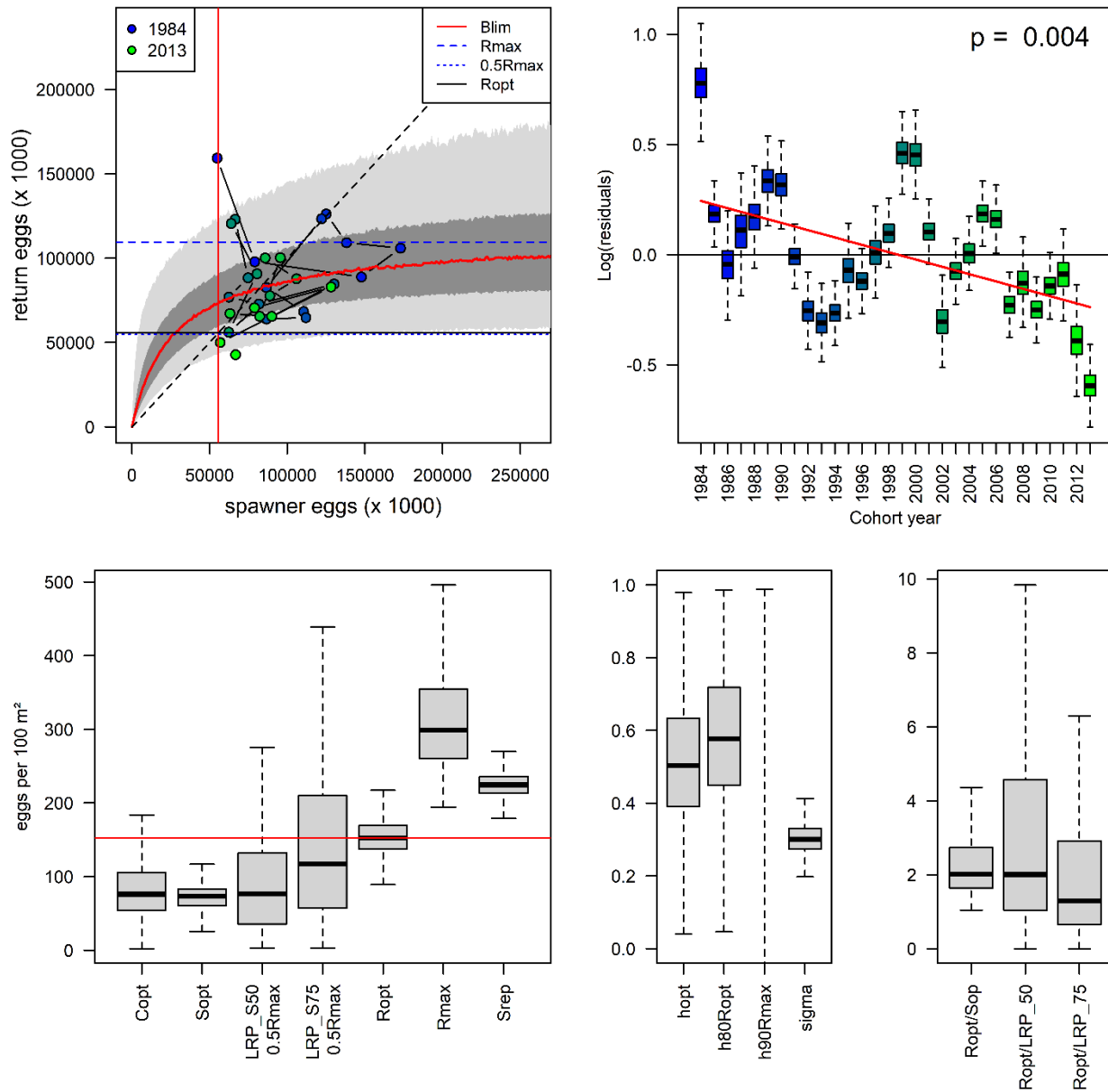


Figure A2.9. Diagnostics and reference values of fitting the Beverton-Holt stock and recruitment function fit to the egg to egg (eggs per 100 m² of habitat area for the river) time series for the Southwest River, 1984 to 2013 cohorts.

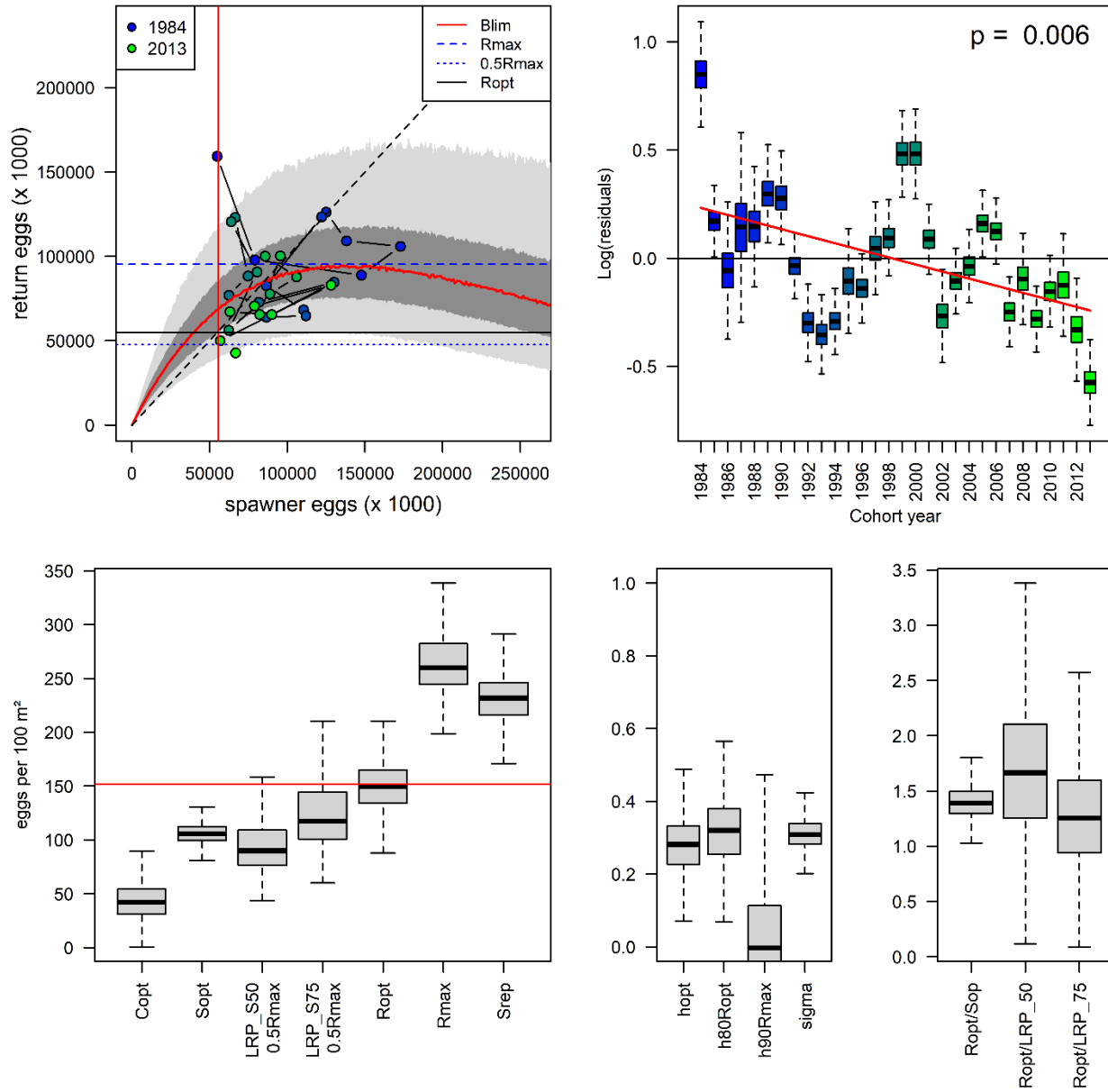


Figure A2.10. Diagnostics and reference values of fitting the Ricker stock and recruitment function fit to the egg to egg (eggs per 100 m² of habitat area for the river) time series for the Southwest River, 1984 to 2013 cohorts.

APPENDIX 3. MARGAREE RIVER RECONSTRUCTION OF EGGS BY YEAR CLASS AND RESULTS OF THE STOCK AND RECRUITMENT FITS

The data used in the reconstruction of returns and spawners for the Margaree River are presented in the following tables.

Table A3.1. Commercial harvest data for SFA 18 (in kg) obtained from published reports and converted to number of fish, assuming a mean weight of 5 kg per fish, and all large salmon. The commercial harvest data for 1961 to 1966 are from May and Lear (1971) whereas the harvest data for 1967 to 1984 are from Claytor et al. (1987). The harvest of Margaree River origin salmon is estimated assuming 30% of the total commercial harvests of SFA 18 are Margaree River origin (Chaput and Jones 1992).

Year	Commercial harvest (kg) in SFA 18	Commercial harvest (number of fish) in SFA 18	Commercial harvest (number of fish) of Margaree River origin
1961	11773	2355	706
1962	14491	2898	869
1963	12299	2460	738
1964	11405	2281	684
1965	12961	2592	778
1966	14745	2949	885
1967	12852	2570	771
1968	12537	2507	752
1969	9429	1886	566
1970	12874	2575	772
1971	4740	948	284
1972	8022	1604	481
1973	9340	1868	560
1974	14258	2852	855
1975	11727	2345	704
1976	10910	2182	655
1977	12913	2583	775
1978	11369	2274	682
1979	3199	640	192
1980	9946	1989	597
1981	5457	1091	327

Year	Commercial harvest (kg) in SFA 18	Commercial harvest (number of fish) in SFA 18	Commercial harvest (number of fish) of Margaree River origin
1982	10179	2036	611
1983	12647	2529	759
1984	6193	1239	372

Table A3.2. Recreational catch times series data, by small and large fish retained and released. Data for the years 1961 to 1986 are from Claytor et al. (1987). Data for the years 1987 to 2019 are extracted from the recreational fisheries catch statistics for Nova Scotia in the SalmoNS database.

Year	Retained small	Released small	Retained large	Released large
1961	40	0	49	0
1962	46	0	410	0
1963	87	0	212	0
1964	120	0	289	0
1965	86	0	254	0
1966	92	0	165	0
1967	92	0	210	0
1968	63	0	197	0
1969	206	0	136	0
1970	85	0	214	0
1971	21	0	92	0
1972	41	0	106	0
1973	165	0	116	0
1974	59	0	107	0
1975	36	0	64	0
1976	95	0	82	0
1977	68	0	140	0
1978	25	0	158	0
1979	605	0	62	19
1980	169	0	138	2
1981	899	0	105	34
1982	692	0	103	76
1983	72	0	106	43
1984	148	0	12	109
1985	223	0	0	312
1986	295	0	0	754

Year	Retained small	Released small	Retained large	Released large
1987	822	150	0	1847
1988	771	130	0	1979
1989	444	130	0	1607
1990	502	153	0	1520
1991	575	198	0	1808
1992	568	131	0	1999
1993	556	213	0	1090
1994	290	137	0	1478
1995	205	138	0	1091
1996	284	954	0	1938
1997	195	116	0	2105
1998	209	143	0	1341
1999	197	114	0	808
2000	133	128	0	696
2001	142	222	0	854
2002	161	202	0	611
2003	184	143	0	1137
2004	251	267	0	1408
2005	206	212	0	1340
2006	253	191	0	1256
2007	187	152	0	788
2008	359	382	0	1504
2009	49	123	0	1015
2010	220	293	3	1480
2011	201	407	0	2213
2012	12	68	0	373
2013	99	111	0	1072

Year	Retained small	Released small	Retained large	Released large
2014	29	70	0	520
2015	12	220	0	613
2016	2	109	0	602
2017	2	217	0	518
2018	0	206	0	979
2019	0	277	0	1028

Table A3.3. Age frequency distribution obtained from the 1987-1996 Margaree River trapnet monitoring. Data include wild fish only. Total age is calculated as smolt age plus sea age plus one for the spawning year.

Size Group	Sea age	Smolt age	Total age	Frequency
small	1	2	4	599
small	1	3	5	374
small	1	4	6	28
small	1	5	7	1
large	1	2	4	13
large	1	3	5	3
large	1	4	6	2
large	1	5	7	0
large	2	2	5	1480
large	2	3	6	875
large	2	4	7	22
large	2	5	8	0
large	3	2	6	156
large	3	3	7	56
large	3	4	8	3
large	3	5	9	0
large	4	2	7	99
large	4	3	8	50
large	4	4	9	1
large	4	5	10	0
large	5	2	8	30
large	5	3	9	7
large	5	4	10	0
large	5	5	11	0
large	6	2	9	21
large	6	3	10	3

Size Group	Sea age	Smolt age	Total age	Frequency
large	6	4	11	0
large	6	5	12	0
large	7	2	10	4
large	7	3	11	0
large	7	4	12	0
large	7	5	13	0
large	8	2	11	3
large	8	3	12	0
large	8	4	13	0
large	8	5	14	0

Table A3.4. Proportions of fish by age category calculated from age frequency distribution obtained from the 1987-1996 Margaree River trapnet monitoring. Data include wild fish only.

Age category	Large salmon (n)	Small salmon (n)	Proportion of large salmon	Proportion of small salmon
4	13	599	0.005	0.598
5	1483	374	0.524	0.373
6	1033	29	0.365	0.029
7	177	na	0.063	na
8	122	na	0.043	na

Table A3.5. Proportion of wild (i.e. non-hatchery) fish in the Margaree estimated from trapnet monitoring in 1987-1996 (from Table 4 in LeBlanc et al. 2005). For all other years in the time series, the average of these years is used to calculate the proportion of wild fish (0.83 small wild fish, 0.945 large wild fish). This proportion is used to subtract the contribution of hatchery fish in the returns and spawners.

Year	Proportion wild of small salmon	Proportion wild of large salmon
1987	0.63	0.96
1988	0.99	0.99
1989	0.95	0.95
1990	0.94	0.94
1991	0.81	0.91
1992	0.79	0.95
1993	0.67	0.93
1994	0.80	0.93
1995	0.89	0.95
1996	0.85	0.94

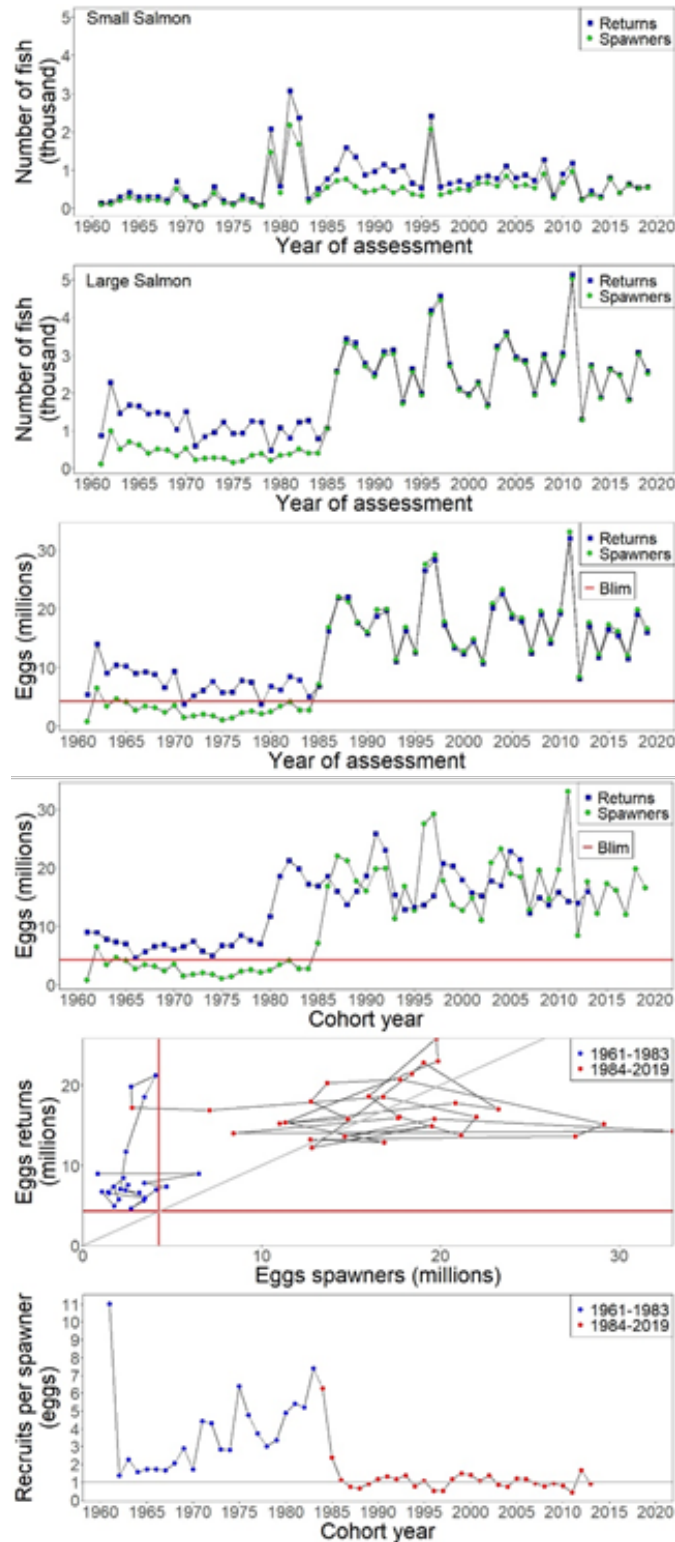


Figure A3.1. Reconstructed return and spawners by small salmon (first row) and large salmon (second row), reconstructed total eggs (millions) in spawners and eggs in returns by year of assessment (third row) and by cohort year (fourth row), scatter plot of eggs in spawners and eggs in returns by cohort year (fifth row) and recruits per spawner (eggs) by cohort year (bottom row). The horizontal (and vertical) red line in the panels is the LRP in total egg equivalent for the Margaree River (DFO 2018b).

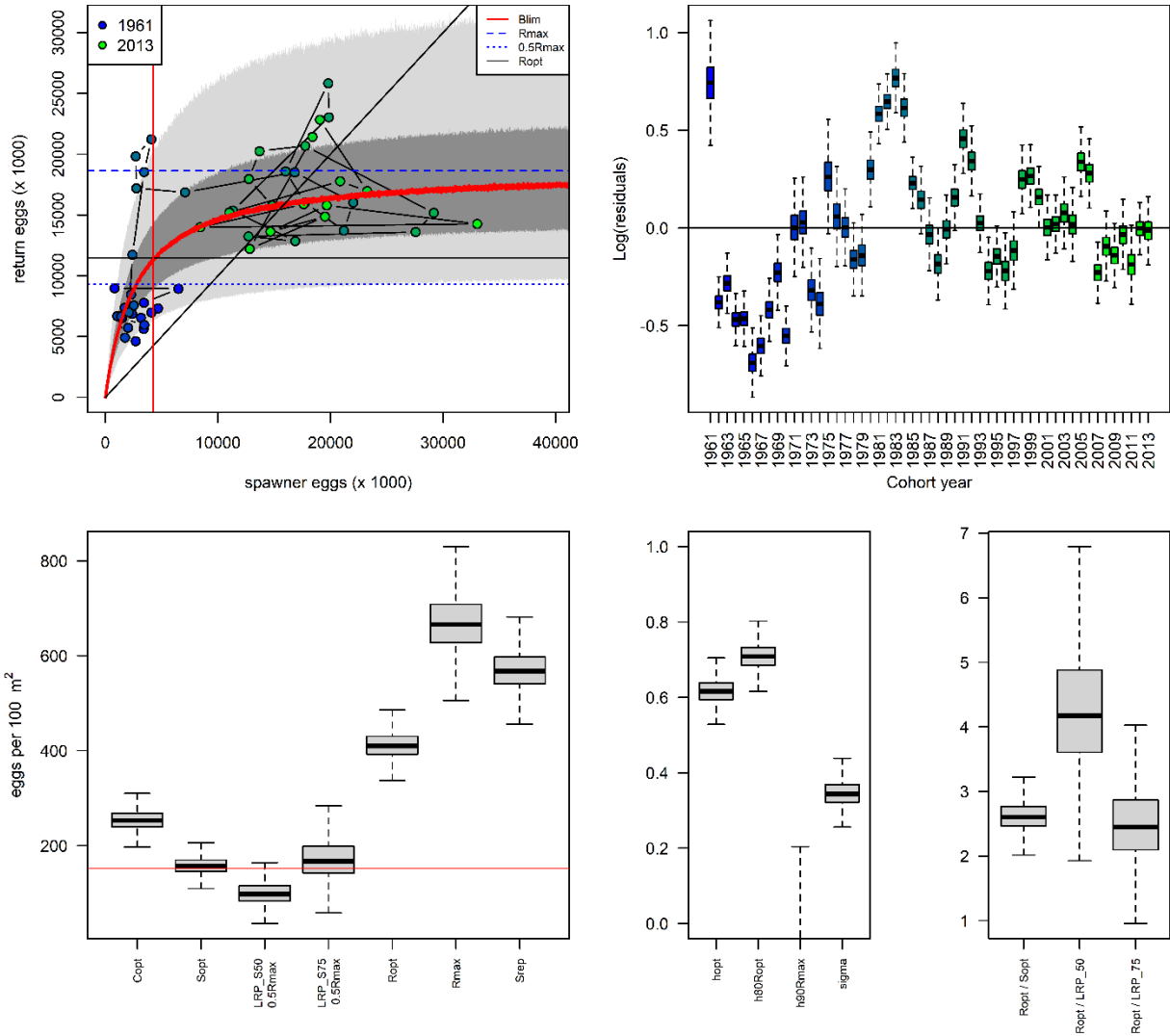


Figure A3.2. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the Margaree River, 1961 to 2013 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

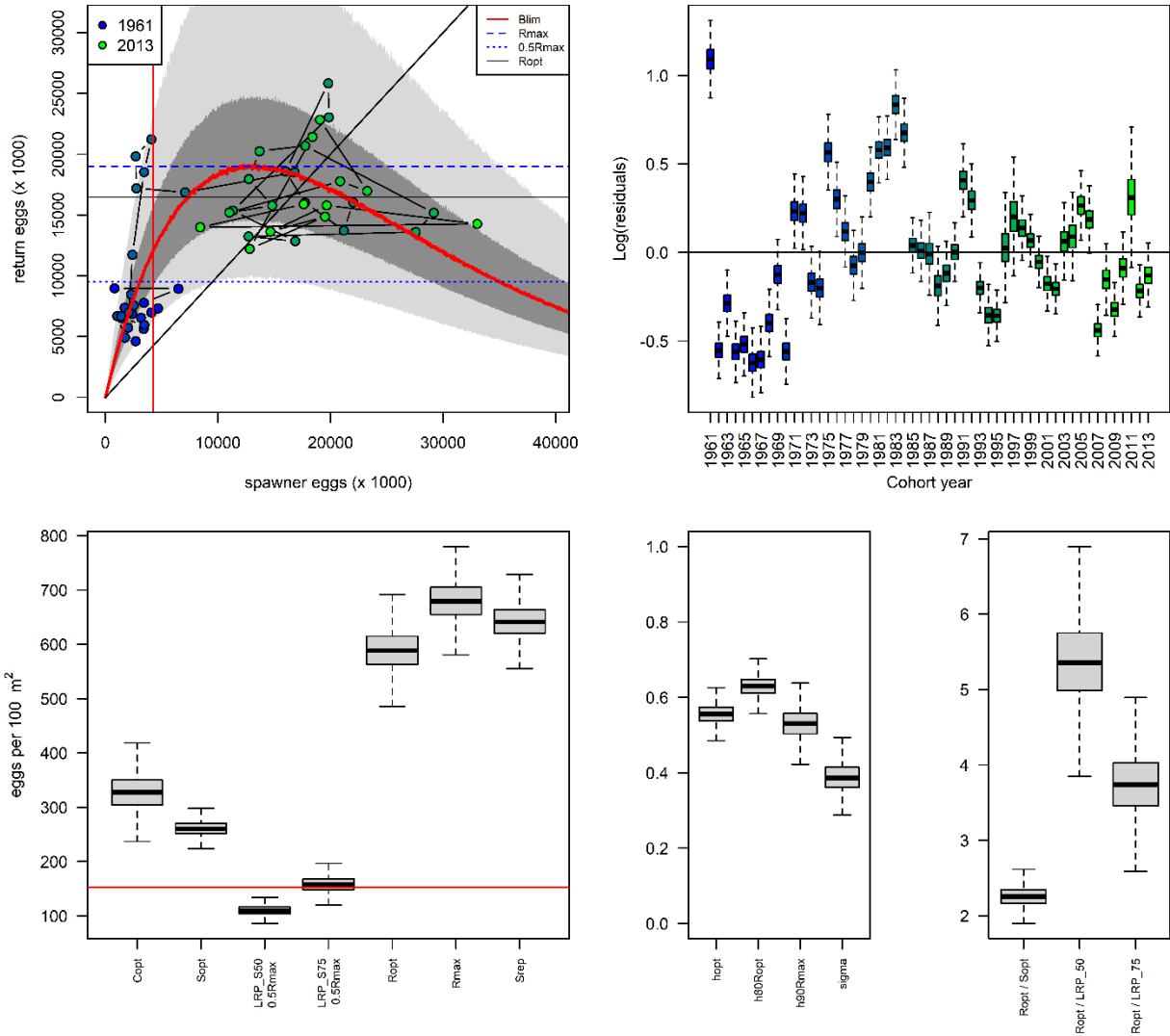


Figure A3.3. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Margaree River, 1961 to 2013 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

APPENDIX 4. QUEBEC RIVERS RESULTS OF THE INDEPENDENT AND HIERARCHICAL STOCK AND RECRUITMENT FITS

The reconstruction of the time series of eggs in spawners and returns from twelve rivers of Quebec is described in Dionne et al. (2015).

Appendix 4A. Fits and diagnostics of the Beverton-Holt model fitted independently to the twelve rivers of Quebec

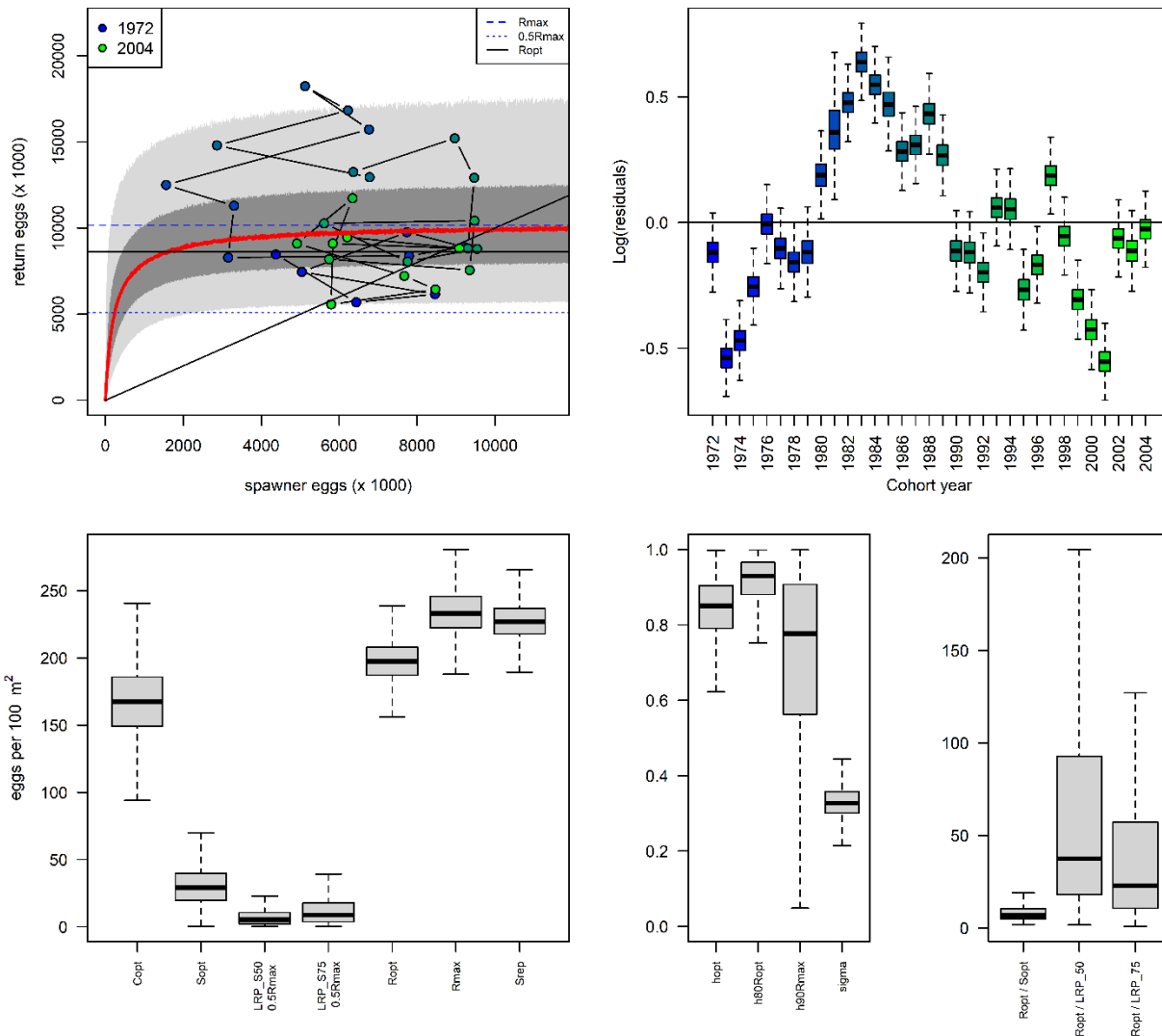


Figure A4.A.1. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the Bonaventure River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

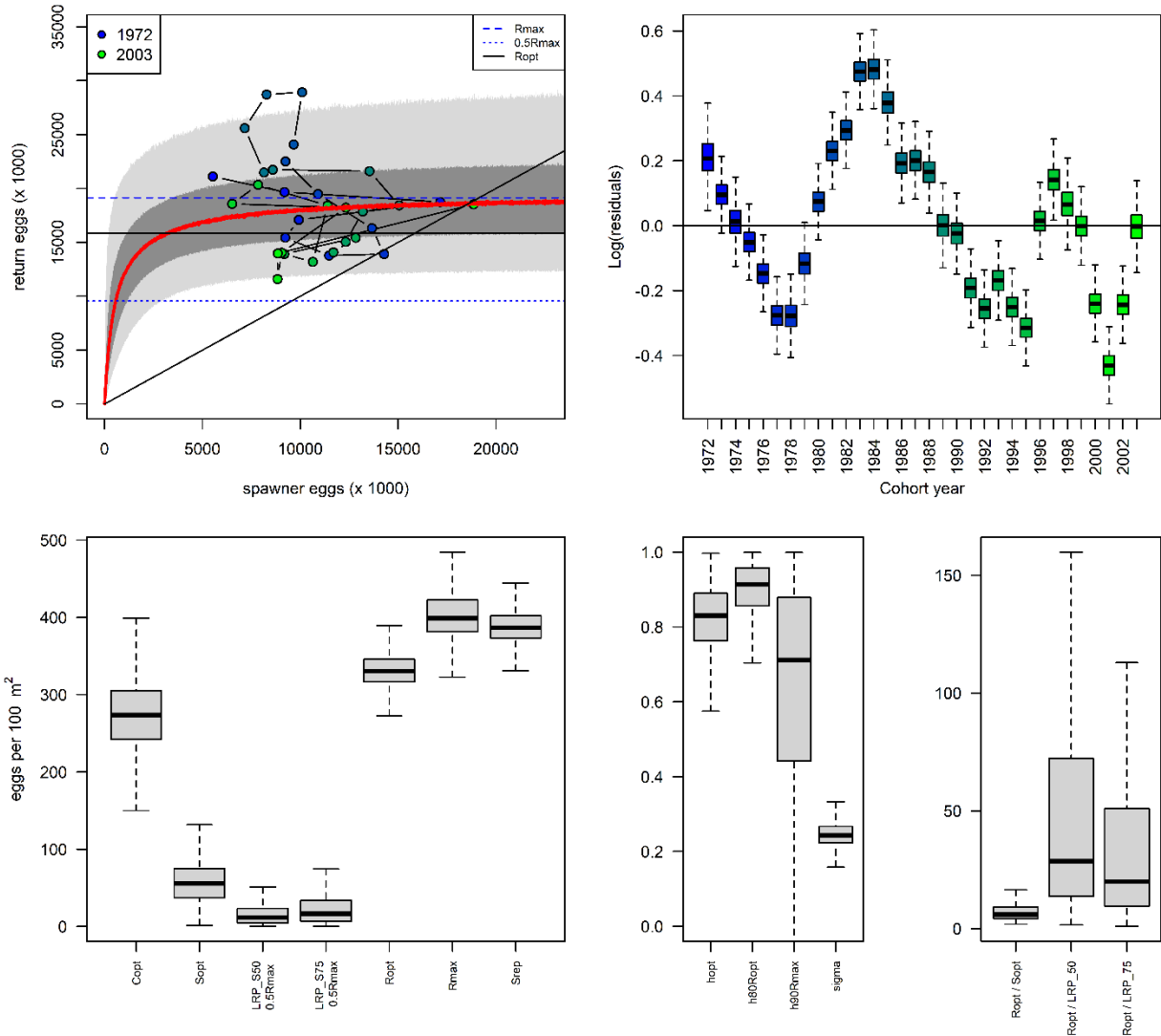


Figure A4.A.2. Diagnostics and reference values of fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for Cascapédia River, 1972 to 2003 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

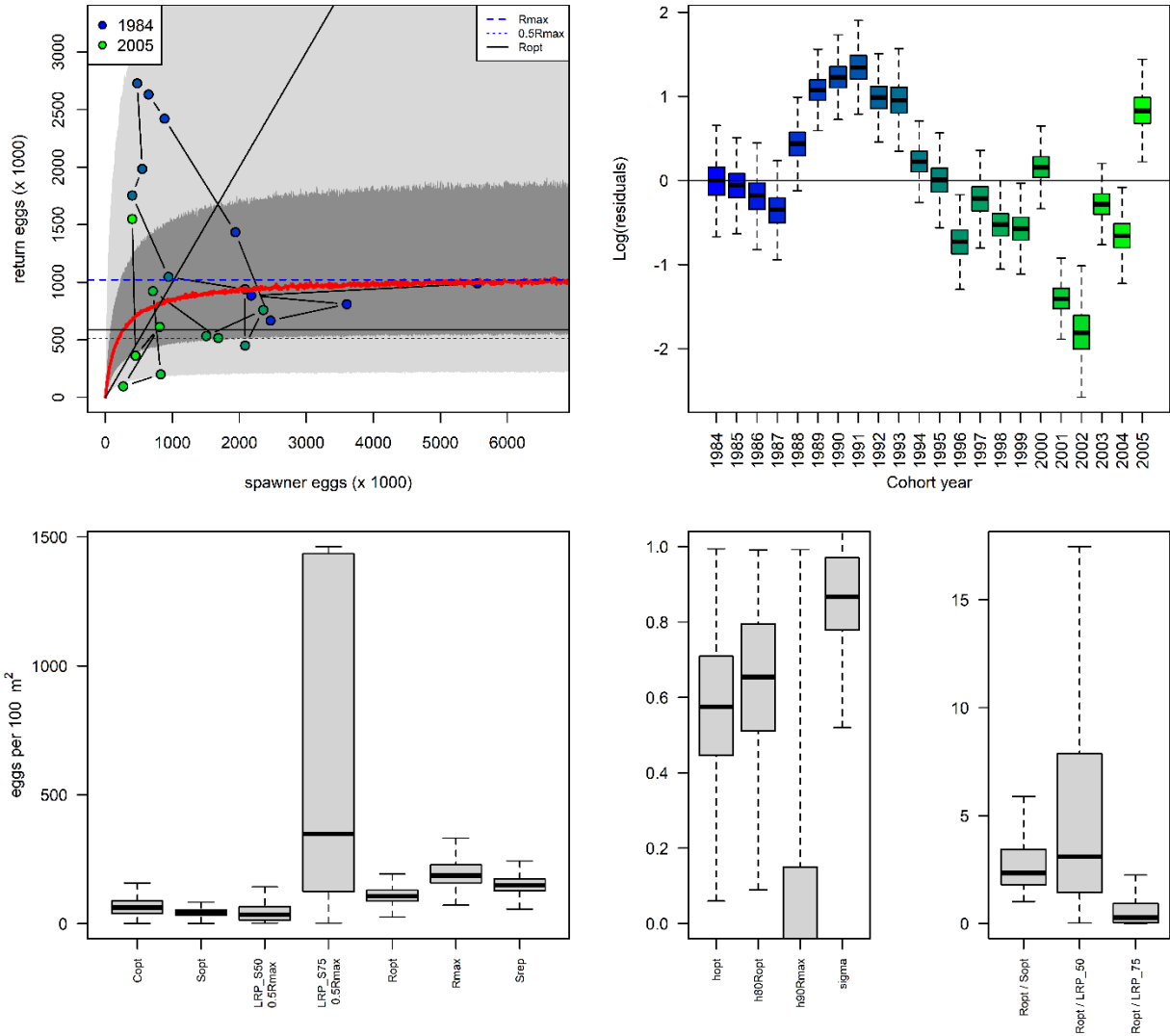


Figure A4.A.3. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the Chaloupe River, 1984 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

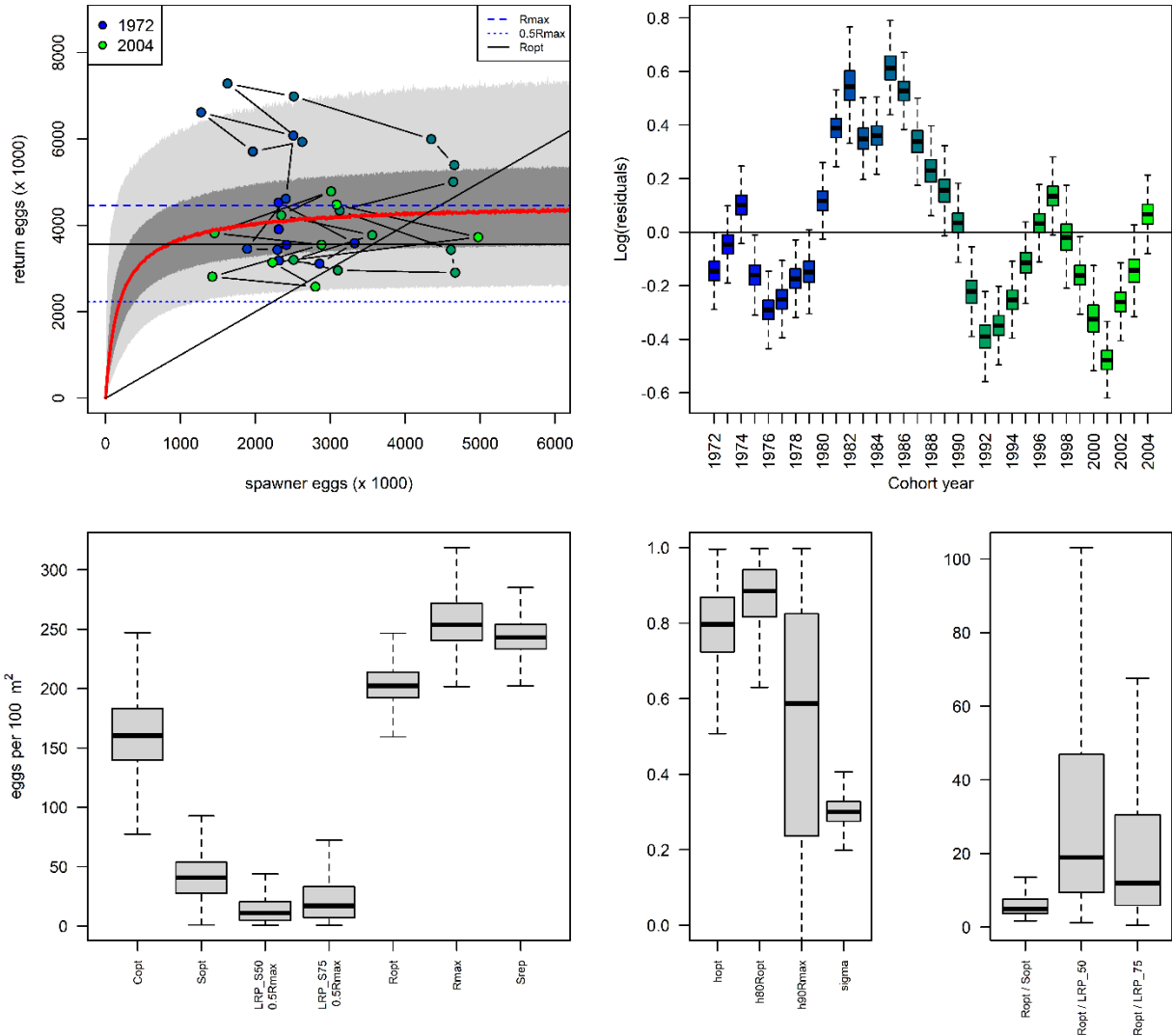


Figure A4.A.4. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the Dartmouth River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

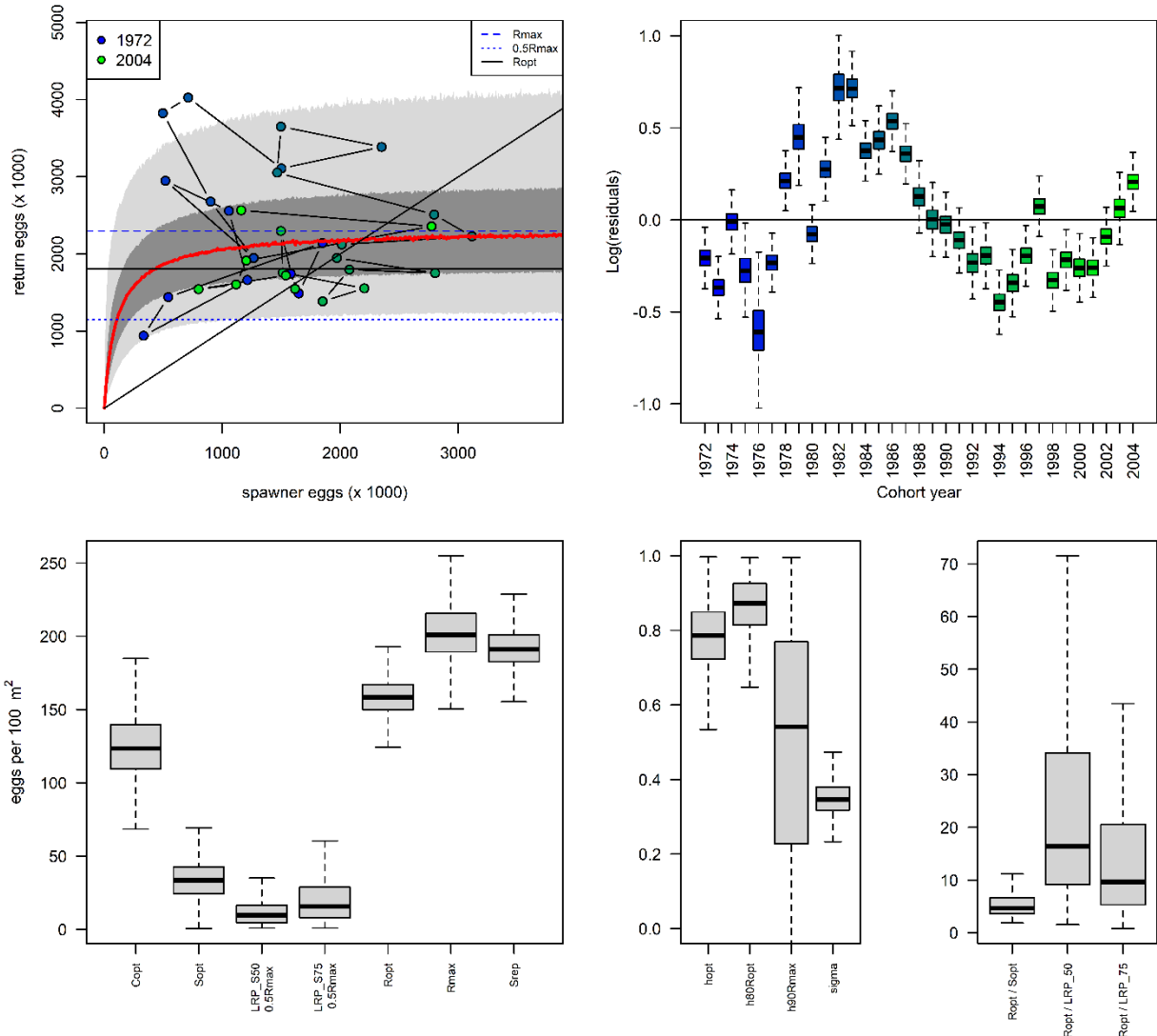


Figure A4.A.5. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the Grande Rivière River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

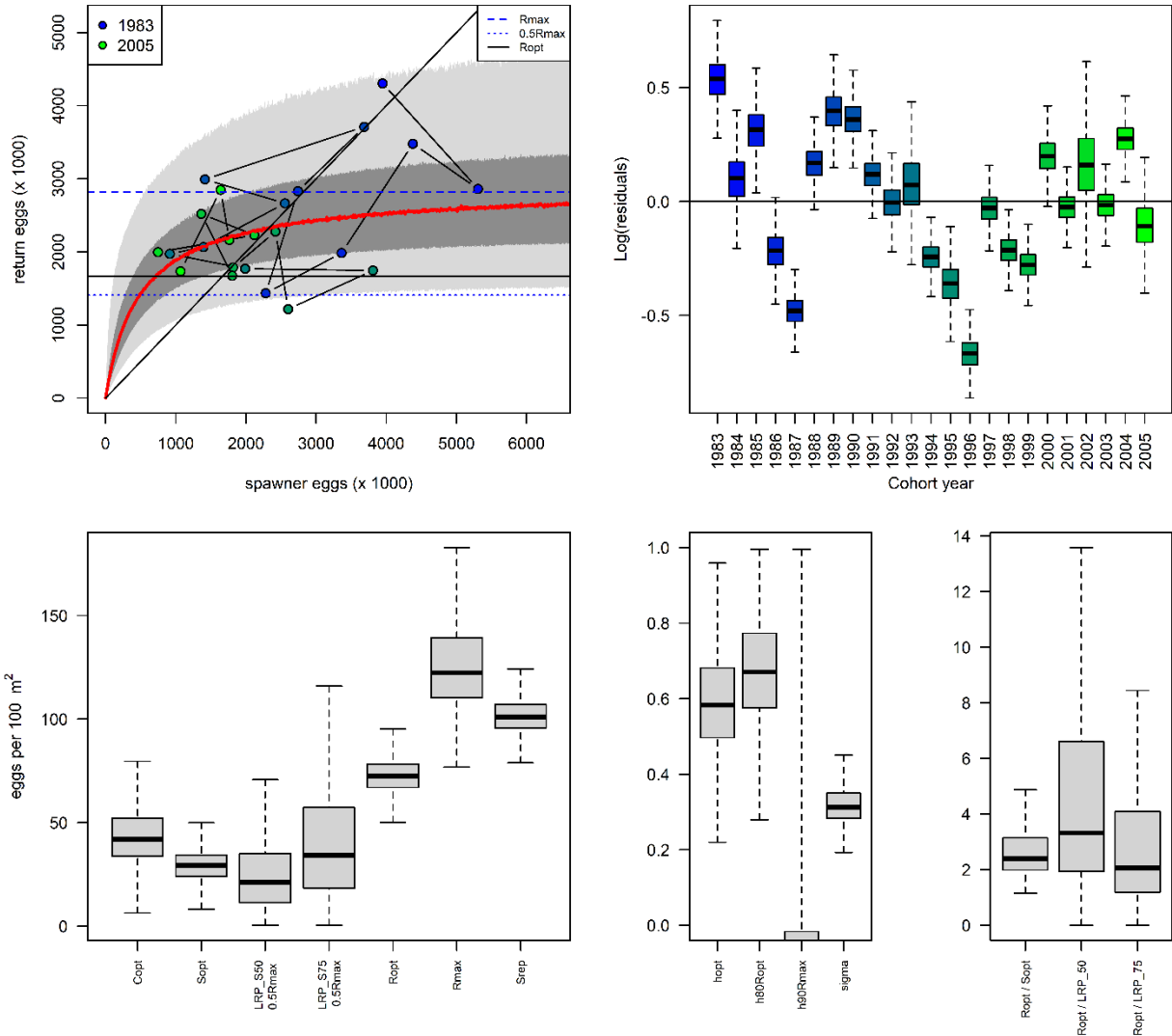


Figure A4.A.6. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the Jupiter River, 1983 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

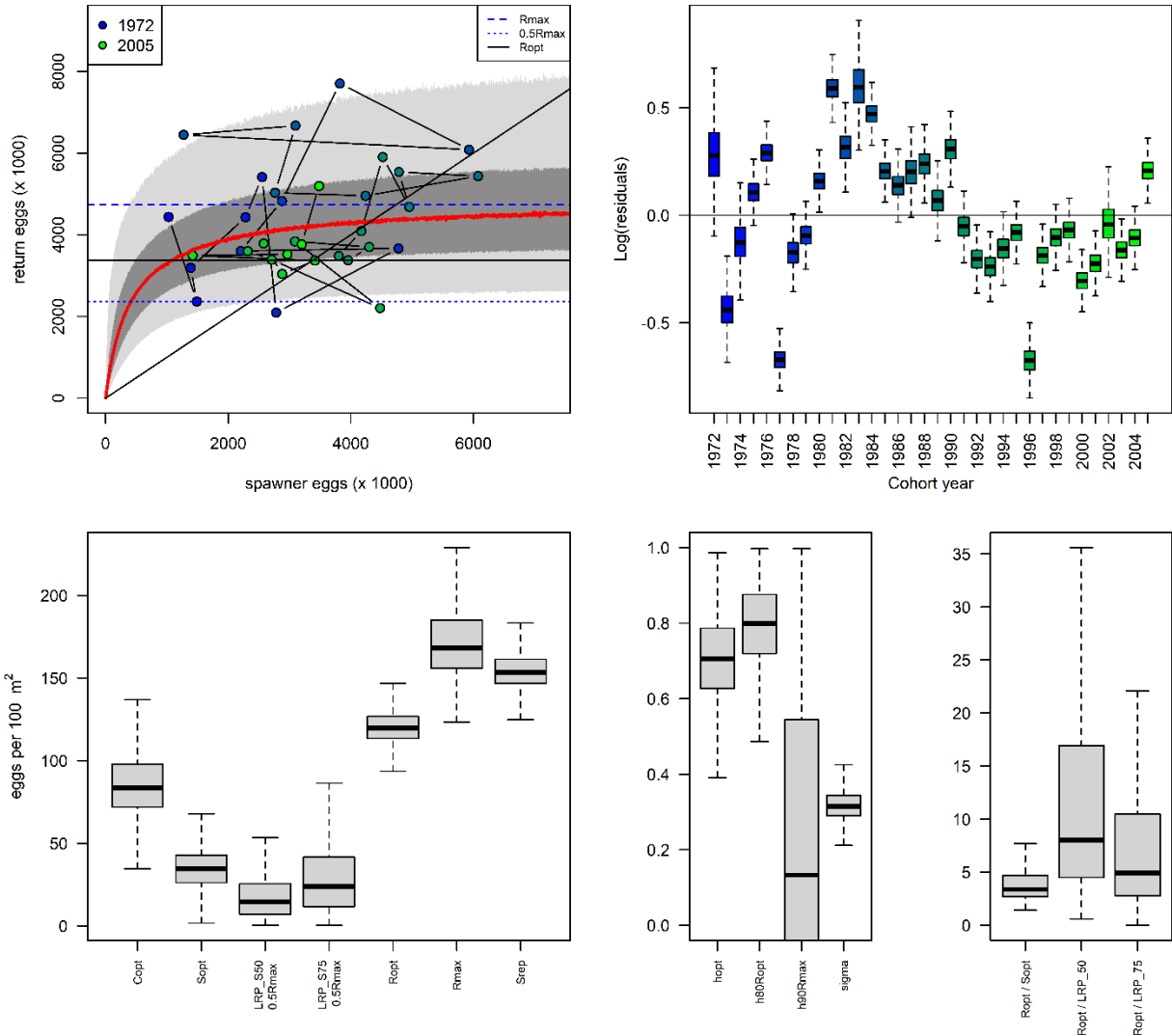


Figure A4.A.7. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the Madeleine River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

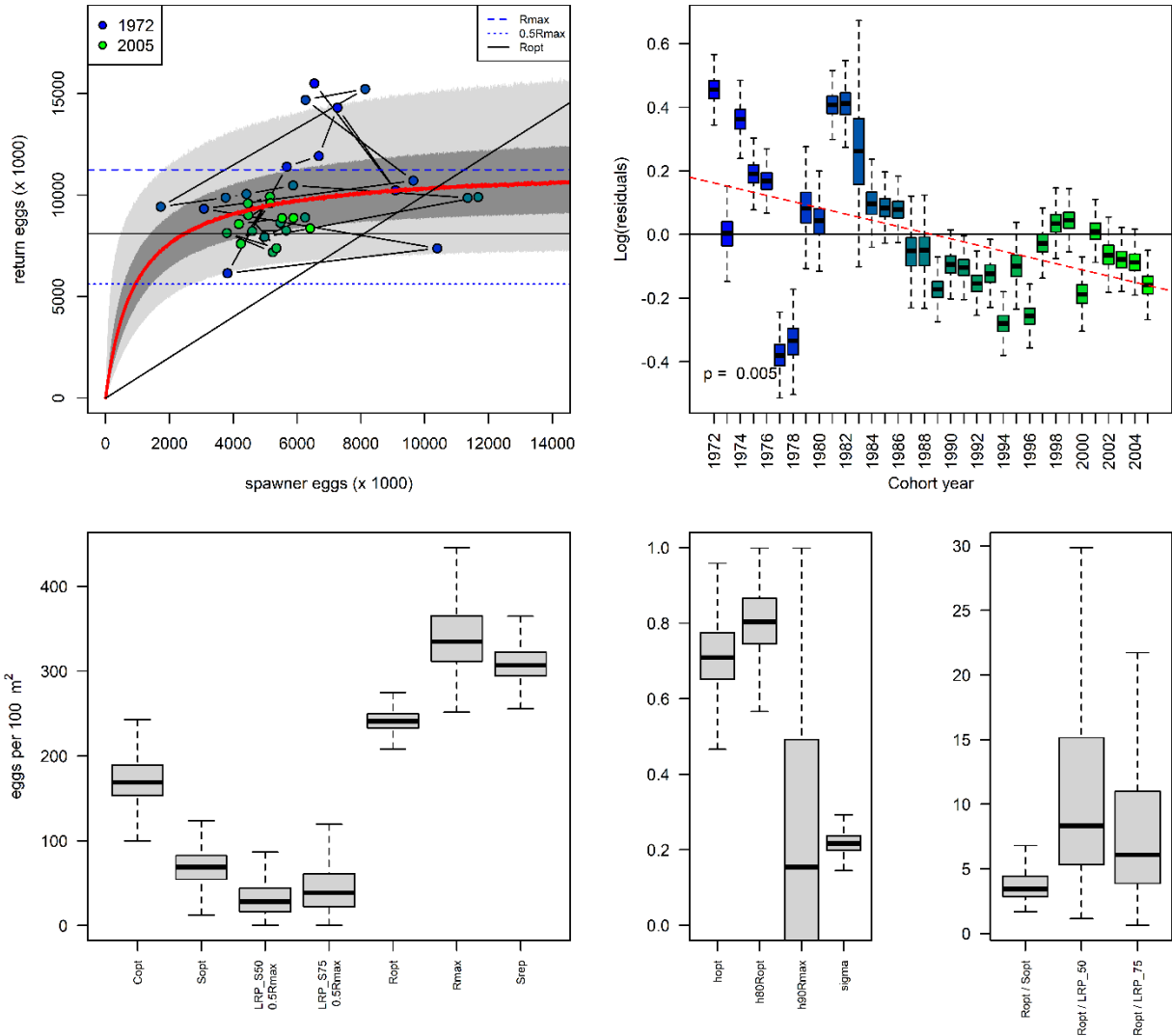


Figure A4.A.8. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the Matane River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

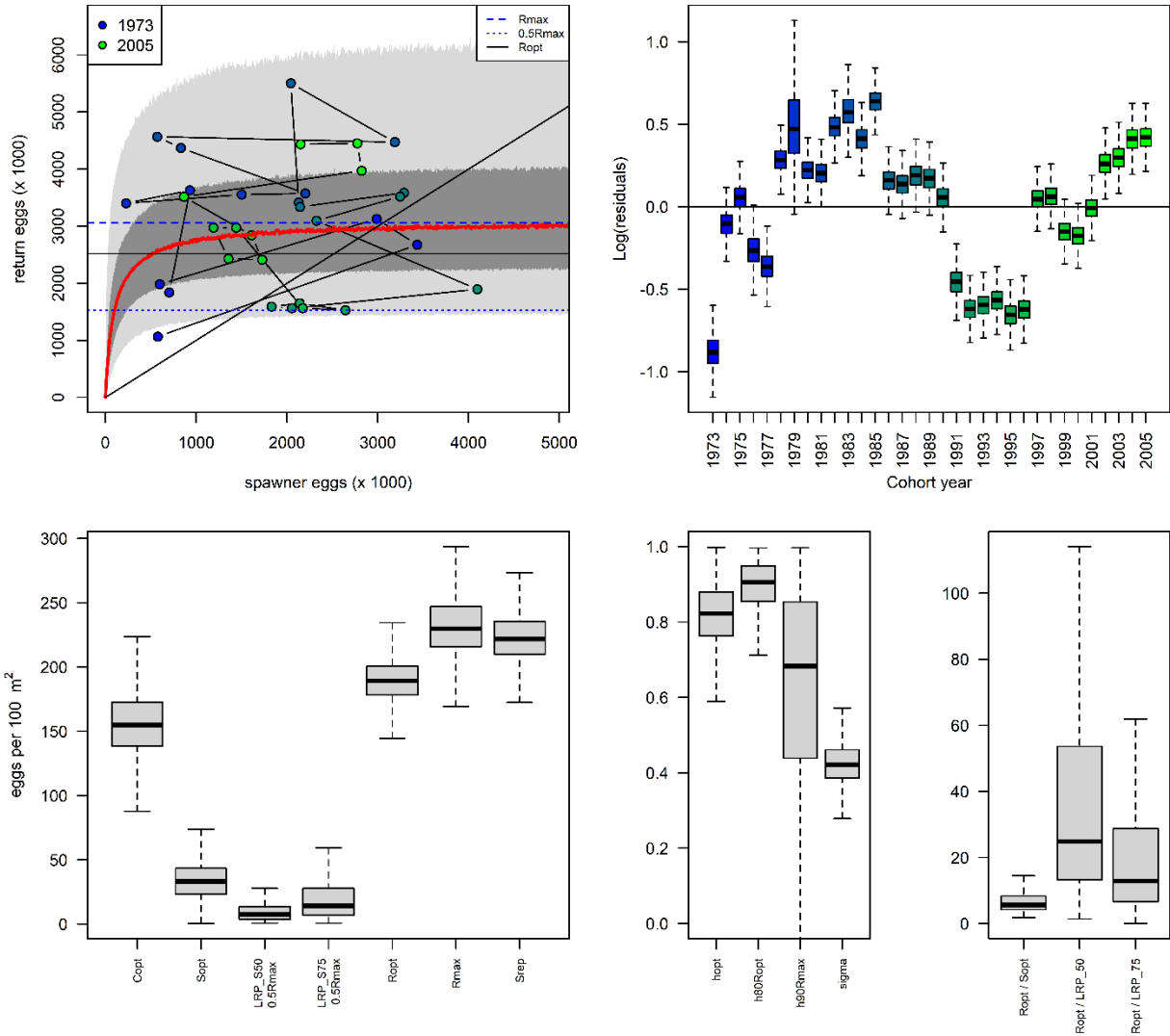


Figure A4.A.9. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the Sainte-Anne River, 1973 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

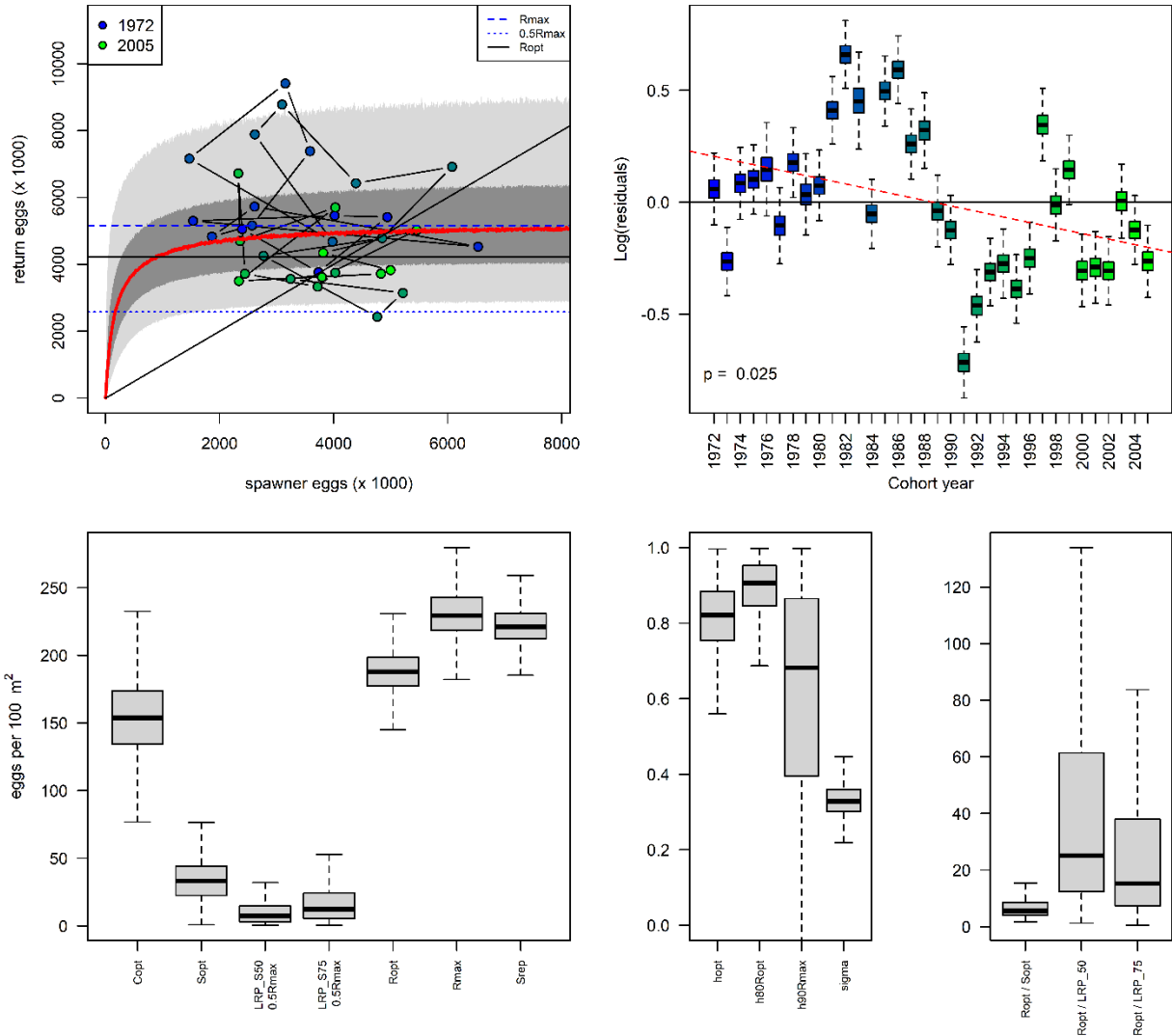


Figure A4.A.10. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the Saint-Jean River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

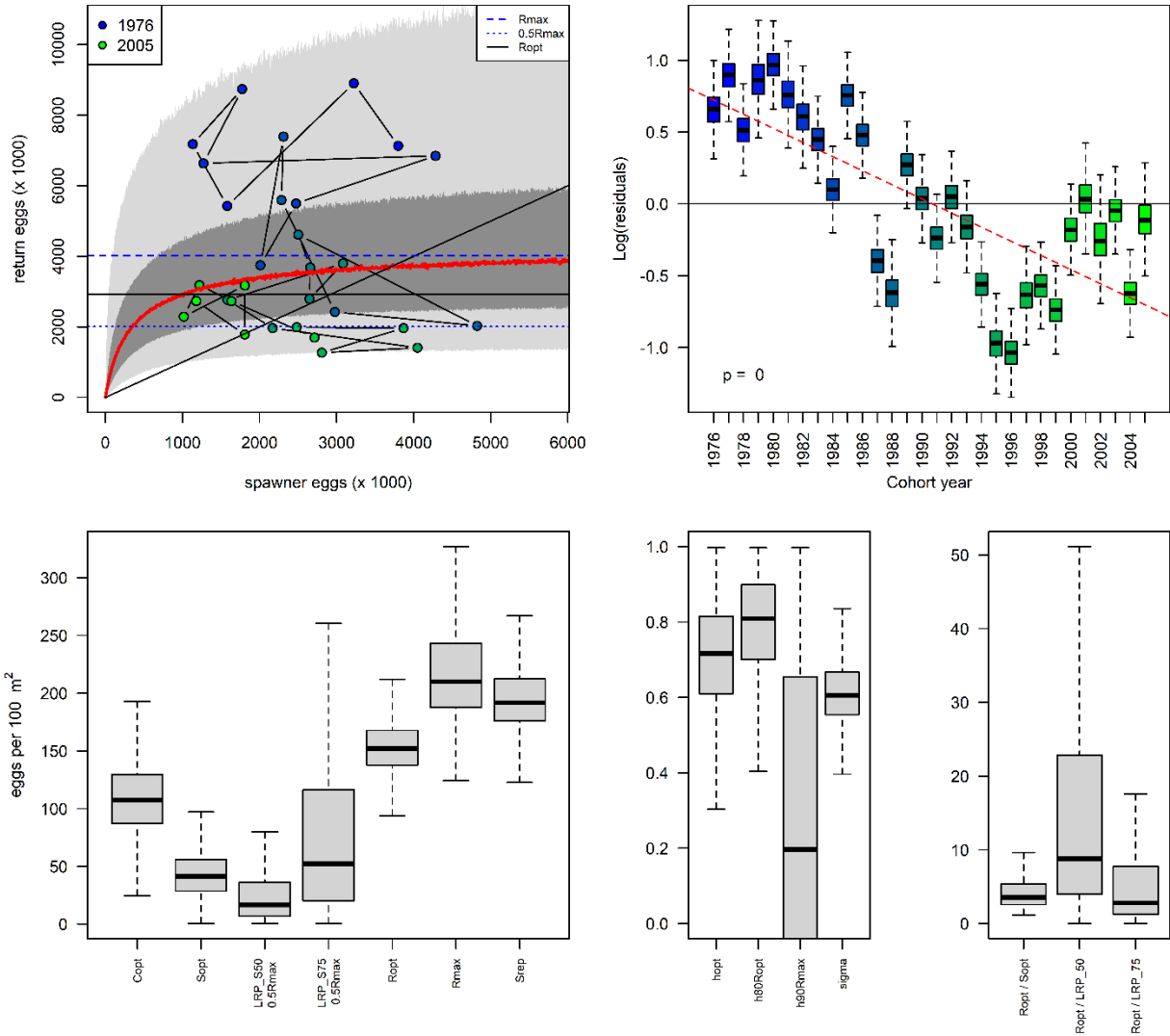


Figure A4.A.11. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for de la Trinité River, 1976 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

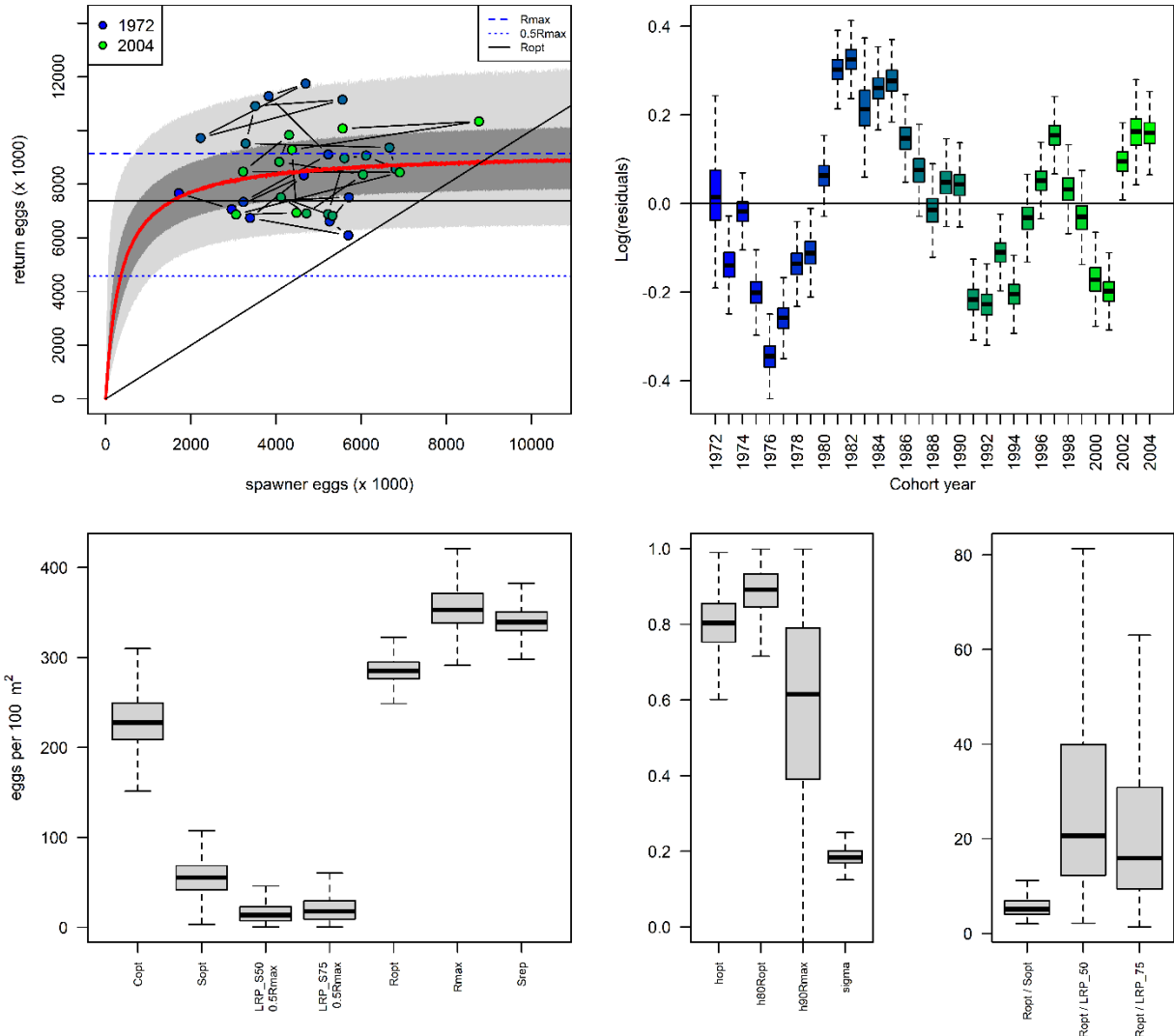


Figure A4.A.12. Diagnostics and reference values of independently fitting the Beverton-Holt stock and recruitment function to the egg to egg time series for the York River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

Appendix 4B. Fits and diagnostics of the Ricker model fitted independently to the twelve rivers of Quebec

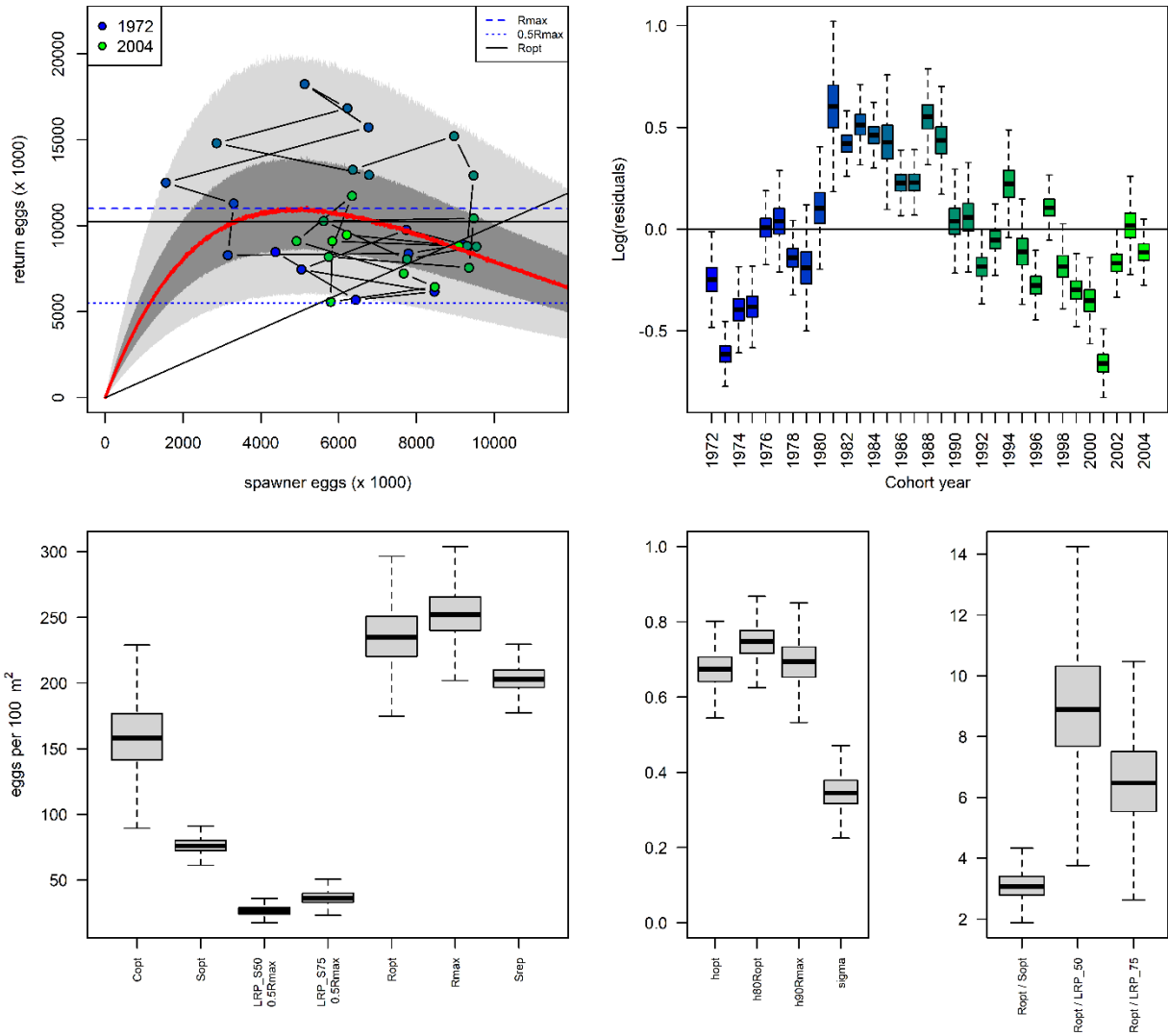


Figure A4.B.1. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Bonaventure River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

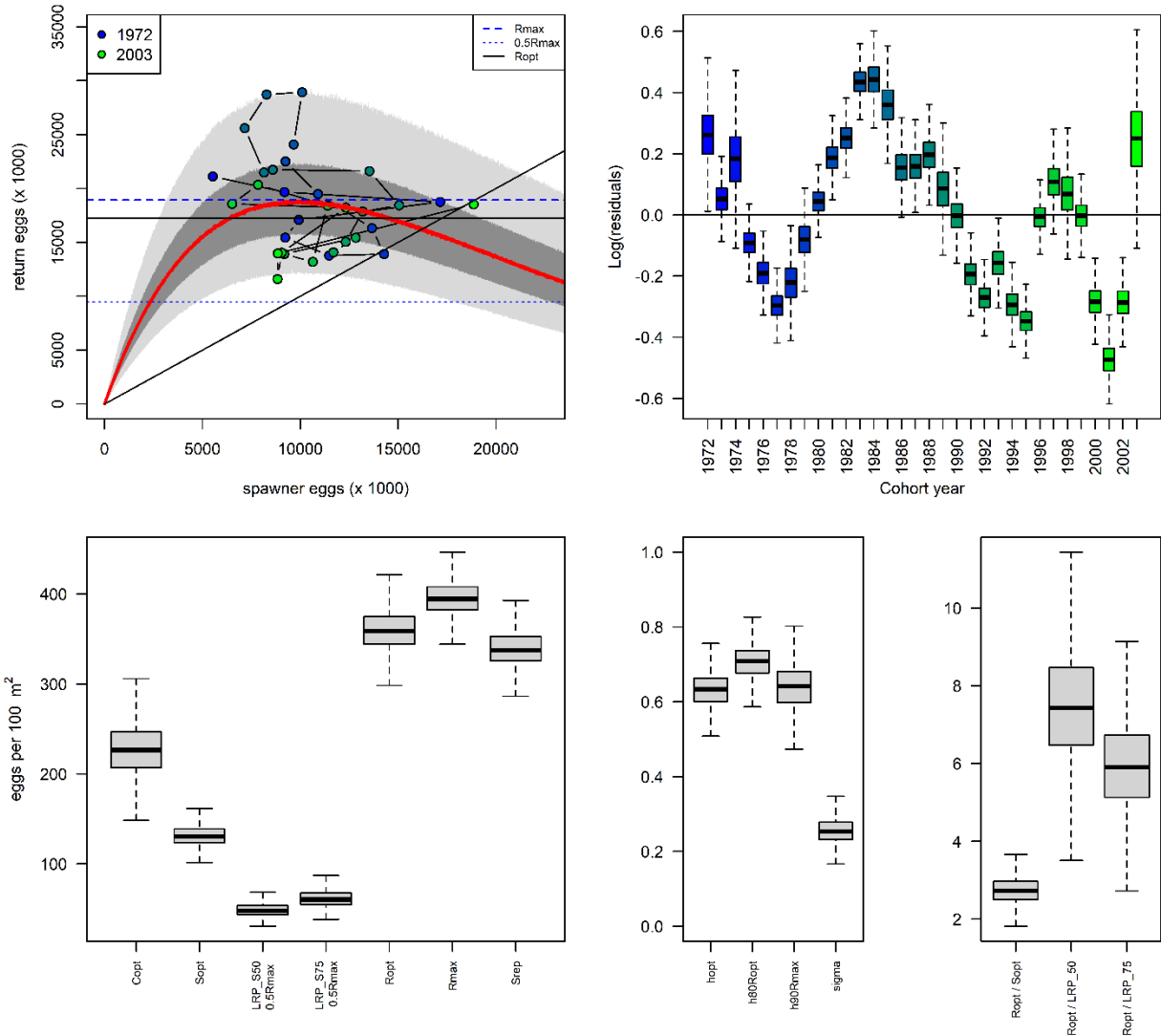


Figure A4.B.2. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Cascapédia River, 1972 to 2003 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

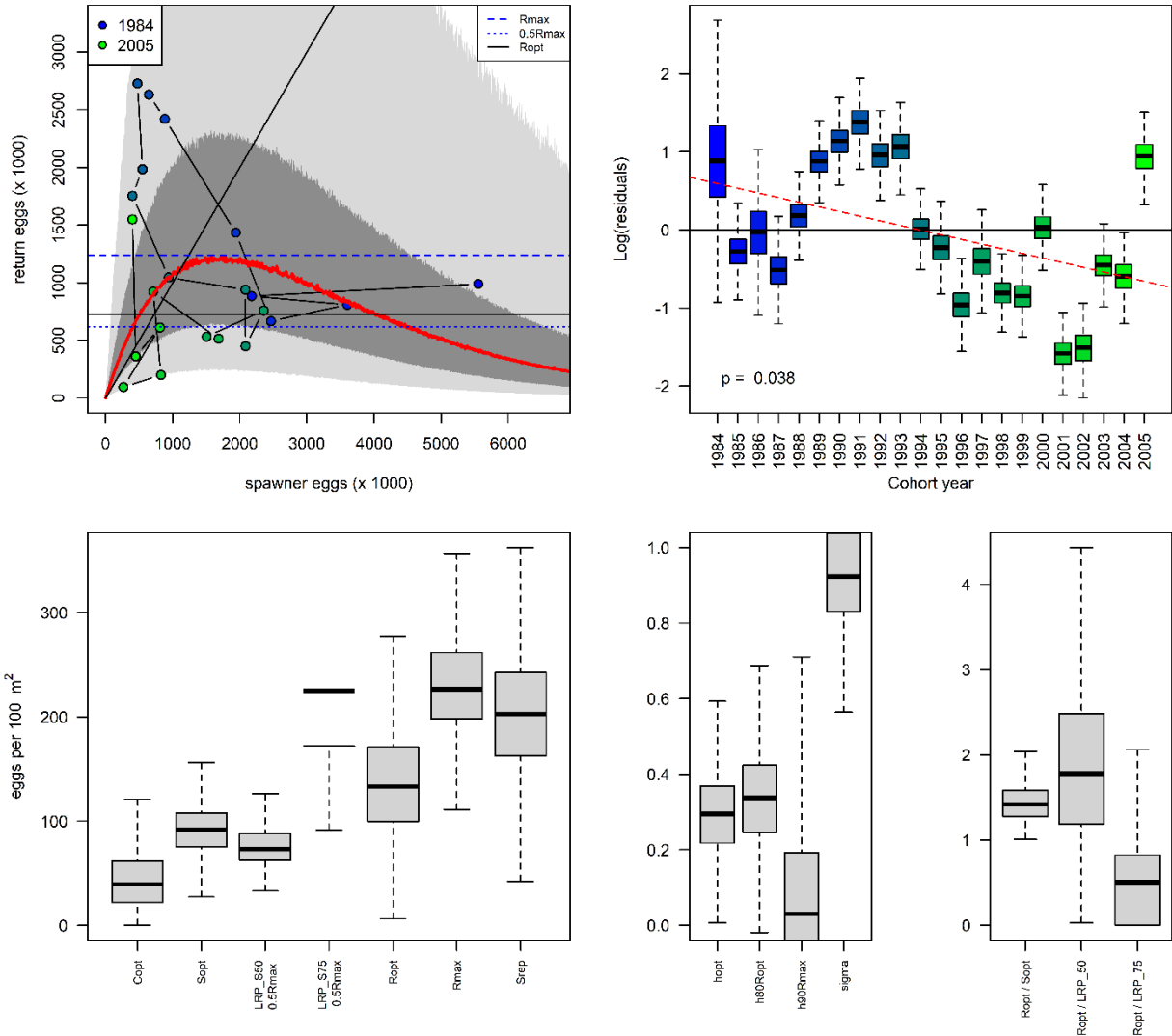


Figure A4.B.3. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Chaloupe River, 1984 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

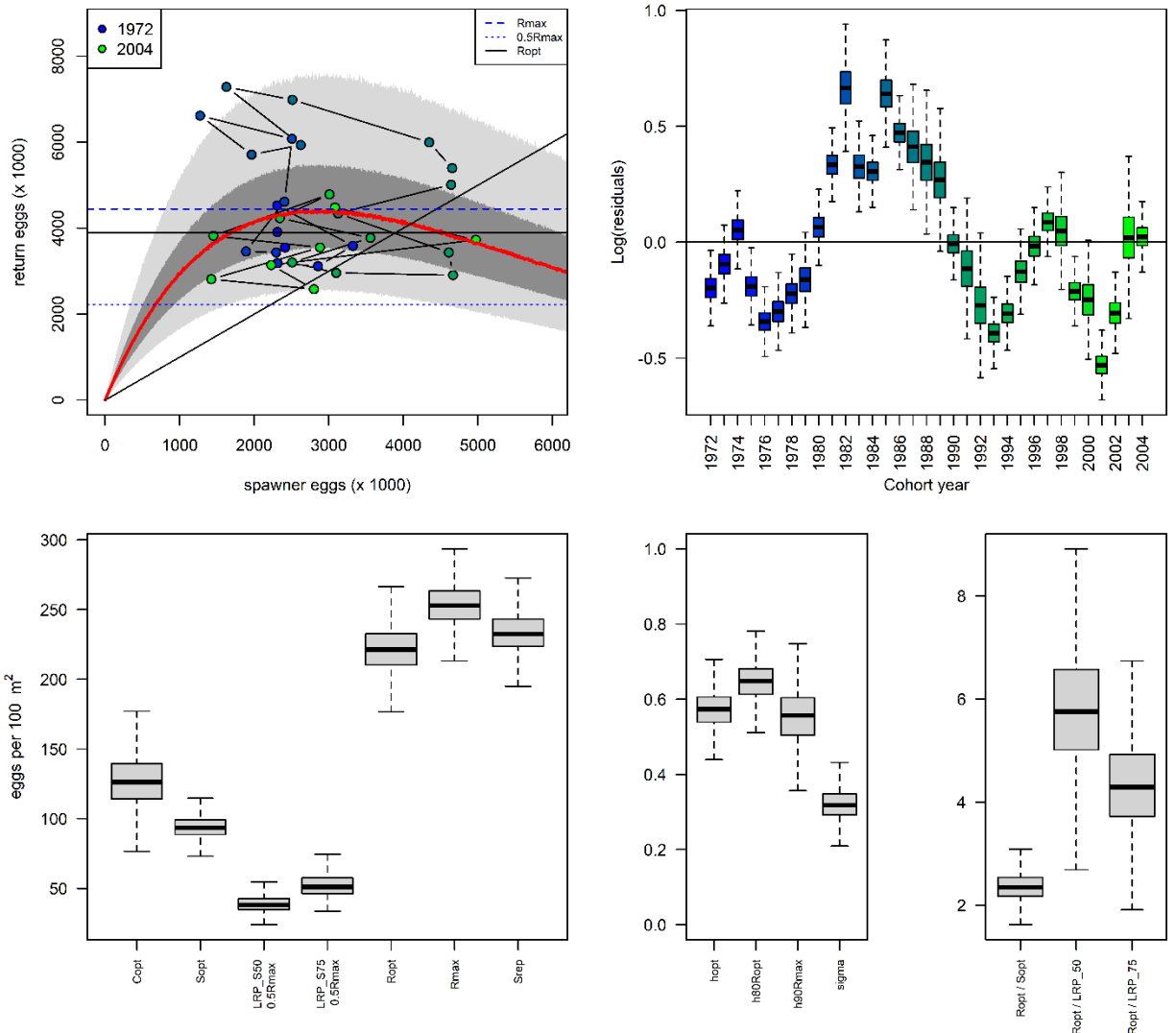


Figure A4.B.4. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Dartmouth River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

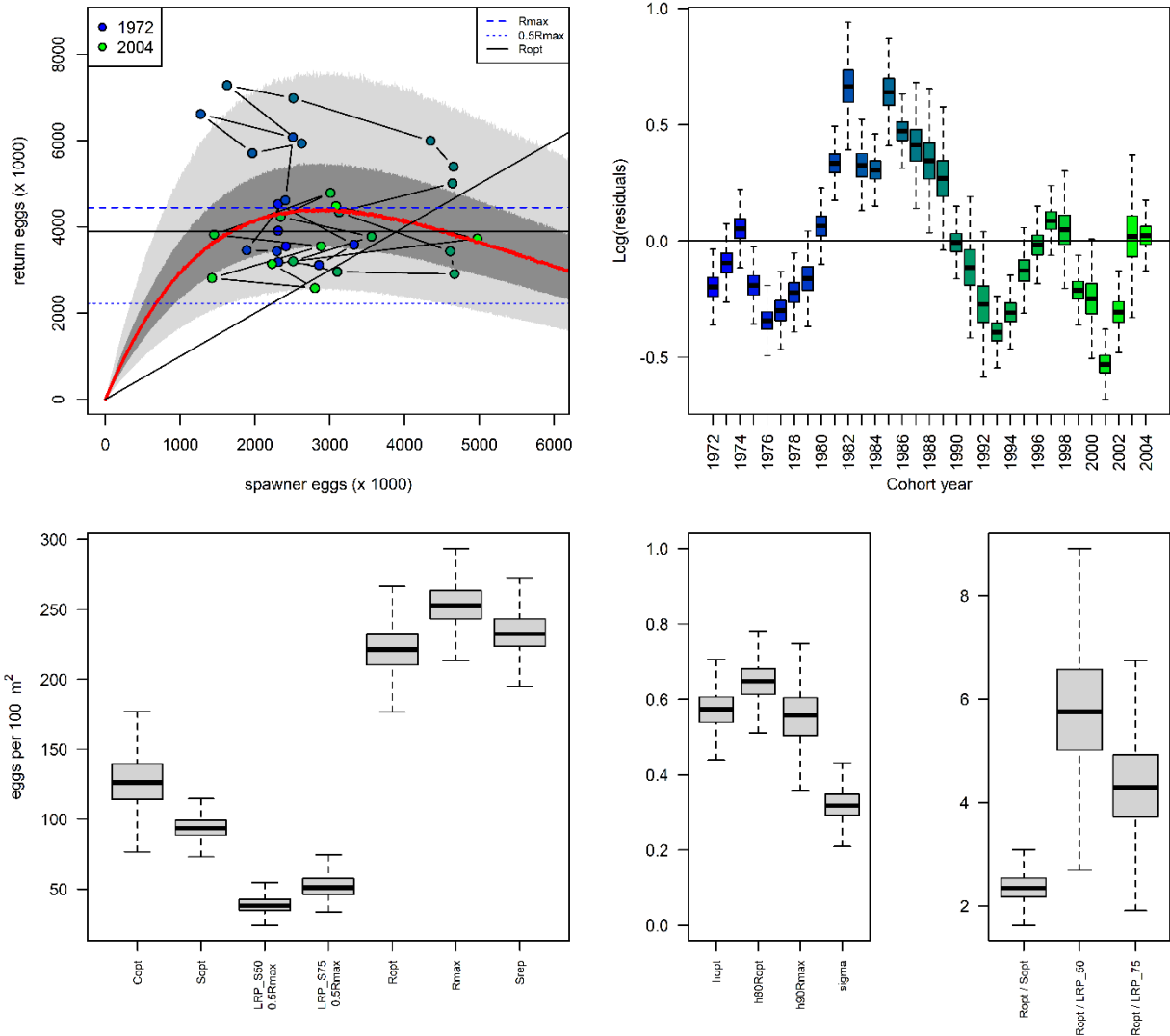


Figure A4.B.5. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Grande-Rivière River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

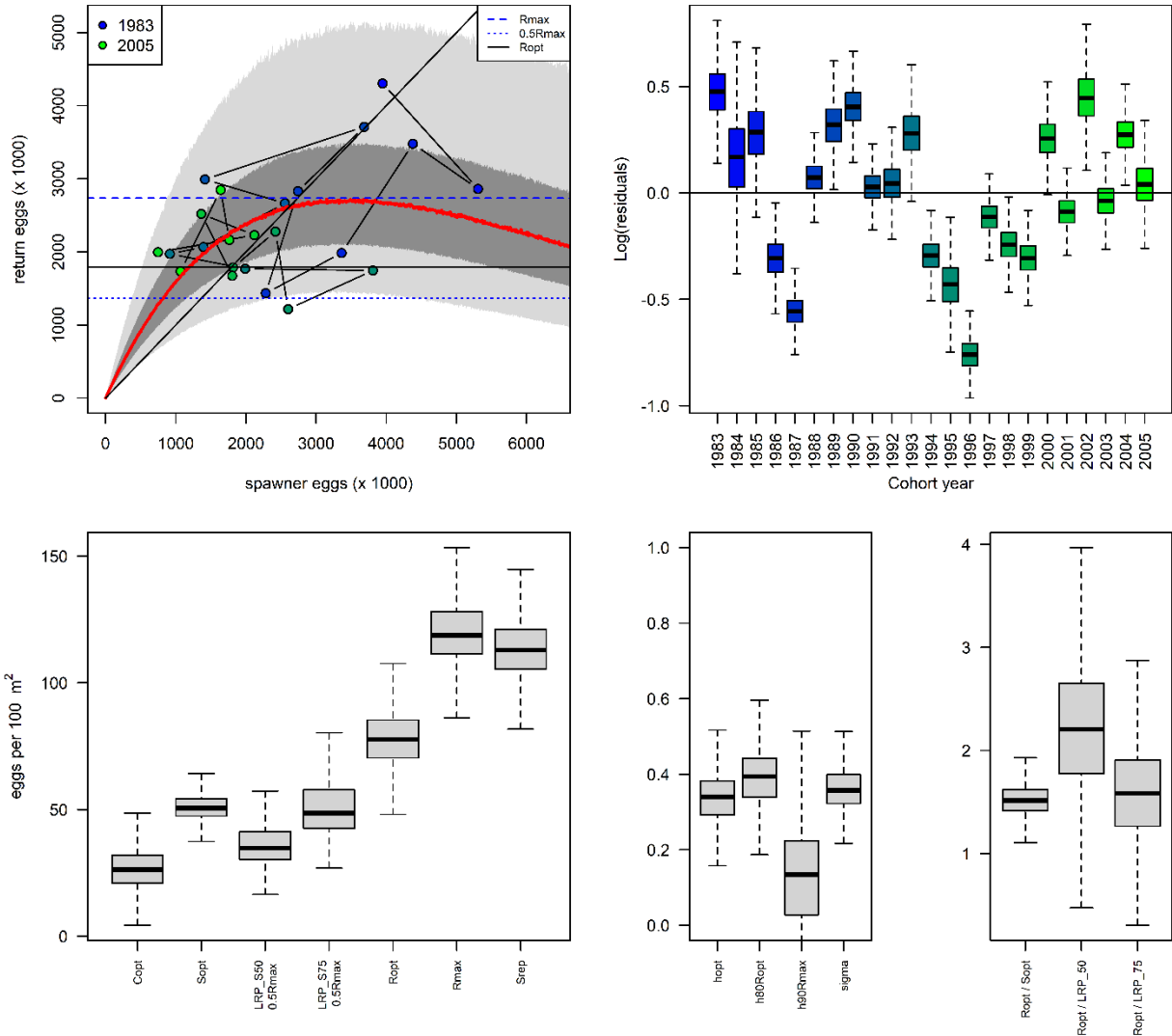


Figure A4.B.6. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Jupiter River, 1983 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

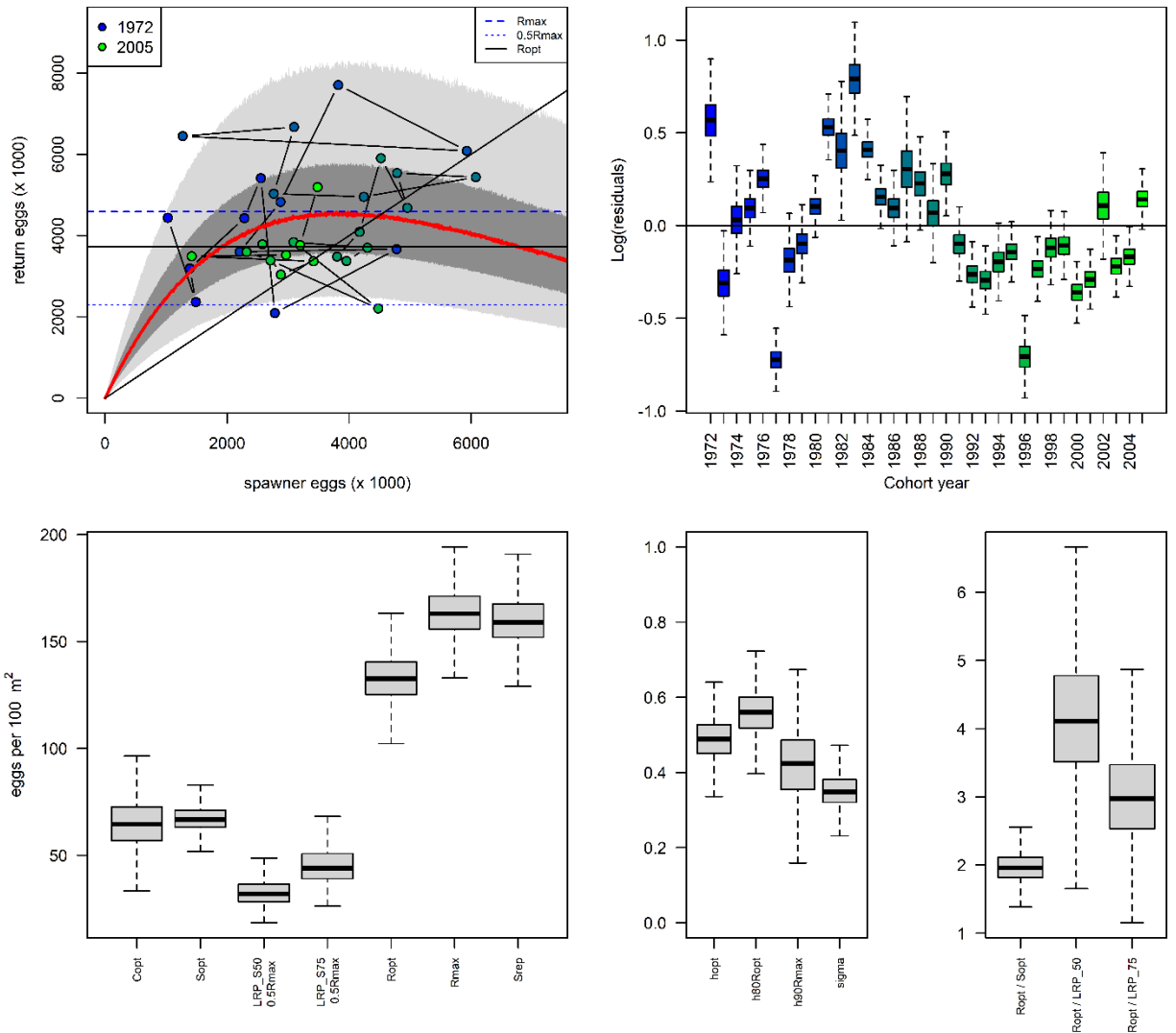


Figure A4.B.7. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Madeleine River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

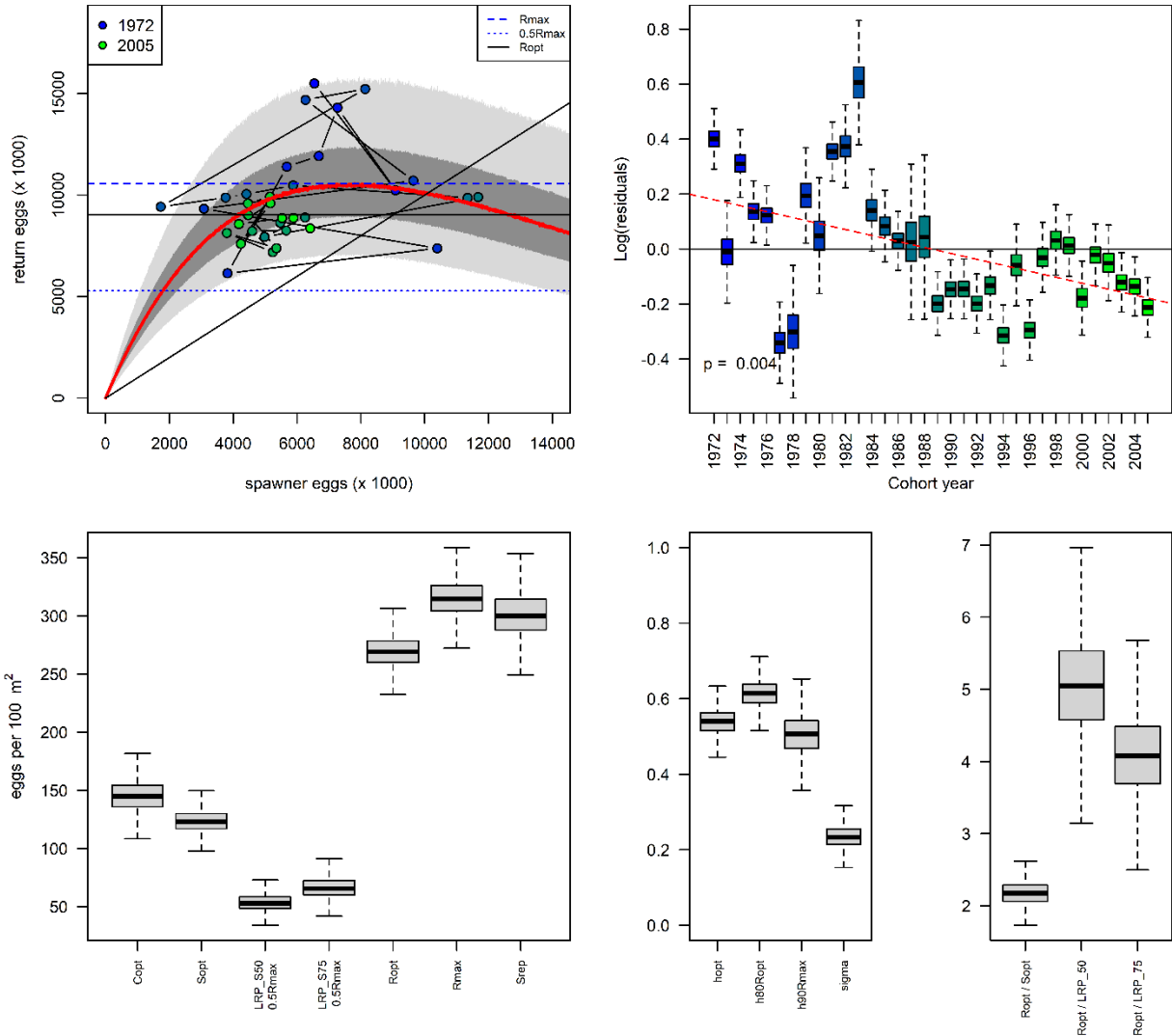


Figure A4.B.8. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Matane River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

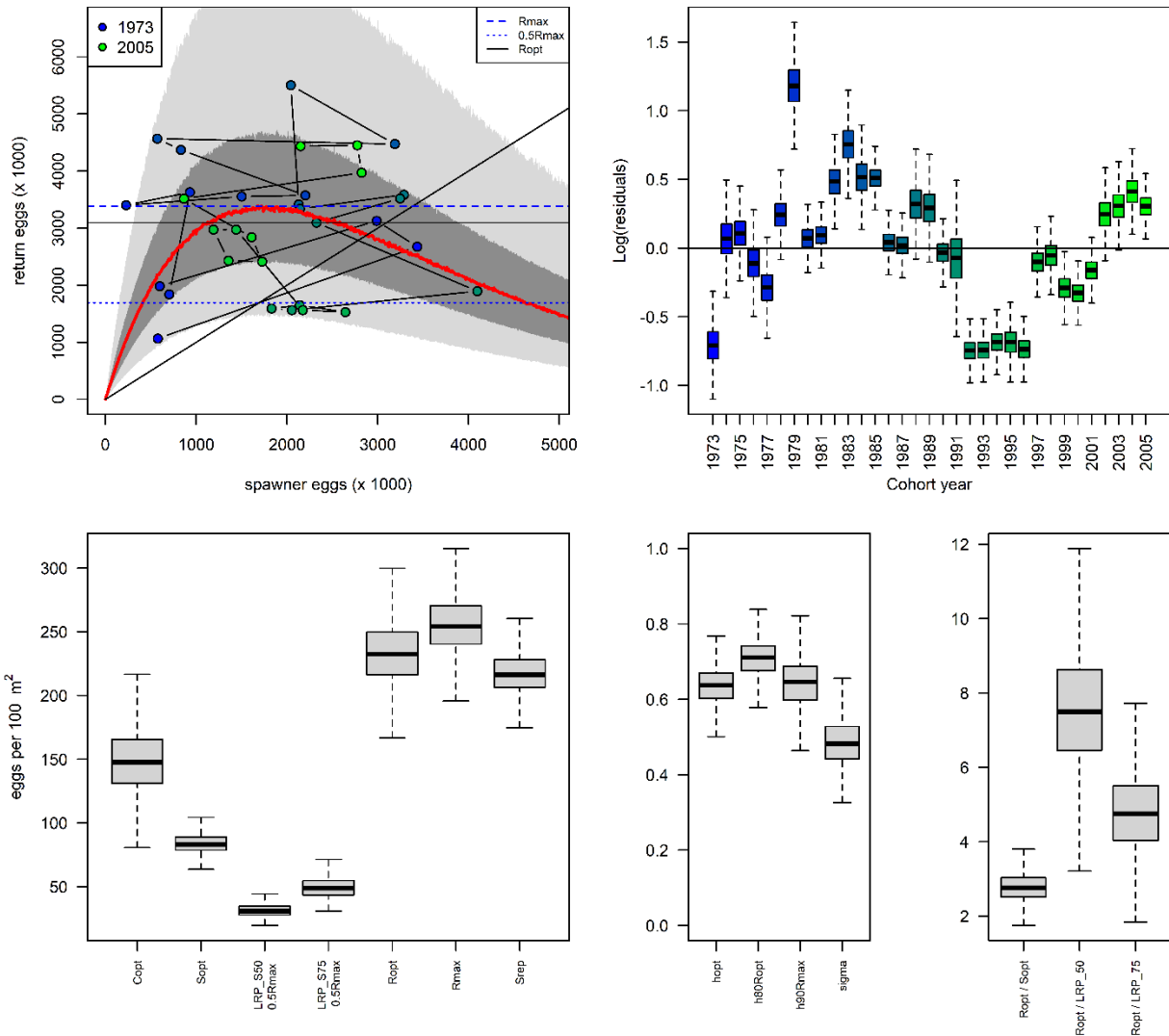


Figure A4.B.9. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Sainte-Anne River, 1973 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

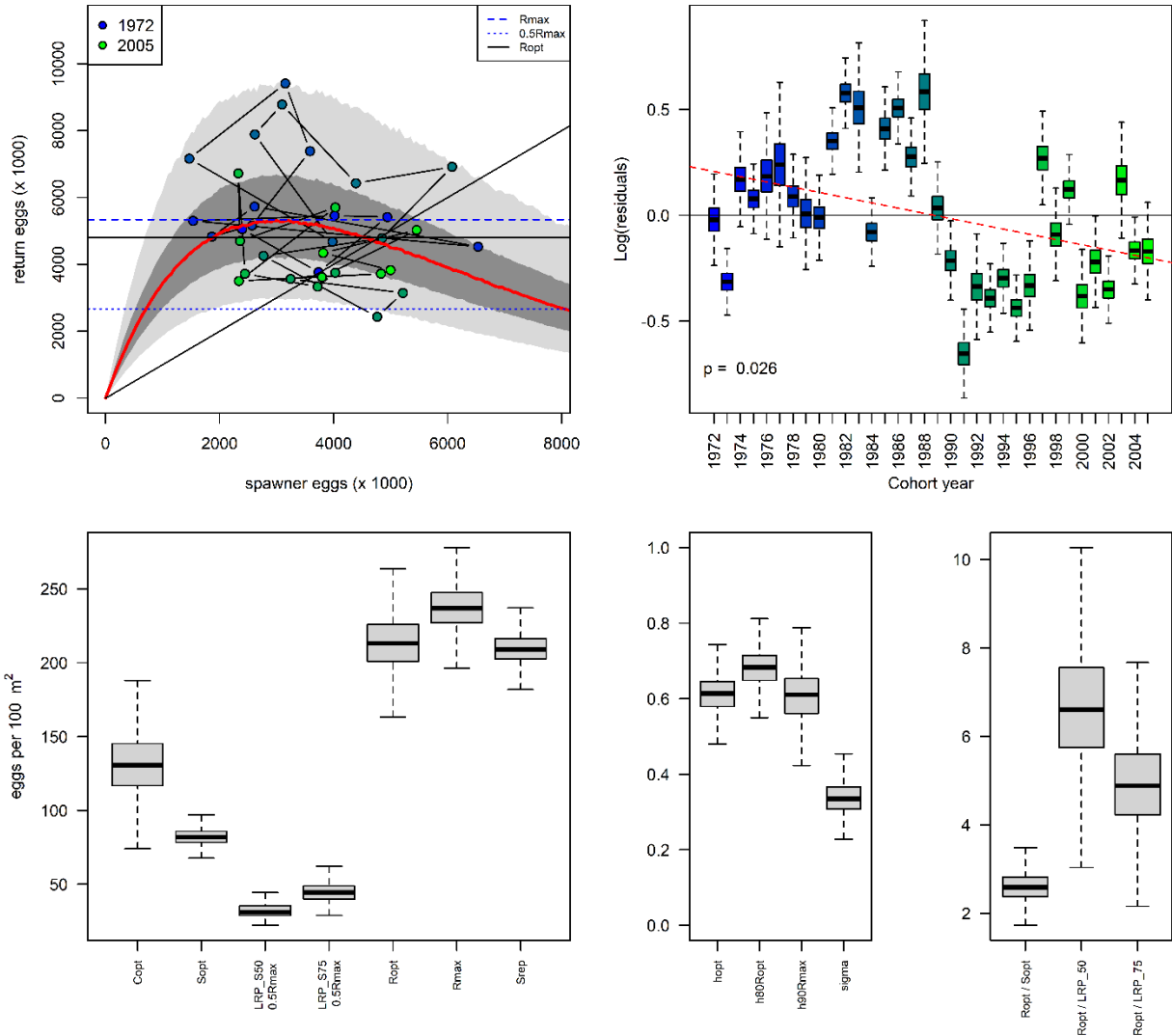


Figure A4.B.10. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the Saint-Jean River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

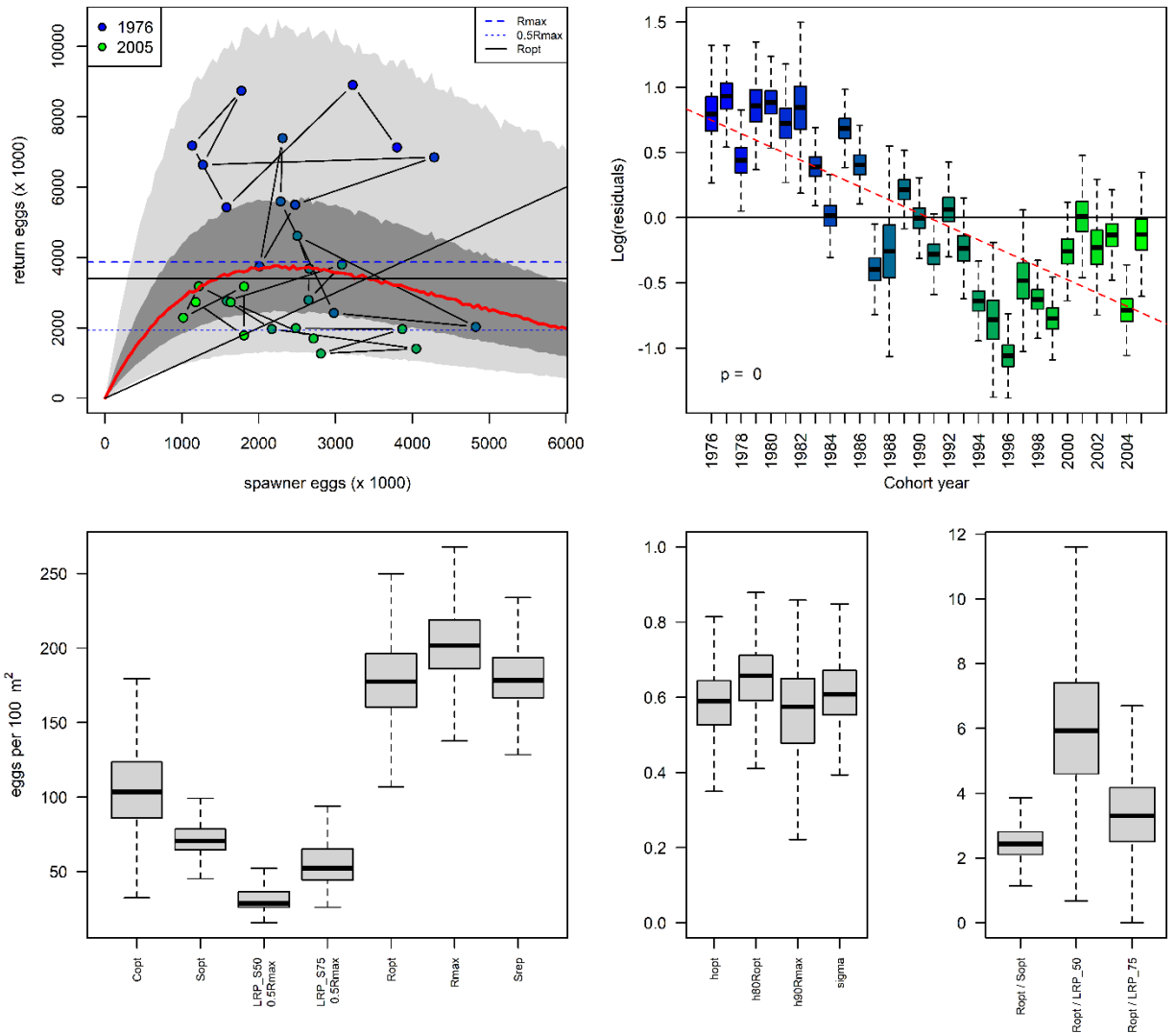


Figure A4.B.11. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for de la Trinité River, 1976 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

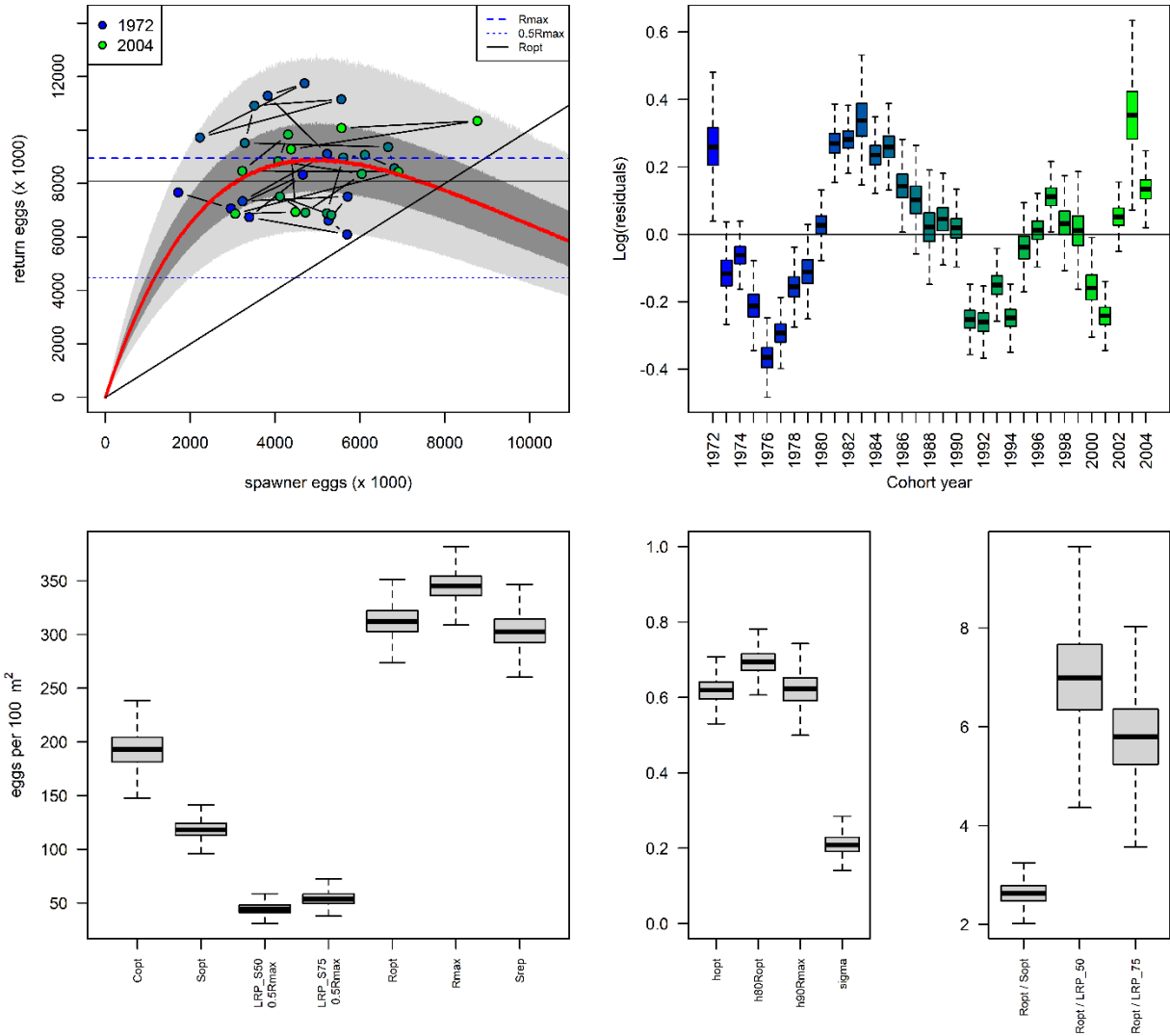


Figure A4.B.12. Diagnostics and reference values of independently fitting the Ricker stock and recruitment function to the egg to egg time series for the York River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

Appendix 4C. Fits and diagnostics of the hierarchical Ricker model fitted to ten rivers of Quebec and two rivers from the Gulf Region

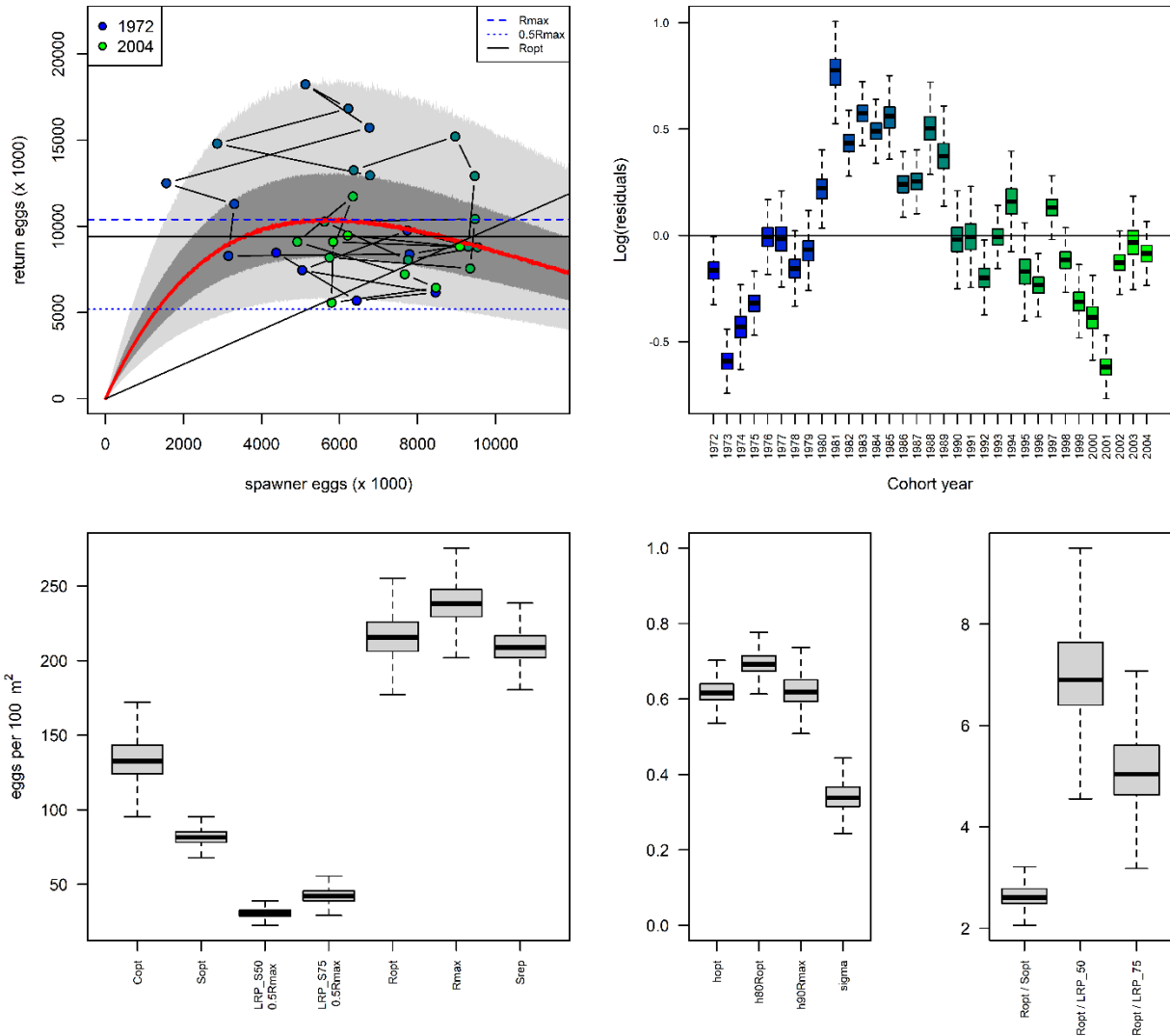


Figure A4.C.1. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the Bonaventure River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

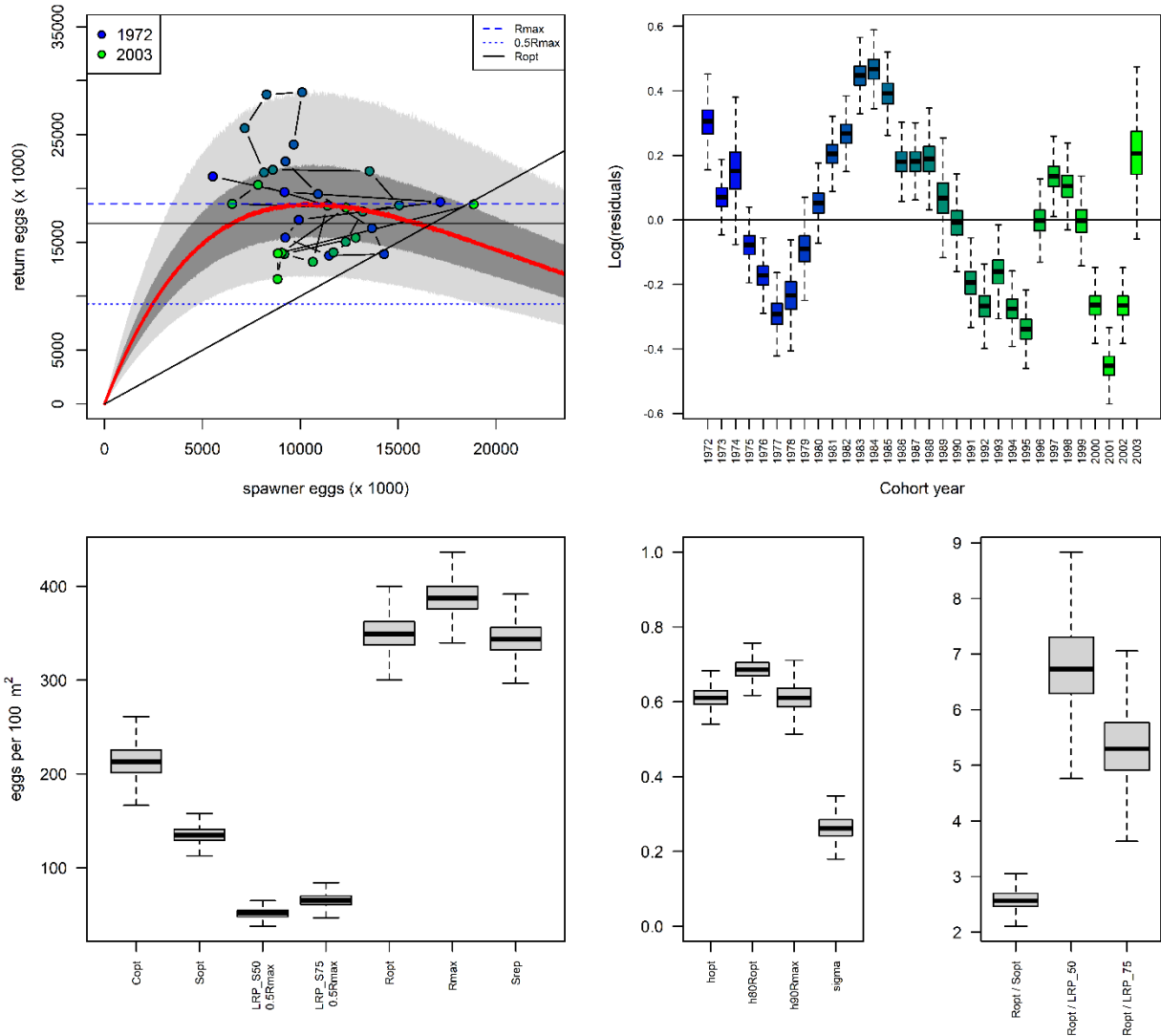


Figure A4.C.2. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the Cascapédia River, 1972 to 2003 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

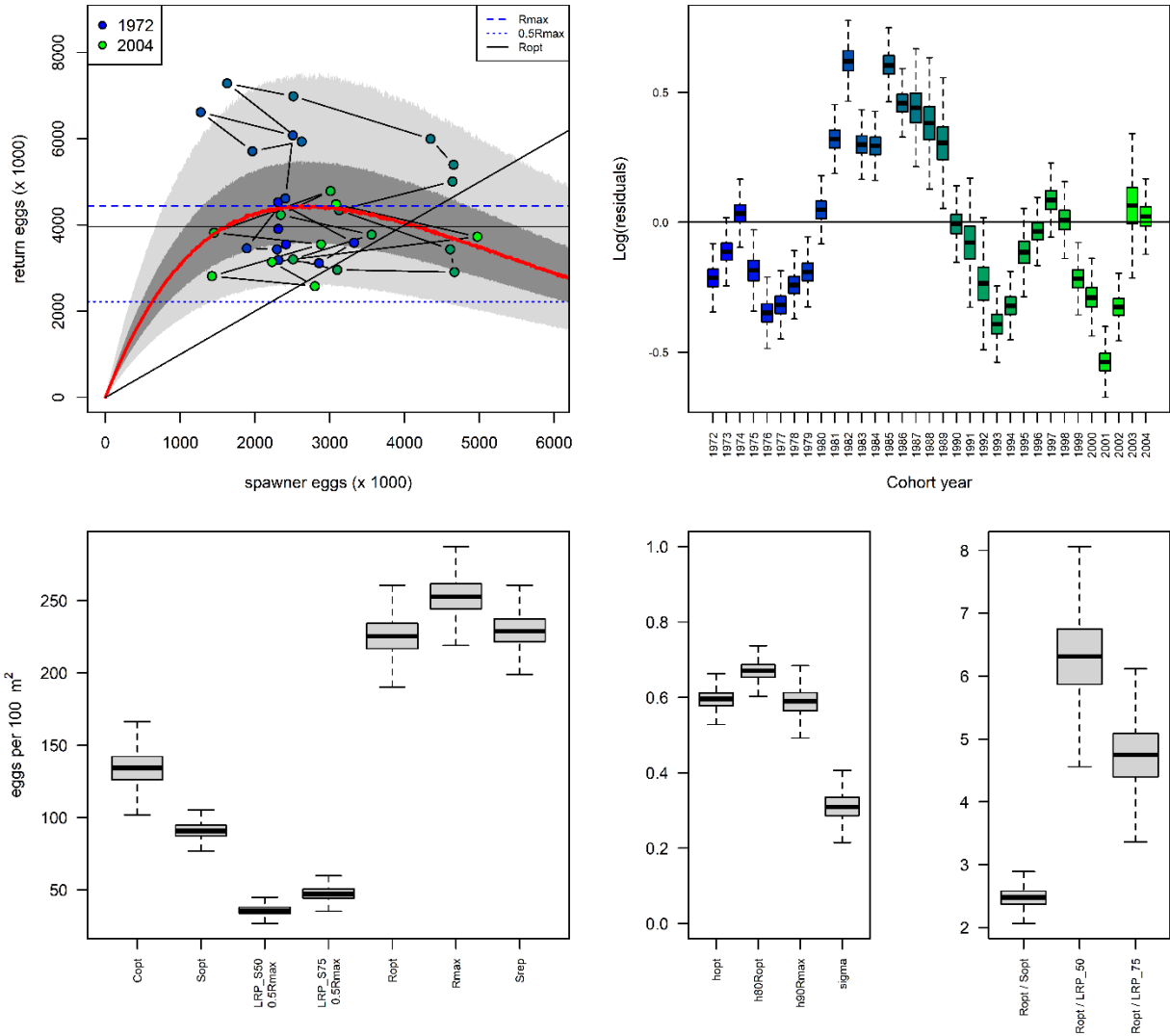


Figure A4.C.3. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the Dartmouth River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

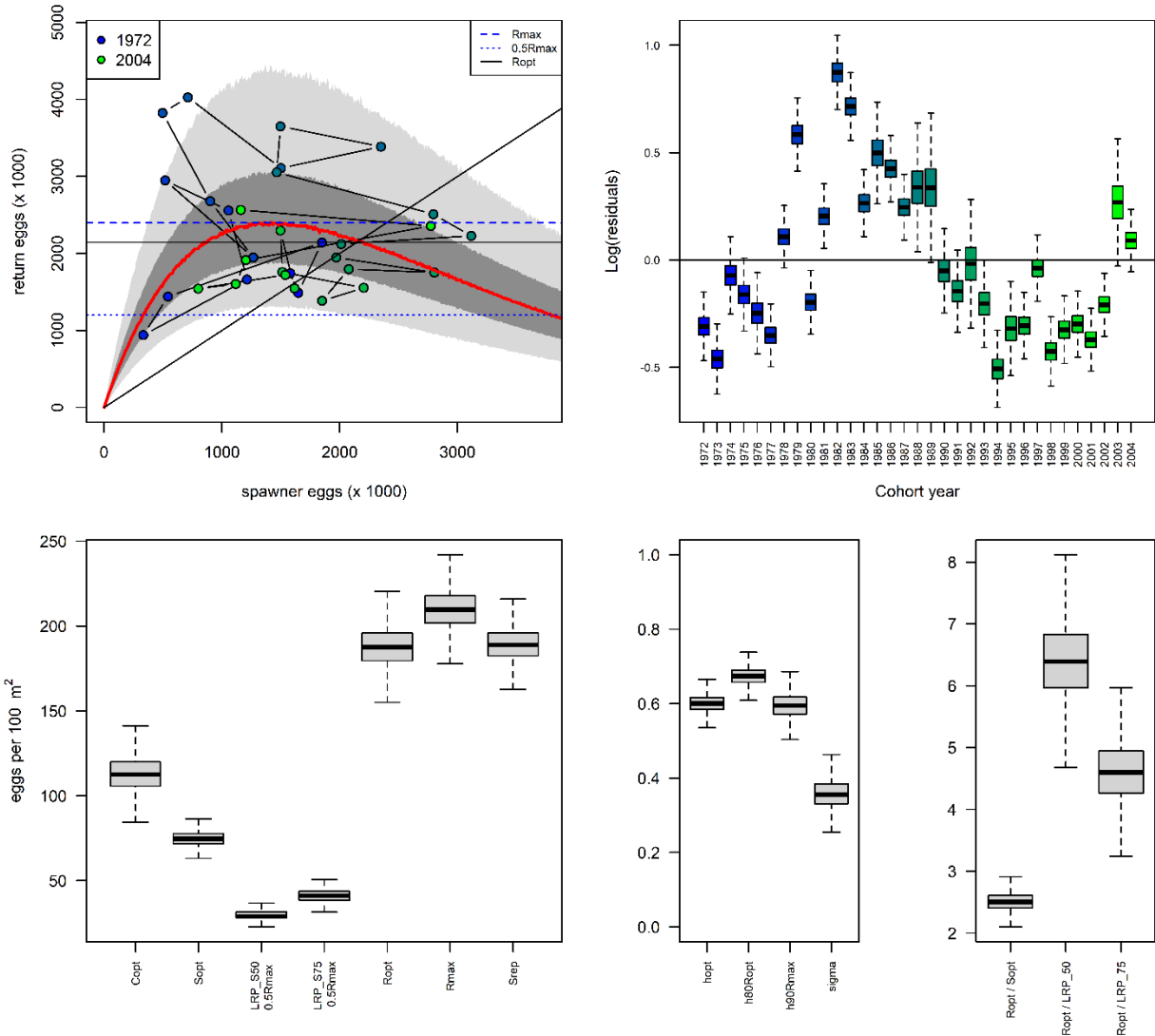


Figure A4.C.4. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the Grande-Rivière, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

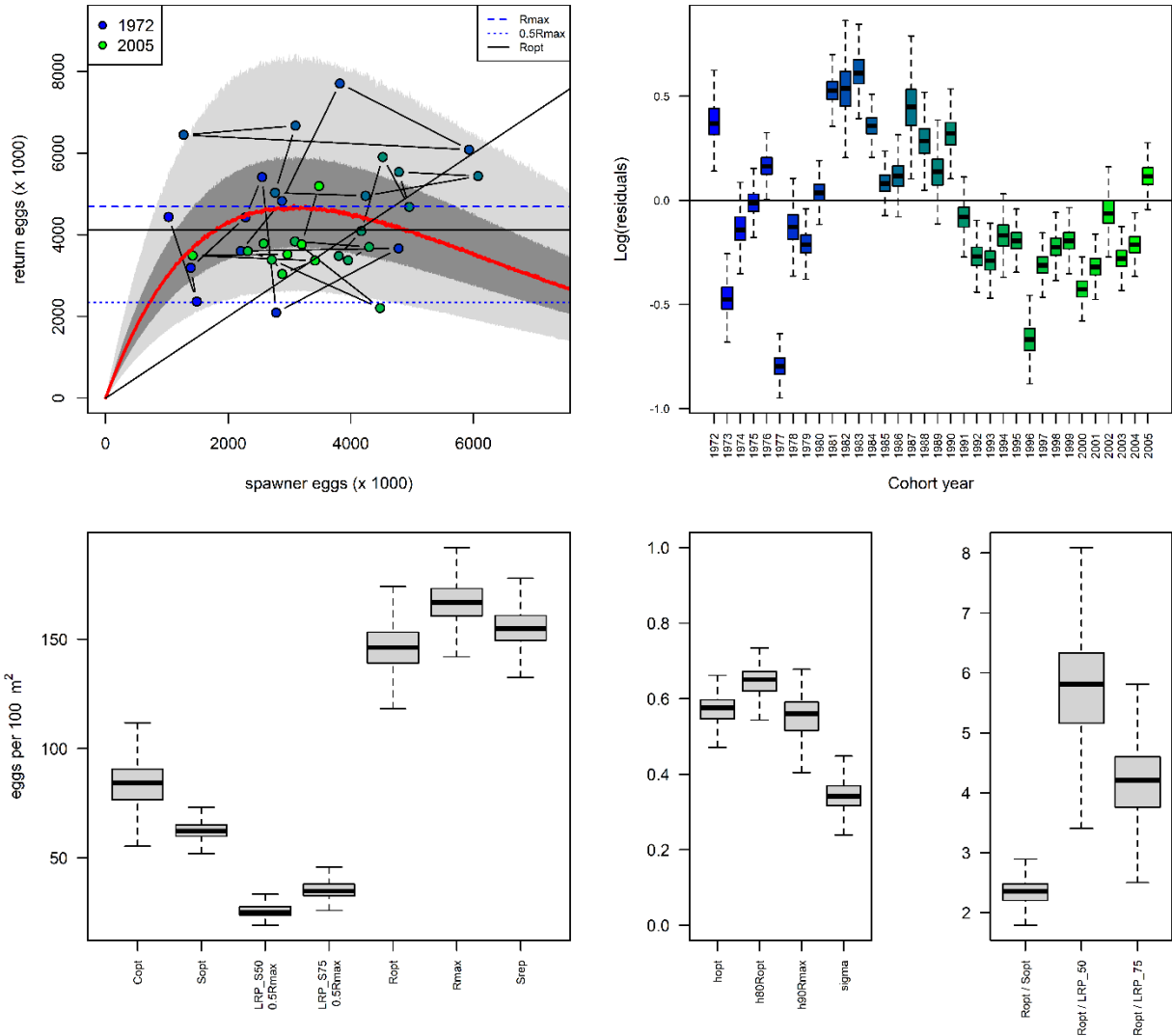


Figure A4.C.5. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the Madeleine River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

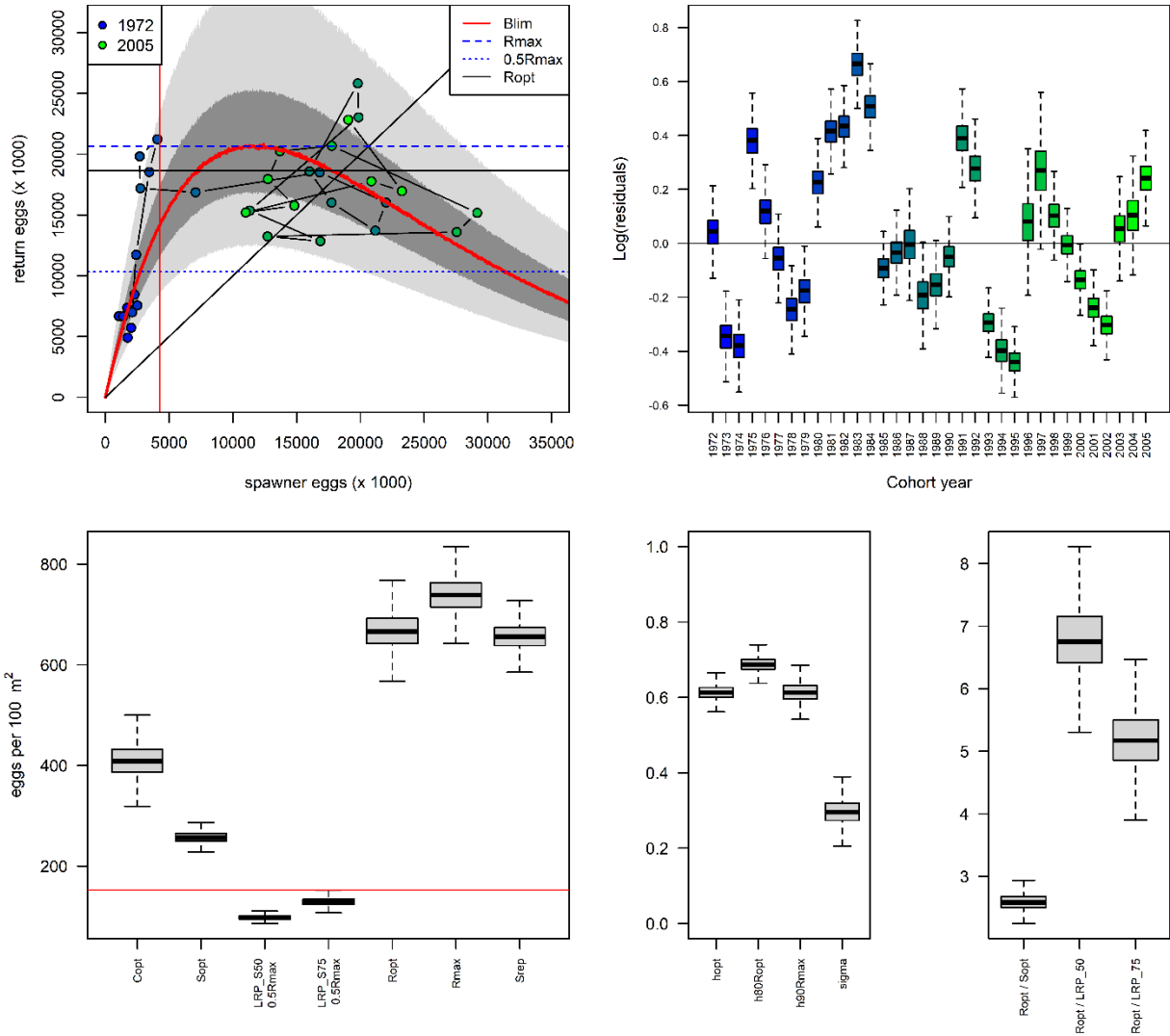


Figure A4.C.6. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the Margaree River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

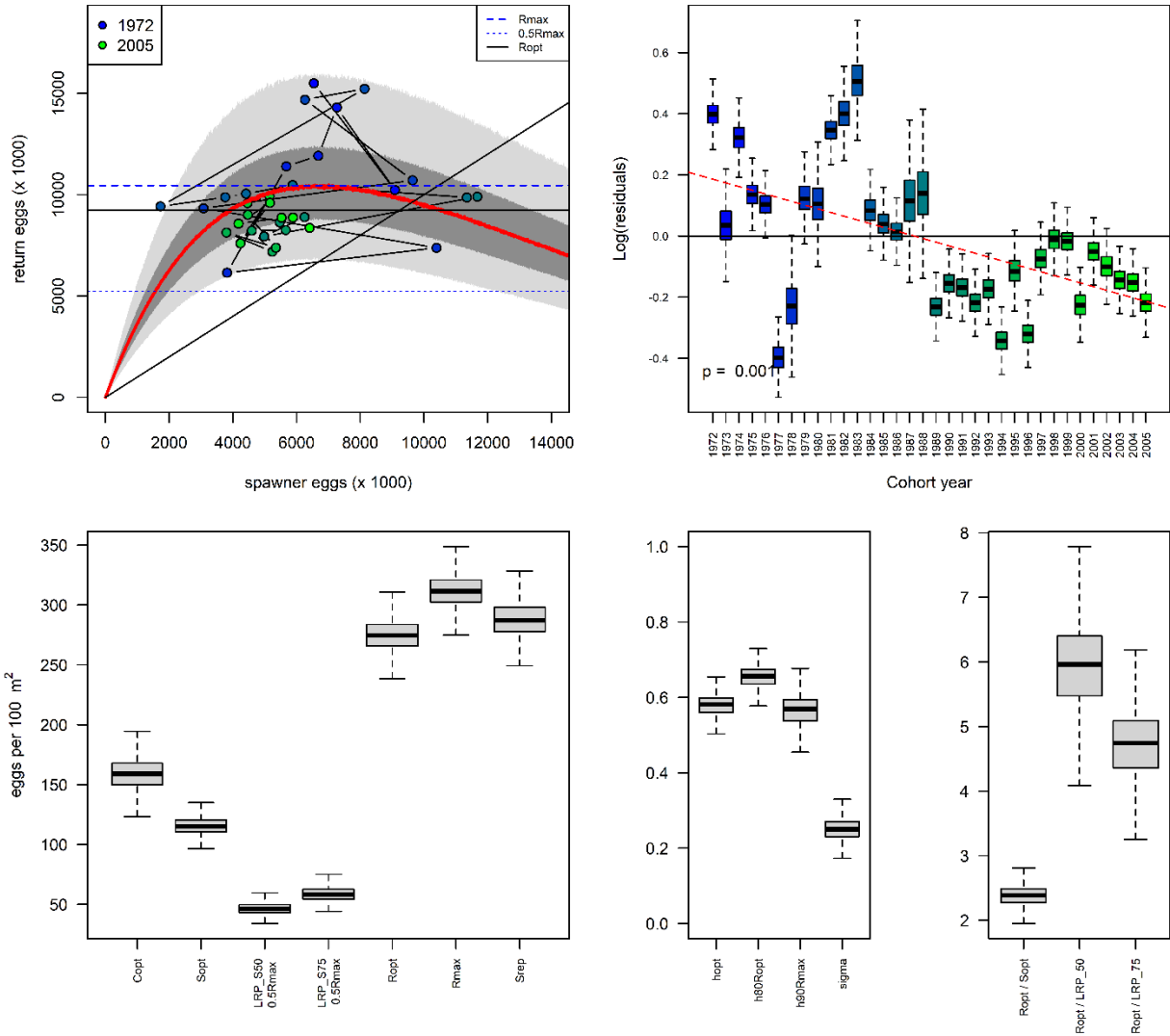


Figure A4.C.7. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the Matane River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

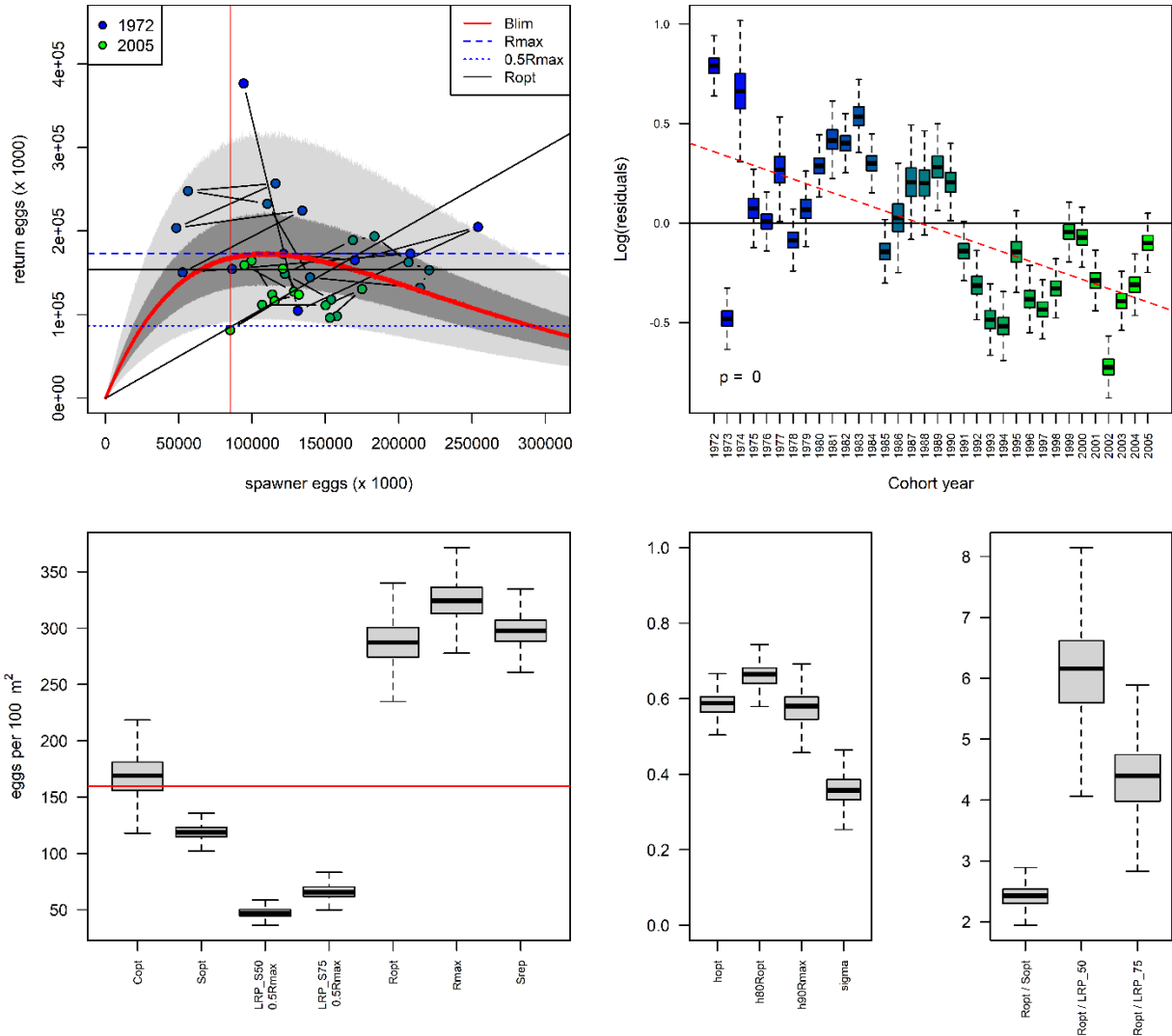


Figure A4.C.8. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the Miramichi River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

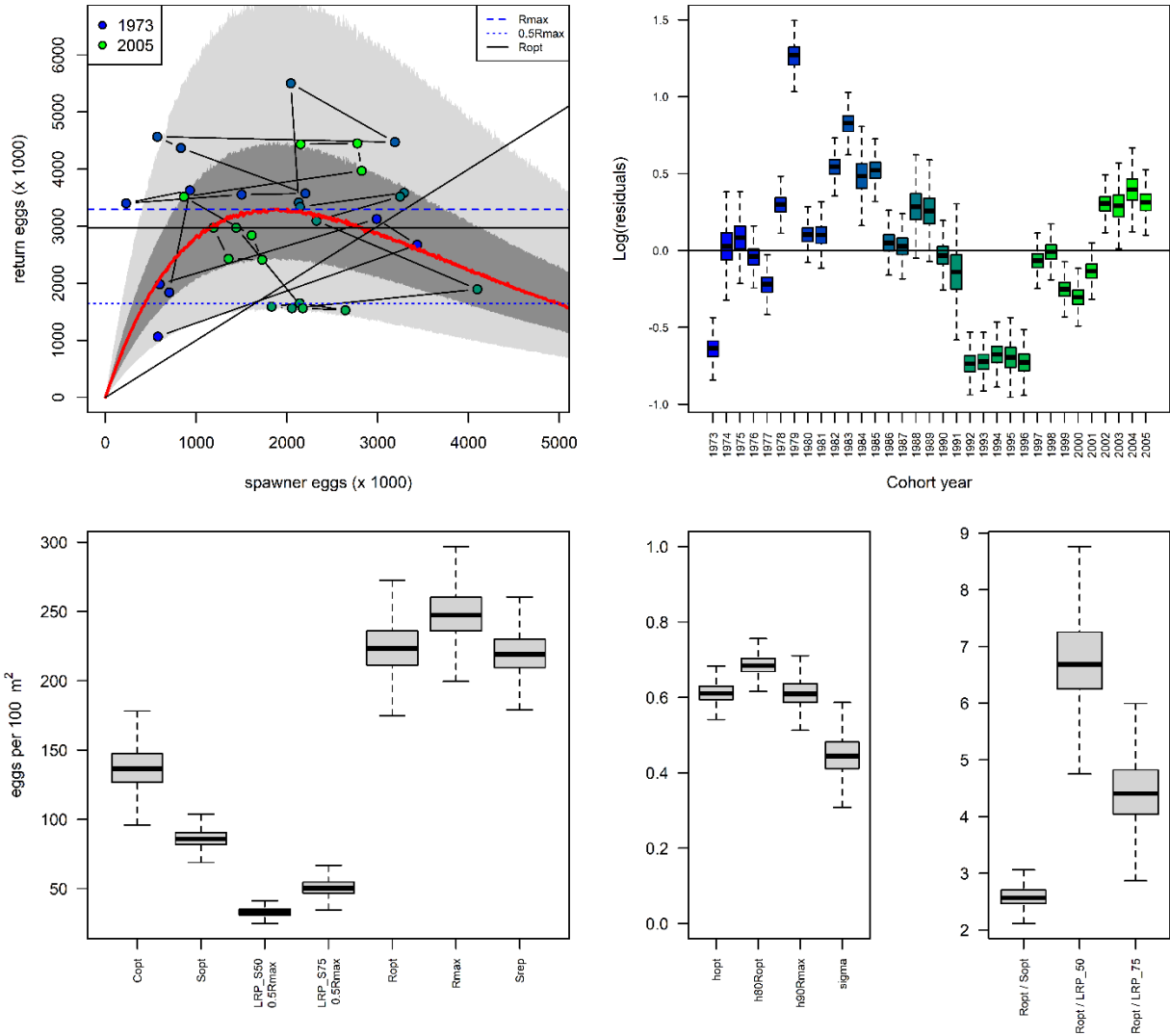


Figure A4.C.9. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the Sainte-Anne River, 1973 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

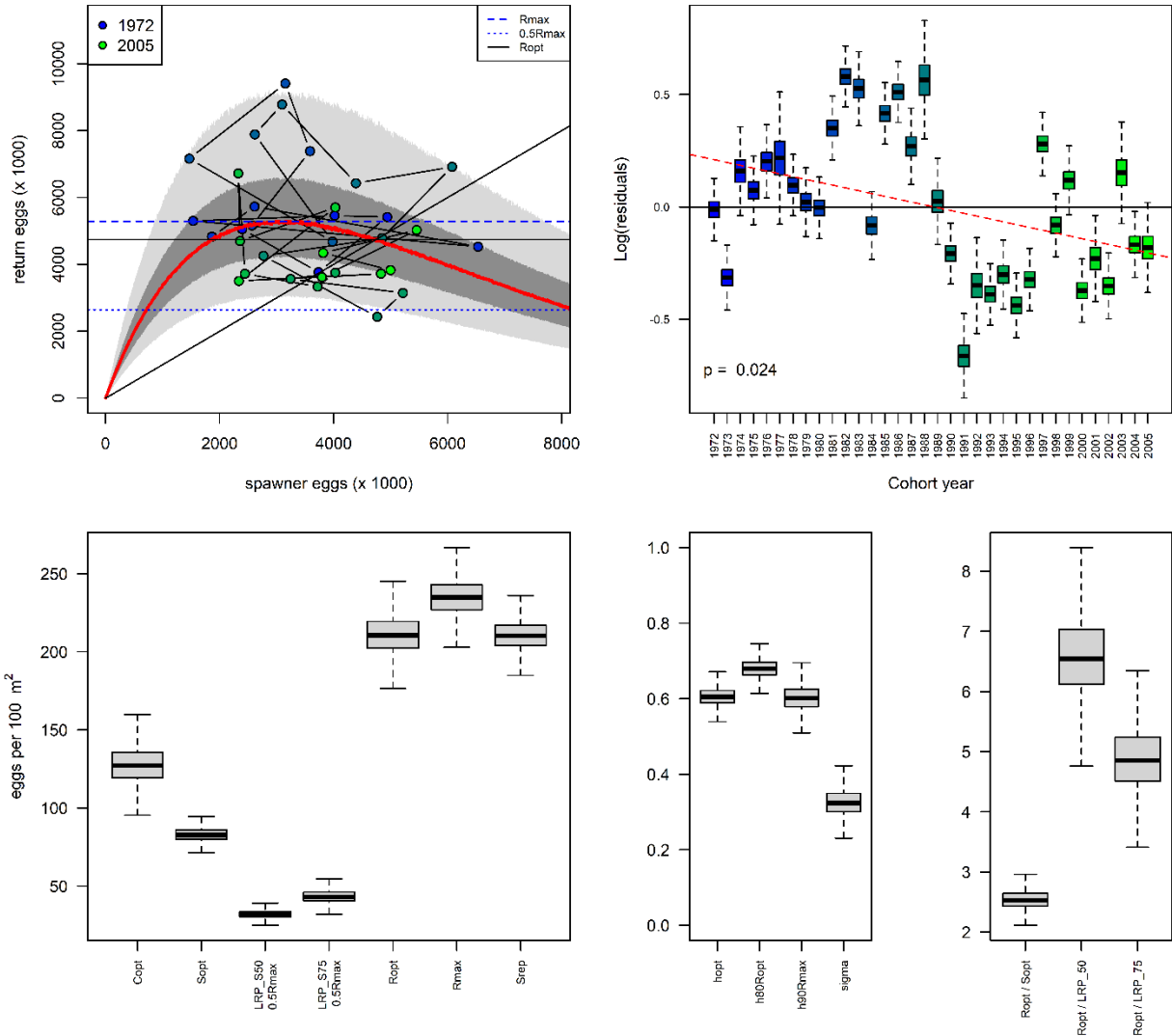


Figure A4.C.10. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the Saint-Jean River, 1972 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

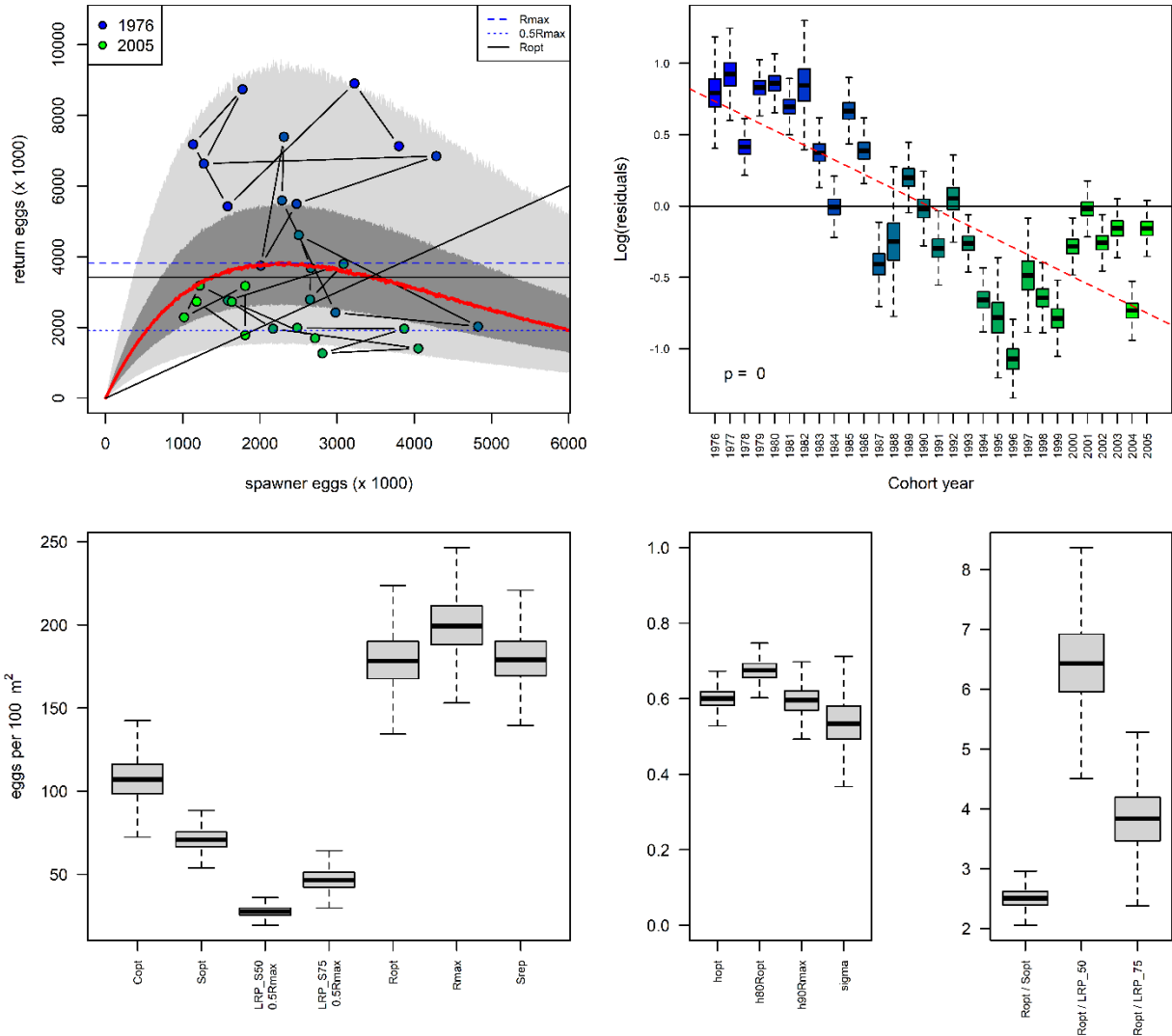


Figure A4.C.11. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for de la Trinité River, 1976 to 2005 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

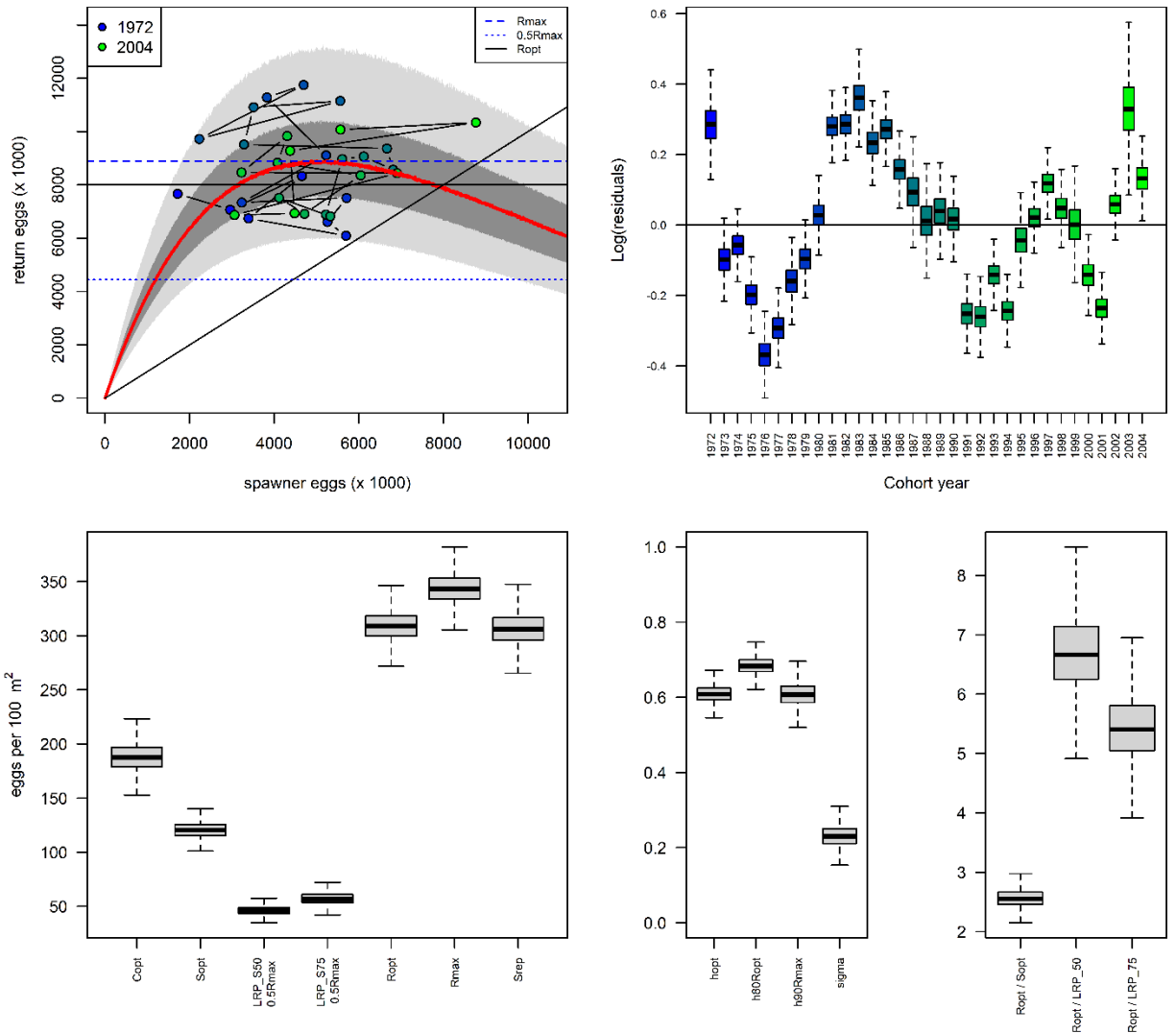


Figure A4.C.12. Diagnostics and reference values of the hierarchical fitting the Ricker stock and recruitment function to the egg to egg time series for the York River, 1972 to 2004 cohorts. Parameters of interest in the bottom left corner were converted in eggs per 100 m² of habitat area of the river for ease of comparison between rivers.

APPENDIX 5. STOCK AND RECRUITMENT RELATIONSHIPS PARAMETERIZED IN TERMS OF MANAGEMENT PARAMETERS C* AND H* (SCHNUTE AND KRONLUND 1996)

Based on Schnute and Kronlund (1996), the Ricker and Beverton Holt stock and recruitment relationships can be written generally as:

$$f(S; \alpha, \beta, \gamma) = \alpha S(1 - \beta\gamma S)^{1/\gamma}$$

with $\gamma = 0$ representing the Ricker relationship: $f(S; \alpha, \beta) = \alpha S e^{-\beta S} e^\varepsilon$, and

$\gamma = -1$ representing the Beverton-Holt relationship: $f(S; \alpha, \beta) = \frac{\alpha S}{1 + \beta S} e^\varepsilon$.

Schnute and Kronlund (1996) propose parametrizing these equations in terms of two management parameters, equilibrium catch at maximum sustainable yield (C^*) and equilibrium harvest rate at maximum sustainable yield ($h^* = h_{opt}$), with the following general equation:

$$f(S; C^*, h^*, \gamma) = \frac{S}{1-h^*} \left(1 + \gamma h^* - \frac{\gamma h^{*2}}{1-h^*} \frac{S}{C^*} \right)^{1/\gamma}$$

For the Ricker equation ($\gamma = 0$), Schnute and Kronlund (1996; eq. A.7) remind us:

$$\lim_{\gamma \rightarrow 0} (1 + \gamma x)^{\frac{1}{\gamma}} = \exp^x$$

therefore, rewriting the equation in terms of $(1 + \gamma x)^{\frac{1}{\gamma}}$:

$$f(S; C^*, h^*, \gamma) = \frac{S}{1-h^*} \left(1 + \gamma \left(h^* - \frac{h^{*2}}{1-h^*} \frac{S}{C^*} \right) \right)^{1/\gamma}$$

and applying the value function for the limit as $\gamma \rightarrow 0$ gives:

$$f(S; C^*, h^*) = \frac{S}{1-h^*} \exp \left(h^* - \frac{h^{*2}}{1-h^*} \frac{S}{C^*} \right)$$

Expressed in the more common Ricker formulation:

$$f(S; C^*, h^*) = S \left(\frac{\exp^{h^*}}{1-h^*} \right) \exp \left(- \left(\frac{h^{*2}}{(1-h^*)C^*} \right) S \right)$$

with the transition equations from C^* and h^* to α and β as:

$$\alpha = \frac{\exp^{h^*}}{1-h^*}$$

$$\beta = \frac{h^{*2}}{(1-h^*)C^*}$$

For the Beverton-Holt equation, $\gamma = -1$ and the general equation in terms of C^* and h^* becomes

$$f(S; C^*, h^*) = \frac{S}{1-h^*} \left(1 + (-1)h^* - \frac{(-1)h^{*2}}{1-h^*} \frac{S}{C^*} \right)^{1/(-1)}$$

or

$$f(S; C^*, h^*) = \frac{\frac{S}{1-h^*}}{1-h^* + \frac{h^{*2}}{1-h^*} \frac{S}{C^*}}$$

Multiplying the numerator and denominator by $\frac{1}{1-h^*}$

$$f(S; C^*, h^*) = \frac{\frac{S}{1-h^*} \frac{1}{1-h^*}}{\left(1-h^* + \frac{h^{*2}}{1-h^*} \frac{S}{C^*}\right) \frac{1}{1-h^*}}$$

gives:

$$f(S; C^*, h^*) = \frac{\frac{S}{(1-h^*)^2}}{\left(1 + \frac{h^{*2}}{(1-h^*)^2} \frac{S}{C^*}\right)}$$

and expressed in the more common Beverton-Holt formulation gives:

$$f(S; C^*, h^*) = \frac{\frac{1}{(1-h^*)^2} S}{1 + \frac{h^{*2}}{(1-h^*)^2} \frac{S}{C^*}}$$

with the transition equations from C^* and h^* to α and β as:

$$\alpha = \frac{1}{(1-h^*)^2}$$

$$\beta = \frac{h^{*2}}{(1-h^*)^2 C^*}$$

This also provides (algebraically) the following stock and recruitment parameters of interest:

$$S^* = S_{opt} = \text{spawners for MSY} = \frac{1-h^*}{h^*} C^*$$

$$R^* = R_{opt} = \text{recruitment at MSY} = \frac{C^*}{h^*}$$

$$S_{rep} = \text{spawners at replacement}$$

$$= \frac{(\alpha-1)}{\beta} \text{ [Beverton-Holt]}$$

$$= -\frac{\log(1/\alpha)}{\beta} \text{ [Ricker]}$$

$$R_{max} = \text{maximum recruitment}$$

$$= \frac{\alpha}{\beta} \text{ [Beverton-Holt]}$$

$$= \frac{\alpha}{\beta} e^{-1} \text{ [Ricker] (Hilborn and Walters 1992)}$$

$$S_{max} = \text{spawners at maximum recruitment}$$

$$= \infty \text{ [Beverton-Holt]}$$

$$= \frac{1}{\beta} \text{ [Ricker] (Hilborn and Walters 1992)}$$

For the Beverton-Holt equation above, $S_{0.5Rmax} = \frac{1}{\beta}$ but there is no analytical solution to the Ricker equation.

DFO (2015;2018) used the spawners that resulted in 50% of R_{max} , with a 75% probability, as a limit reference point for Atlantic Salmon. The value of $S_{0.5Rmax}$ that results in 75% chance or greater of attaining 50% R_{max} is calculated from the posterior distribution of the Beverton-Holt or Ricker stock and recruitment equation that includes the variance (e^ε) of the recruitment process.

Alternate parameterization using h^* and S^*

Using h^* and S^* as parameters with priors, we can regain α and β and other management related parameters. Recalling that:

$$S^* = \frac{1-h^*}{h^*} C^* \text{ then}$$

$$C^* = \frac{S^* h^*}{(1-h^*)}$$

For Beverton-Holt:

$$\alpha = \frac{1}{(1-h^*)^2}$$

$$\beta = \frac{h^{*2}}{(1-h^*)^2 C^*}$$

or in terms of S^*

$$\beta = \frac{h^*}{(1-h^*) S^*}$$

For Ricker:

$$\alpha = \frac{e^{h^*}}{1-h^*}$$

$$\beta = \frac{h^{*2}}{(1-h^*) C^*}$$

or in terms of S^*

$$\beta = \frac{h^*}{S^*}$$

APPENDIX 6. LIST OF ATLANTIC SALMON RIVERS IN DFO GULF REGION AND THEIR CORRESPONDING ABUNDANCE REFERENCE POINTS. THE LIST IS TAKEN FROM DFO (2018B) WITH NEW VALUES FOR THE USR AND TR REFERENCE POINTS

Salmon Fishing Area	River	Drainage area (km ²)	Fluvial area (million m ²)	LRP (eggs; million)	USR (eggs, million)	TR (eggs, million)
15	Restigouche (NB)	6,589	26.390	40.113	152.429	189.333
15	Eel River	217	0.422	0.641	2.436	3.026
15	Charlo	282	0.423	0.643	2.443	3.035
15	South Charlo	118	0.177	0.269	1.022	1.270
15	Blackland Brook	na	na	na	na	na
15	New Mills	na	na	na	na	na
15	Benjamin	161	0.242	0.366	1.391	1.728
15	Nash Creek	na	na	na	na	na
15	Louison River	142	0.213	0.324	1.231	1.529
15	Jacquet	510	1.135	1.725	6.555	8.142
15	Armstrong Brook	na	na	na	na	na
15	Patapat Brook (Belledune)	na	na	na	na	na
15	Fournier Brook	na	na	na	na	na
15	Elmtree River	297	0.446	0.678	2.576	3.200
15	Little Elmtree River	na	na	na	na	na
15	Nigadoo	168	0.252	0.383	1.455	1.808

Salmon Fishing Area	River	Drainage area (km ²)	Fluvial area (million m ²)	LRP (eggs; million)	USR (eggs, million)	TR (eggs, million)
15	Millstream	229	0.344	0.523	1.987	2.469
15	Peters River	na	na	na	na	na
15	Tetagouche	364	0.299	0.455	1.729	2.148
15	Middle (Gloucester Co.)	401	0.950	1.444	5.487	6.816
15	Little River	na	na	na	na	na
15	Nepisiguit	2,312	3.973	6.039	22.948	28.504
15	Bass (Gloucester Co.)	198	0.297	0.451	1.714	2.129
15	Miller Brook	na	na	na	na	na
15	Teagues Brook	237	0.356	0.541	2.056	2.554
15	Little Pokeshaw River	na	na	na	na	na
15	Pokeshaw River	na	na	na	na	na
15	Riviere du Nord	na	na	na	na	na
15	Caraquet	373	0.560	0.851	3.234	4.017
15	Pokemouche	481	0.248	0.377	1.433	1.779
15	Little Tracadie	192	0.288	0.438	1.664	2.067
15	Tracadie	527	0.601	0.914	3.473	4.314
16	Tabusintac	704	0.824	1.25	4.750	5.900
16	Burnt Church	135	0.299	0.46	1.748	2.171
16	Oyster	na	na	na	na	na

Salmon Fishing Area	River	Drainage area (km ²)	Fluvial area (million m ²)	LRP (eggs; million)	USR (eggs, million)	TR (eggs, million)
16	Bartibog	512	1.135	1.73	6.574	8.166
16	Northwest Miramichi	2,138	8.230	14.48	55.024	68.346
16	Northwest Millstream	210	0.479	0.84	3.192	3.965
16	Little Southwest Miramichi	1,345	8.070	14.2	53.960	67.024
16	Southwest Miramichi	5,840	29.530	44.89	170.582	211.881
16	Renous	1,429	5.820	8.85	33.630	41.772
16	Barnaby	490	1.304	1.98	7.524	9.346
16	Napan	115	0.115	0.17	0.646	0.802
16	Black (Northumberland Co.)	277	0.277	0.42	1.596	1.982
16	Bay du Vin	284	0.284	0.43	1.634	2.030
16	Eel River	116	na	na	na	na
16	Portage River	na	na	na	na	na
16	Riviere au Portage	na	na	na	na	na
16	Black (Kent Co.)	343	0.343	0.52	1.976	2.454
16	Rankin Brook	na	na	na	na	na
16	Kouchibouguac (Kent Co.)	389	0.588	0.89	3.382	4.201
16	Ruisseau des Major	25	na	na	na	na
16	Kouchibouguacis	360	0.549	0.83	3.154	3.918
16	Saint Charles	149	na	na	na	na

Salmon Fishing Area	River	Drainage area (km ²)	Fluvial area (million m ²)	LRP (eggs; million)	USR (eggs, million)	TR (eggs, million)
16	Molus River	172	na	na	na	na
16	Bass River	115	na	na	na	na
16	Richibucto	449	1.226	1.86	7.068	8.779
16	Coal Branch	212	na	na	na	na
16	Saint Nicholas	194	na	na	na	na
16	Chockpish	129	0.129	0.2	0.760	0.944
16	Black	na	na	na	na	na
16	Buctouche	566	0.661	1	3.800	4.720
16	Cocagne	333	0.283	0.43	1.634	2.030
16	Shediac	219	0.216	0.33	1.254	1.558
16	Scoudouc	159	0.146	0.22	0.836	1.038
16	Aboujagane	120	0.120	0.18	0.684	0.850
16	Kinnear Brook	na	na	na	na	na
16	Kouchibouguac (Westmorland Co.)	346	na	na	na	na
16	Tedish River	na	na	na	na	na
16	Gaspereau (Westmorland Co.)	170	0.170	0.26	0.988	1.227
16	Baie Verte	38	0.058	0.09	0.342	0.425
17	Cains Brook, Mill River	30.9	0.023	0.036	0.137	0.170

Salmon Fishing Area	River	Drainage area (km ²)	Fluvial area (million m ²)	LRP (eggs; million)	USR (eggs, million)	TR (eggs, million)
17	Carruthers Brook, Mill River	47.9	0.035	0.056	0.213	0.264
17	Trout River (Coleman)	107.1	0.140	0.222	0.844	1.048
17	Trout River, Tyne Valley	48.3	0.063	0.096	0.365	0.453
17	Little Trout River	21.3	0.028	0.042	0.160	0.198
17	Bristol (Berrigans) Creek	41.4	0.054	0.082	0.312	0.387
17	Morell River	170.6	0.237	0.375	1.425	1.770
17	Midgell River	63.8	0.083	0.127	0.483	0.599
17	St. Peters River	44.6	0.058	0.089	0.338	0.420
17	Cow River	22.8	0.030	0.045	0.171	0.212
17	Naufrage River	43.6	0.057	0.087	0.331	0.411
17	Bear River	17.2	0.022	0.034	0.129	0.160
17	Hay River	25.7	0.034	0.051	0.194	0.241
17	Cross Creek	44.3	0.058	0.088	0.334	0.415
17	Priest Pond Creek	24.9	0.033	0.049	0.186	0.231
17	North Lake Creek	47.7	0.062	0.095	0.361	0.448
17	Vernon River	69.2	0.091	0.138	0.524	0.651
17	Clarks Creek	46.3	0.061	0.092	0.350	0.434
17	Pisquid River	47.6	0.062	0.095	0.361	0.448
17	Head of Hillsborough R.	53.1	0.070	0.106	0.403	0.500

Salmon Fishing Area	River	Drainage area (km ²)	Fluvial area (million m ²)	LRP (eggs; million)	USR (eggs, million)	TR (eggs, million)
17	North River	99.0	0.130	0.197	0.749	0.930
17	Clyde River	41.7	0.054	0.083	0.315	0.392
17	West River	114.1	0.185	0.292	1.110	1.378
17	Dunk River	165.7	0.193	0.305	1.159	1.440
17	Wilmot River	83.4	0.110	0.166	0.631	0.784
18	Salmon River	na	na	na	na	na
18	Blair River	58	0.097	0.148	0.562	0.699
18	Red River	35	0.059	0.089	0.338	0.420
18	Grande Anse River	51	0.085	0.13	0.494	0.614
18	Mackenzies River	75	0.124	0.189	0.718	0.892
18	Fishing Cove River	31	0.052	0.079	0.300	0.373
18	Corneys Brook	na	na	na	na	na
18	Anthony Aucoin's Brook	na	na	na	na	na
18	Rigwash Brook	na	na	na	na	na
18	Chéticamp River	298	0.319	0.489	1.858	2.308
18	Aucoin Brook	na	na	na	na	na
18	Fiset Brook	na	na	na	na	na
18	Farm Brook	na	na	na	na	na
18	Margaree River	1,100	2.798	4.252	16.158	20.069

Salmon Fishing Area	River	Drainage area (km ²)	Fluvial area (million m ²)	LRP (eggs; million)	USR (eggs, million)	TR (eggs, million)
18	Smiths Brook	na	na	na	na	na
18	Broad Cove River	na	na	na	na	na
18	Mill Brook	na	na	na	na	na
18	Northeast Mabou River	254	0.424	0.645	2.451	3.044
18	Southwest Mabou River	123	0.154	0.234	0.889	1.104
18	Mabou River	188	0.235	0.357	1.357	1.685
18	Captains Brook	34	0.057	0.086	0.327	0.406
18	Judique Intervale Brook	44	0.074	0.112	0.426	0.529
18	Graham River	na	na	na	na	na
18	Campbells Brook	na	na	na	na	na
18	Chisholm Brook	17	0.028	0.042	0.160	0.198
18	Mill Brook (Strait of Canso)	na	na	na	na	na
18	Wrights River	na	na	na	na	na
18	Tracadie River	120	0.053	0.08	0.304	0.378
18	Afton River	43	0.019	0.029	0.110	0.137
18	Pomquet River	176	0.077	0.117	0.445	0.552
18	South River	217	0.095	0.144	0.547	0.680
18	West River (Antigonish)	353	0.480	0.73	2.774	3.446
18	North River	na	na	na	na	na

Salmon Fishing Area	River	Drainage area (km ²)	Fluvial area (million m ²)	LRP (eggs; million)	USR (eggs, million)	TR (eggs, million)
18	MacInnis Brook	na	na	na	na	na
18	Doctors Brook	na	na	na	na	na
18	Vameys Brook	na	na	na	na	na
18	Baileys Brook	na	na	na	na	na
18	Barneys River	156	0.213	0.323	1.227	1.525
18	French River (Merigomish)	128	0.174	0.264	1.003	1.246
18	Russell Brook	na	na	na	na	na
18	Sutherlands River		0.067	0.101	0.384	0.477
18	Pine Tree Brook	na	na	na	na	na
18	East River (Pictou)	536	0.729	1.108	4.210	5.230
18	Middle River (Pictou)	217	0.295	0.449	1.706	2.119
18	West River (Pictou)	245	0.333	0.506	1.923	2.388
18	Haliburton Brook	na	na	na	na	na
18	Big Caribou River	na	na	na	na	na
18	Toney River	na	na	na	na	na
18	River John	292	0.397	0.604	2.295	2.851
18	Waughs River	230	0.313	0.476	1.809	2.247
18	French River	206	0.280	0.426	1.619	2.011
18	Wallace River	458	0.623	0.947	3.599	4.470

Salmon Fishing Area	River	Drainage area (km ²)	Fluvial area (million m ²)	LRP (eggs; million)	USR (eggs, million)	TR (eggs, million)
18	Pugwash River	182	0.247	0.375	1.425	1.770
18	River Philip	726	0.962	1.462	5.556	6.901
18	Shinimicas River	na	na	na	na	na
