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Updated Methods For Assessing Harvest Rules For Fraser River Sockeye Salmon (*Oncorhynchus nerka*)

Méthodes mises à jour pour l'évaluation des règles de pêche au saumon rouge (*Oncorhynchus nerka*) du fleuve Fraser

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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ABSTRACT

The Fraser River Sockeye Spawning Initiative (FRSSI) has been an on-going process to develop guidelines for setting annual spawning and exploitation targets for Fraser River sockeye salmon stocks. The initiative began in early 2002, and has since evolved through a series of workshops and on-going feedback from stakeholders. A quantitative modeling tool has been used to support the planning process, and was reviewed by PSARC in 2003. The model has evolved substantially since then, and was reviewed again by CSAS in 2010. Changes include assumptions about spawner-recruit relationships (e.g. delayed density dependence effects), the range of strategies that can be explored (e.g. allowable mortality rules), mixed-stock simulations (i.e. 19 stocks in 4 management groups), and additional biological mechanisms (e.g. environmental management adjustments, pre-spawn mortality, future patterns in productivity).

This Research Document provides an update on model expansions and revisions, and presents simulation results to illustrate the range of questions that can be explored with the model.

RÉSUMÉ

Le Projet de reproduction du saumon rouge du fleuve Fraser (PRSRFF) est un processus en continu en vue de l'élaboration de directives pour l'établissement de cibles annuelles en matière de production et d'exploitation pour les stocks de saumon rouge du fleuve Fraser. Le projet a commencé au début de 2002 et, depuis, s'est développé à l'aide d'une série d'ateliers et de rétroaction continue des intervenants. Un outil de modélisation quantitative a été utilisé à l'appui du processus de planification et a été passé en revue par le Comité d'examen des évaluations scientifiques du Pacifique (CEESP) en 2003. Le modèle a été considérablement modifié depuis et a de nouveau été passé en revue par le SCCS en 2010. Parmi les changements, il y a des hypothèses sur les relations reproducteurs-recrues (p. ex., effets tardifs de la dépendance à la densité), l'éventail de stratégies qui peuvent être examinées (p. ex., règles sur la mortalité admissible), des simulations pour les stocks mixtes (c.-à-d., 19 stocks dans 4 groupes de gestion) et des mécanismes biologiques additionnels (p. ex., ajustements pour la gestion environnementale, mortalité avant le frai, modèles futurs de productivité).

Ce document de recherche donne une mise à jour sur les ajouts et les révisions pour le modèle et il présente les résultats de la simulation afin d'illustrer l'éventail de questions pouvant être examinées à l'aide du modèle.

ACKNOWLEDGEMENTS

The simulation model described in this report is part of an on-going planning process, and many individuals have contributed over the last 8 years (e.g. annual workshop series, science reviews in 2003 and 2010). Paul Ryall (DFO), Mike Staley (IAS Ltd), Les Jantz (DFO), Jeff Grout (DFO), Diana McHugh (DFO), and Michael Folkes (DFO) have particularly guided model development as long-term members of the FRSSI Working Group. Mike Lapointe (PSC), Sue Grant (DFO), Carrie Holt (DFO), Catherine Michielsens (DFO), Merran Hague (DFO), and Dave Patterson (DFO) provided data and advice for this latest version of the model.

New spawner-recruit analyses by Ann-Marie Huang were done in conjunction with research for a graduate thesis supervised by Sean Cox (SFU). Al Cass (DFO) and Mike Staley (IAS Ltd.) served as advisors.

A draft version of this report was reviewed by the Salmon Subcommittee of the *Centre for Science Advice – Pacific* in May 2010. Carrie Holt (DFO) and Josh Korman (Ecometric Research Inc.) provided extensive comments in writing prior to the meeting.

PREFACE

Revisions resulting from the CSAS review include clarifications identified by the reviewers, more detail and additional analysis around spawner-recruit models as discussed in the meeting, and more extensive sensitivity analyses. Reviewer's comments, author's responses, and discussions during the meeting are documented in a proceedings report (DFO 2011a). A summary is included in the *Science Advisory Report* from the meeting (DFO 2011b).

Written reviews and comments during the CSAP meeting focused on methods (e.g. alternative approaches for estimating spawner-recruit parameters, range of options for simulating en-route mortality) and did not deal with sample results (e.g. whether the base case in the draft Research Document was considered plausible). Participants recognized that there is a separate planning process for using the modeling tool and having that type of discussion.

Revisions since the CSAP review were completed within the broader context of the 2009-2010 sockeye returns and informed by several on-going research and review processes. These include:

- The Working Paper *Fraser sockeye (Oncorhynchus nerka) Wild Salmon Policy Evaluation of Stock Status: State and Rate* by Grant et al. was reviewed by CSAP in November 2010, and has recently been published as Grant et al. (2011).
- Science reports and expert testimony under the Cohen Commission looked at population dynamics and harvest policies for Fraser River sockeye salmon (e.g. Peterman and Dorner 2011).

However, readers should note that the bulk of revisions on this Research Document was completed before the above processes had come to a conclusion, and before observations from 2009-2010 could be included in the spawner-recruit data sets.

Note: This report carries over some text from two previous reports (Cass et al. 2004, Pestal et al. 2008)

1 INTRODUCTION

1.1 PURPOSE OF THIS RESEARCH DOCUMENT

The Fraser River Sockeye Spawning Initiative (FRSSI) has been a multi-year collaborative planning process to develop a long-term escapement strategy for Fraser River sockeye salmon.

A simulation model to evaluate alternative harvest control rules for Fraser River sockeye salmon was reviewed by PSARC in June 2003. The resulting CSAS Research Document provided the background for a series of multi-interest stakeholder workshops (Cass et al. 2004).

The simulation model evolved considerably as the initiative progressed over years of collaborative development and implementation. The FRSSI process and its application to annual escapement planning are documented in Pestal et al. (2008).

Given the substantial amount of accumulated revisions to the model and its underlying assumptions since 2004, a review of the methods became once again necessary.

The objective of this Research Document is to:

- Review methods to evaluate the performance of alternative escapement strategies (i.e. harvest control rules) for stocks of Fraser River sockeye salmon.
- Explore the sensitivity of different escapement strategies to key sources of uncertainty (e.g. alternative population dynamics, patterns of productivity)

Methods documented in this Research Document support the evaluation of alternative management strategies, such as target levels of total allowable mortality that change with run size. These management strategies shape pre-season fishing plans, guide in-season management decisions, and provide a point of reference for post-season review.

1.2 POPULATION STRUCTURE AND LIFE HISTORY OF FRASER RIVER SOCKEYE SALMON

Sockeye salmon spawn in over 150 natal areas throughout the Fraser River watershed, ranging from near the estuary to as far as 1,300 km upstream. More than 270 groups of spawning sockeye have been identified in the watershed, each with a specific combination of spawning location and migration time (Holtby and Ciruna 2007). Sockeye are not persistently present at all of these sites, but were recorded there at least once in the available assessment data.

The Fraser River watershed is vast at over 220,000 km^2, and the spawning migration is protracted from June to October, so that these spawning groups are aggregated into production units, called *stocks*, for the purpose of monitoring status (e.g. Cass et al. 2000) , developing forecasts (e.g. Grant et al. 2010), and analyzing population dynamics (e.g. Ricker 1997). Stocks are identified based on the geographic location of spawning streams and rearing lakes, as well as the timing of adult migration. Most of the system's recent production is accounted for by a few large stocks or stock groups: Birkenhead, Weaver, Chilko, Quesnel, Stellako, Stuart (Early and Late), Adams and Shuswap (Table 1). The model documented in this Research Document incorporates 19 distinct stocks that capture most spawning populations and most of the annual sockeye production. However, in some recent years, *miscellaneous* stocks that are not covered in the model have contributed 30-40% of the Early Summer run size (Table 2).

Stocks are further aggregated into management groups based on similar migratory timing during their return from the ocean. These management groups overlap to a varying degree each year, and discrete harvest of individual stocks or stock aggregates downstream of terminal areas is not possible for three of four timing groups (p. 18).

The management groups are, in order of adult migration:

- *Early Stuart:* about 7 individual spawning sites in the Takla-Trembleur lake system, arriving in the lower Fraser River from late June to late July. Early Stuart is modelled as a single stock.
- *Early Summer:* about 75 individual spawning sites throughout the Fraser system, arriving in the lower Fraser River from mid-July to mid-August; Early Summer is modelled as 8 stocks (Bowron, Raft, Seymour, Fennel Creek, Scotch Creek, Gates, Nadina, Upper Pitt River). In annual implementation, escapement strategies for Early Summer are scaled up to account for the expected abundance of miscellaneous other stocks.
- *Summer:* about 12 individual spawning sites, mostly in the Chilko, Quesnel, Stellako and Stuart systems, arriving in the lower Fraser River from mid-July to early September.
- *Late:* about 160 individual spawning sites in the lower Fraser, Harrison-Lillooet, Thompson and Seton-Anderson systems, arriving in the river from late August to mid-October. The Late group is modelled as 6 stocks (Late Shuswap, Birkenhead, Cultus, Portage, Weaver, Harrison).

Finer distinctions have been used in recent years. For example, some components of the Late run were managed differently from the other components which were thought to experience a higher rate of en-route mortality (i.e. Birkenhead-type lates vs. true lates). Following a decision by the Fraser Panel in 2010, the Birkenhead-type lates were re-integrated into the Late management group, including the planning model described in this paper.

As implementation of the *Wild Salmon Policy* (DFO 2005) unfolds, the focus of salmon management is shifting to functionally distinct conservation units (CU). A methodology for delineating CUs has been established (Holtby and Ciruna 2007), but the resulting list of CUs is still undergoing scientific and public review (e.g. Grant et al. 2011). CUs for Fraser River sockeye salmon are generally based on rearing lakes and timing, which is reflected in the CU name (e.g. Takla/Trembleur-EStu). Figure 1 matches modelled stocks to CUs.

The life history of Fraser River sockeye salmon is complex, and has been intensively studied (e.g. Groot and Margolis 1991, Roos 1991, Ricker 1997). A brief summary follows: Fraser River sockeye salmon spawn in small streams, large rivers, or lakes. Juveniles generally rear in large lakes for one year as fry before migrating seaward as smolts, entering the Strait of Georgia and moving north along the continental shelf into the Gulf of Alaska. The majority of Fraser River sockeye salmon rear in the Gulf of Alaska for two winters before returning to the Fraser River as 4-year old adults. The technical notation for this life cycle is 4_2, designating a total life span of four years, with the first 2 winters spent in the freshwater environment. Most Fraser sockeye return at age 4. A small but variable proportion of adults return as 5-year olds, and some males also return as smaller 3-year olds called jacks. One notable exception are river-type Harrison sockeye, which don't rear in the lake and return as 3 or 4 year olds after spending 2 or 3 years in the ocean. Returning adults typically approach the North Coast of BC, and then migrate south to the Fraser River estuary.

Assumptions about the life history of Fraser River sockeye salmon strongly influence the simulated performance of alternative management strategies, with vigorous on-going debate about the following:

- Estimates of inherent productivity (i.e. recruits / spawner at low abundance)
- Estimates of productive capacity (i.e. abundance of spawners that maximizes recruitment)

- Effect of large spawner abundance in the brood year
- Effect of large spawner abundance in some previous year (i.e. cyclic dominance / delayed density dependence effects)

Section 2.2.4 covers these topics related to model structure and parameter estimates.

1.3 DEVELOPING ESCAPEMENT STRATEGIES FOR FRASER RIVER SOCKEYE SALMON

Pestal et al. (2008) summarize escapement planning for Fraser River sockeye salmon since the mid-1980s. A brief overview follows below. Implementation details are documented in the annual reports of the Fraser River Panel (e.g. PSC 2009).

Following the signing of the Pacific Salmon Treaty in 1985, a *Rebuilding Plan* was designed to increase annual escapements incrementally from historical levels (Collie et al. 1990, FRAP-FMG 1995). A DFO task force identified *Interim Escapement Goals* between escapements observed at the time and estimated optimal escapements. A basic premise of the rebuilding plan was to increase escapements each year beyond brood year levels to maintain an increasing rebuilding trajectory towards interim escapement targets. In periods of high or increasing survival, these escapement targets can be met with little short-term economic losses. To meet rebuilding targets during years of low survival, a higher fraction of the run is allocated to escapement rather than catch.

An implementation plan was developed which identified:

- Lower bounds for annual target escapement designed to maintain escapements above brood year levels for Early Summer, Summer and Late Run aggregates.
- Lower bound for annual target escapement on the Early Stuart aggregate fixed at 66,000 spawners and then revised to 75,000 spawners through consultations.
- Upper bounds on annual target escapement for all aggregates based on a 65% exploitation rate ceiling.

This implementation plan guided escapement management from 1987 to 2002, but stocks and harvests didn’t respond as hoped (Figure 2, Figure 3, Figure 4, Figure 5). Productivity fluctuated considerably (Figure 6, Figure 7), and has shown a marked overall decrease in recent years (Figure 8, top panel). In addition, harvest opportunities on abundant and productive stocks were constrained by less productive or less abundant stocks intercepted in the same fisheries (e.g. Interior Fraser River coho salmon, steelhead). Due to a combination of these factors, the management balance has shifted from catch to spawner abundance (Figure 8, middle and bottom panel). Larger total abundances and catches could likely have been achieved from the increased escapements of the 1990s and early 2000s if productivity had remained stable at the levels observed in the 1970s and 1980s. A recent review by Martell et al. (2008) even suggests that higher than recent exploitation rates may maximize long-term catch for the 9 most abundant stocks if optimal escapement levels were known. However, we consider it likely that spawner levels and resulting returns would have been much lower for many of the Fraser River sockeye salmon stocks if pre-1987 exploitation rates had been maintained in the face of reduced productivity. In Section 4.3 we identify future analyses to explore how the results of Martell et al. (2008) would be affected by including 10 more stocks with smaller population abundances, less data and different productivities (Figure 6) in a mixed-stock management setting, and with the added objective of avoiding low escapement on any component stock to preserve biological diversity within the Fraser aggregate.

Support for the rebuilding plan, as conceived in the 1980s, had diminished by the early 2000s due to a decline in catch, difficulty of accommodating multiple objectives, and the constraints of a strict rebuilding schedule (Cass et al. 2000, Pestal et al. 2008).

DFO initiated a review of the rebuilding plan in 2003 to address the growing concerns expressed by First Nations and stakeholders, as well as recommendations from the 2002 Ministerial review of Fraser River sockeye fisheries (DFO 2003). The mandate of the review process was to incorporate new information, integrate emerging policies such as the *Wild Salmon Policy* (DFO 2005), and establish a formal framework for setting annual escapement targets. Over the next 8 years DFO led a collaborative process, called the *Fraser River Sockeye Spawning Initiative* (FRSSI), and regularly brought together participants from First Nations, the commercial fishing industry, recreational fishing, environmental non-government organizations, the United States, and the provincial and federal governments.

The technical groundwork was laid through the development of a simulation model (Cass et al. 2004) which was refined over three years and six workshops, leading up to an intensive two-year planning exercise that merged FRSSI into a pilot implementation of the integrated management processes envisioned under the *Wild Salmon Policy* (WSP).

Since 2006, the simulation model has been fully integrated into the annual management cycle for Fraser River sockeye, which is bracketed by two phases of public consultation, the *post-season review* in the fall and *pre-season planning* in the spring (Figure 9). Both of these consultations unfold as a combination of formal advisory processes (e.g. *Integrated Harvest Planning Committee),* bilateral meetings with First Nations, and townhall-style meetings with the general public (e.g. in coastal communities). Each year, the FRSSI model is used to examine a range of alternative escapement strategies for each management group. A shortlist of 3 to 5 options for each management group is selected based on pre-season expectations for each alternative and a summary of simulation results. These options are then presented for broad public review during the annual pre-season consultations (e.g. draft Integrated Fisheries Management Plan, annual technical memo). Occasionally, additional options are generated during the review process. One option is then included in the final management plan.

The ultimate goal was to converge on long-term strategy, so that the annual process would not be needed. However, each year there has been additional work identified through in-season implementation, post-season reviews, and pre-season consultations. Also, as part of the initial implementation in 2006, DFO committed to a major review and update after a full 4-year cycle of returns (e.g. the 2010 CSAS review, workshops in 2011, this Research Document).

The modelling framework developed for the *Spawning Initiative* is consistent with the biological principles outlined in the WSP. For example, the 19 stocks included in the simulation model closely match up with conservation units (Figure 1) and escapement strategies are evaluated based on the performance of individual stocks, not management groups. The lack of spawner-recruit data for some CUs presents an on-going challenge for the operational aspects of the *Wild Salmon Policy,* but is much less of an issue for Fraser Sockeye (Table 2) than for other areas or species.

2 METHODS

2.1 MODEL OVERVIEW

2.1.1 Intent

The FRSSI model is intended as a formalized, quantitative tool for exploring the expected long-term performance of escapement strategies for Fraser sockeye under a wide range of alternative assumptions (e.g. population dynamics, future patterns in productivity). It is designed as a big-picture model to address long-term management questions, such as "*Which types of strategies tend to be robust to uncertainty in population dynamics?*" It does not address operational questions such as "*What is the optimal fishing plan for next week, given the latest estimates of abundance, timing, and management adjustments?*" Nor is it meant to be a predictive tool to answer questions such as "*What will the return of sockeye be two years from now?"* As an illustration, the FRSSI model can be thought of as similar to a regional planning tool that helps compare alternative transit plans for a region, rather than an engineering tool that simulates earthquake safety of alternative bridge designs.

The model is simply a thinking aid, a consistent way of linking and tracking some of the many considerations that are debated during the annual planning process. Alternative options and assumptions can be easily explored through a series of "what if?" scenarios. This process of exploring alternative strategies works best in a collaborative setting, but the inevitable complexities create substantial communication challenges in multi-stakeholder workshops and the broader public engagement processes.

Given this intent, the FRSSI model does not attempt to explicitly incorporate all of the biological mechanisms that are being investigated for Fraser River sockeye. There are other processes, with their own models, that deal with them in more detail. For example:

- Annual forecasting models for each stock to shape pre-season expectations (Grant et al. 2010)
- Pre-season fisheries planning model and management adjustment (MA) models that support deliberations of the Fraser River Panel (Cave and Gazey 1995, Patterson and Hague 2007, Macdonald et al. 2010)
- Population viability model for Cultus sockeye that supports the deliberations of the Cultus Recovery Team (Korman and Grout 2008)
- Conservation Unit (CU) viability models that support the development of benchmarks under the Wild Salmon Policy (Holt et al. 2009, Grant et al. 2011).
- Development of a more detailed in-season management model is currently being funded by DFO in collaboration with Simon Fraser University to assess conservation and management objectives for individual stocks as they move through a sequence of fishing areas in the ocean and within the Fraser watershed.

2.1.2 Current scope

The FRSSI model currently simulates 19 stocks of Fraser sockeye forward for 48 years and applies different long-term escapement strategies chosen by the user. It tracks the performance of management groups as well as individual stocks, and is set up to explore many variations of management approaches that are applied on an annual basis: (1) fixed escapement, (2) fixed exploitation rate, (3) varying total allowable mortality with run size. For each of these, the effect of overlap in return timing can be evaluated. Harvest strategies are specified for management groups, but each stock can be assigned to different management groups or treated as an individual management group. All stocks within a management group are exposed to the same exploitation rate and environmental mortality, and catches are not attributed to any specific area or fishery.

The model allows users to confront a chosen strategy with a wide range of scenarios: (1) alternative spawner-recruit models, (2) alternative future patterns of productivity, (3) alternative assumptions about en-route mortality, and (4) alternative assumptions about pre-spawn mortality.

Figure 10 summarizes these options as a decision tree, where each branch represents one possible scenario to be explored.

The current model is not set up to address the following: (1) in-season management strategies, such as approaches for dealing with uncertain and changing forecasts, (2) alternative fishing plans, such as the timing and location of harvests (3) catch sharing across sectors or areas, and (4) annual adjustments to the long-term strategy.

Section 4.2 discusses the use of the FRSSI model and compares its scope to other models developed for a similar purpose.

2.2 BIOLOGICAL SUB-MODEL

2.2.1 Definitions

The primary data that describe the population dynamics are the estimates of annual spawning abundance and the total number of adult progeny that return 3 to 5 years later, regardless of whether they are caught in fisheries, perish during upriver migration, or survive to spawn. Spawner abundance is estimated directly using systematic surveys of the spawning population. Estimates of the catch removed from each stock, estimates of migration mortality, and estimates of spawner abundance are combined to estimate the total abundance of returning sockeye in a given year.

- Run = adults returning in a brood year (e.g. 2004)
- Catch = total estimated harvest in commercial, recreational, and aboriginal fisheries
- Total spawners = abundance of adults on the spawning grounds in a brood year (e.g. 2004)
- Difference between estimates (DBE) = difference between abundance estimated in the lower river at the Mission hydroacoustics site and abundance on the spawning grounds. Negative DBEs are assumed to be losses due to en-route mortality for the purposes of modeling.
- Effective female spawners = Number of females that successfully contributed to spawning
- Recruits = total adults produced from a brood year (e.g. 2004) and returning 3-5 years later (e.g. 2007 to 2009).
- Productivity = recruits per adult spawner (or per effective female spawner)

The next five sections summarize the current approach to estimating each of these quantities. Figure 11 illustrates how the simulation model links them together.

The simulation model currently includes 19 stocks (Table 1). For 12 of these stocks, escapement and catch by brood year have been routinely measured since 1948. Another 7 stocks with shorter time series of available data were added early in the FRSSI process to better reflect the mixed-stock challenges of management (e.g. differing productivity, more uncertainty in spawner-recruit models). Appendix 3 lists available data for the 19 stocks, which account for 98% of the long-term average annual run size and escapement, but has ranged from a high of 100% to a low of 89% of the total run and 87% of the escapement in 2004 (Table 2).

The spawner-recruit data used in this analysis are maintained by DFO Stock Assessment. For the most up-to-date version of the data, contact Sue Grant (Sue.Grant@dfo-mpo.gc.ca). Note that updated spawner-recruit data include additional years as well as revised estimates for earlier years.

A detailed CU-by-CU inventory of available data and formal status evaluation was reviewed by CSAP in November 2010, and was finalized in 2011 (Grant et al. 2011). Section 4.3 outlines proposed steps for incorporating the results of Grant et al. (2011) into the FRSSI model and process.

2.2.2 Estimates of spawning escapement

Since the late 1930s, escapements have been estimated annually for most of the individual spawning populations in the Fraser River watershed. Over 150 individual populations have been identified. The catch and spawning escapement data for these populations has historically been grouped into 19 stocks for management purposes (Section 1.2).

Between 1937 and 1985, the International Pacific Salmon Fisheries Commission (IPSFC) was responsible for estimating spawner abundance at spawning sites in the Fraser watershed. Experimental work developed during the early years of the IPSFC led to a two-tiered approach for estimating escapement (Atkinson 1944, Howard 1948, Schaefer 1951). Methods used by the IPSFC are described by Woodey (1984). Visual techniques were applied for small populations. For larger populations the estimates were based on mark-recapture experiments and to a lesser extent fence counts. The threshold for switching to these more intensive surveys was originally 25,000, but was raised to 75,000 in 2004.

With the signing of the Pacific Salmon Treaty in 1985, DFO assumed the responsibility for spawner enumeration and has generally followed the approach developed by the IPSFC (Schubert 1998). Pestal and Cass (2009) summarize sampling sites and recent survey coverage.

Visual surveys are either ground or aerial-based and are the least accurate of methods used to estimate salmon spawning escapement. Typically, visual surveys underestimate the known abundance based on fence counts by 2-12 times (Symons and Waldichuk 1984). Expansion factors for Fraser sockeye have been developed by comparing visual estimates to known fence counts in an attempt to account for the bias in visual estimates (Woodey 1984, Schubert 1998). Schubert (1998) reports a factor of 1.8 has been used for Fraser sockeye to expand visual count data. Estimates of total escapement were calculated for river and lake spawning stocks as the product of the maximum daily count of live spawners, the cumulative recovery of carcasses to the day of peak live count and the expansion factor. In glacial systems or lake populations where live fish cannot be observed directly, escapement estimates were the product of the total carcasses recovered and an expansion factor that assumed that each person-day of survey effort recovered 5% of the population. For most populations, however, the reliability of visual survey estimates has not been verified and the uncertainty in accuracy and precision of the estimate is unknown but assumed to be large. Fence counts are considered the most reliable, but are used at relatively few locations for logistical and budgetary reasons (Schubert 1998). Errors in fence counts result from counting or measurement errors, for example, if the fence is breached or damaged from obstructions or high river discharge.

Mark-recapture estimates are potentially positively biased as a result of tag shedding, tagging induced mortality, and abnormal behavioral effects of tagged fish. In comparative studies on the Stellako River, mark-recapture estimate had estimation errors ranging from –1% to 18% compared to the fence counts (Schubert 2000). This error is less than the error reported in other studies where errors of 2-3 times were typical (Simpson 1984).

Alternative escapement estimation methods using DIDSON sonar technology have been assessed against traditional methods in recent years. Paired DIDSON / Mark-Recapture projects were conducted for Horsefly in 2005, 2006, and 2007, and for Chilko in 2006 and 2008 (Welch et al. 2007).

Sampling at the spawning sites provides estimates of the number of precocious males (jacks) and non-jack males and females. Female carcasses are sub-sampled to estimate the proportion of female spawners that contributed to spawning based on estimates of eggs retained in the sampled carcasses. The latter are categorized as "effective females". In some stocks, anomalously low spawning success has occurred in some years as a result of high pre-spawning mortality. For example, estimated effective females for Chilko sockeye in 1963 only constituted 38% of the total female population. High pre-spawning mortality of Chilko sockeye in 1963 was associated with high water temperatures and anomalous early river entry (Anon. 1964).

The FRSSI model includes spawner-recruit relationships based on either total spawners or effective females (Section 2.2.4)

Results presented in this paper use spawner data up to the 2008 return year (Appendix 3).

2.2.3 Estimates of catch, en-route mortality, and recruitment

Historic catch estimates from commercial fisheries are based on landing records on fish tickets from U.S. fisheries and dock tallies and fish sales from Canadian fisheries. The Pacific Salmon Commission (PSC) and formerly the IPSFC were responsible for estimating the catch by age and stock (Woodey 1987, Gable and Cox-Rogers 1993). Historically, the contribution of individual stocks has been estimated mainly by comparing freshwater growth patterns on scales from catch samples with the pattern from stocks of known origin, based on samples from spawning sites (Henry 1961, Gable and Cox-Rogers 1993).

Catch estimation errors of individual stocks in the historical database are the result of insufficient discrimination in scale patterns among stocks, unrepresentative sampling of the catch or spawning sites, or incorrect assumptions about the stock mixture used in the assessment models (Cass and Wood 1994, Gable and Cox-Rogers 1993). Biased estimates result from misallocation of the catch of one or more stocks in a mixture to other stocks in the mixture. The bias is larger for small stocks because proportional errors in large stocks within a mixture result in larger absolute errors in catch of small stocks. Catch allocation bias overestimates the abundance and productivity of small populations in years when catch allocation is based on scale growth patterns. Small stock bias still occurs when using DNA for stock identification, but the magnitude of the bias is smaller than when using scale analysis for stock identification (pers. comm. Steve Latham, Pacific Salmon Commission, Vancouver B.C.)

Other information used in stock discrimination include differences in age and size composition and historical data on run timing and spawning ground arrival data (Gable and Cox-Rogers 1993). The accuracy and precision in estimates of catch by stock depends on the number and size of stocks in the catch mixture and the uniqueness of scale patterns. The latter vary depending on variable annual juvenile growth conditions such as juvenile density (Goodlad et al. 1974).

Scale pattern analysis has been supplemented in recent years using parasite and genetic differences among stocks (Bailey and Margolis 1987, Beacham et al. 1987). DNA-based methods for identifying individual stocks in mixed stock fisheries have improved stock identification accuracy and precision, and are now being used routinely (pers. comm. Mike Lapointe, Pacific Salmon Commission, Vancouver B.C.).

Section 2.2.11 describes data on the difference between estimates (DBE) of sockeye in the lower Fraser River measured at the hydro-acoustic site at Mission, B.C. and estimates of the population at the spawning sites plus in-river catch above Mission. If the differences are considered to be real, that is, if there were actual mortalities that occurred as opposed to biases in estimation methods, then they are incorporated into estimates of total recruitment.

We simulate population dynamics based on two predominant age classes for each stock, with age-4 adults accounting for most of the recruitment in 17 of the 19 stocks (Figure 12). Exceptions are Upper Pitt, which return in higher proportions than other stocks as age-5 adults, and Harrison, which are immediate migrants and have a substantial component of mature 3_1 adults (i.e. spent 2 years in the ocean, similar to age 4_2 sockeye). Jacks contribute little to sockeye fisheries and their reproductive potential is unclear. Jacks are not used in the analysis as spawners, but they are included in the estimates of total recruits.

Results presented in this paper use recruits data up to the 2004 brood year (Appendix 3).

2.2.4 Spawner-recruit models

Spawner-recruit (SR) models predict the number recruits produced from the number of spawners in each brood year. Recruitment by brood year is adjusted to predict the run of age-4 and age-5 year-old sockeye in each return year. We focus on two alternative models: the Ricker model (Ricker 1954, Ricker 1997) and the Larkin model (Larkin 1971, Walters & Staley 1987). SR models typically have 2 estimated parameters: productivity and capacity. Where additional data is available, more complex models can be developed to incorporate additional life stages (e.g. smolt abundance) or environmental factors (e.g. sea surface temperatures when young salmon first enter the ocean).

SR models differ depending on the assumptions they make about:

- Inherent productivity (i.e. recruits / spawner at low abundance)
- Productivity at very low escapement (e.g. is there a point at which production levels fail to provide sufficient recruits to recover due to mechanisms such as density-dependent predation (Section 2.2.13)
- Productivity at large escapement (e.g. is there a pronounced decrease in productivity if escapement exceeds capacity, due to mechanisms such as competition for spawning locations?)
- Interaction between cycle lines (e.g. does a large escapement last year affect survival of this year's brood, due to mechanisms such as reduced food availability and increased predator abundance? Or does periodic large escapement increase long-term production due to the increased marine nutrients transported into the watershed?)

The most widely applied model to quantify the population dynamics of Pacific salmon is the Ricker model.

The classical form of the Ricker model is:

$$\log(R_{BY} / S_{BY}) = \alpha - \beta\, S_{BY} \quad \text{Eq. 1}$$

where recruits (R_{BY}) per spawner (S_{BY}) produced from a brood year are determined based on two parameters. The α parameter is the productivity at low run size (i.e. intrinsic growth rate of the stock) and β is a density-dependent parameter that describes the rate at which productivity decreases as spawner abundance (S_{BY}) increases. An intuitive way to think about the density effect is:

$$\beta = 1/S_{\max} \quad \text{.........Eq. 2}$$

where S_{max} reflects the capacity of the stock (i.e. spawning abundance associated with maximum sustainable yield). Stocks with larger capacity have a smaller β, and less of a density-dependent drop in productivity. The Ricker model is dome-shaped with declining recruitment at higher stock sizes. Mechanisms that can lead to a Ricker-shaped stock-recruitment curve are cannibalism of juveniles by adults, disease transmission, over-crowding on the spawning sites and density-dependent growth coupled with size-dependent mortality (Hilborn and Walters 1992).

The formulation of the Ricker model in Eq.1 was extended by Larkin (1971) to include cross-cycle interactions, as follows:

$$\log(R_{BY}/S_{BY}) = \alpha - \beta_0 \; S_{BY} - \beta_1 \; S_{BY-1} - \beta_2 \; S_{BY-2} - \beta_3 \; S_{BY-3} \quad \text{........... Eq. 3}$$

In Eq. 3 the recruits per spawner (R_{BY}/S_{BY}) produced from a brood year are the result of spawning stock in the brood year (S_{BY}), but also depend on spawning abundance 1 to 3 years earlier. The lag terms (β_1, β_2, β_3) are surrogates for ecological mechanisms, discussed earlier, assuming that the magnitude of the effect (e.g. density dependent predation or disease out-breaks) is related to the abundance of spawners in the preceding years (S_{BY-1}, S_{BY-2} and S_{BY-3}). The classical Ricker model is a subset of the Larkin model wherein the additional lag terms are zero.

Figure 13 summarizes the differences between the Ricker and Larkin models. Other variations (e.g. only 1 lag term) are also conceivable and we evaluate a suite of alternatives (Section 2.2.10)

We explore these assumptions and their implications through varying up-front constraints on parameter estimates. For example, estimates of the capacity parameter can be constrained to some multiple of the highest observed spawner abundance (Sec 2.2.7). Similarly, lag terms describing the interaction between cycle lines can be estimated from the observed data or set to zero (i.e. alternative model structures). The remainder of this section briefly summarizes previous work on these aspects of Fraser sockeye population dynamics.

Of the 19 sockeye stocks in the watershed that are enumerated consistently, 8 have exhibited persistent cycles with a consistent peak in abundance every four years (Cass and Wood 1994) . If this pattern is very pronounced it is referred to as cyclic dominance. In these cases the dominant cycle line is the sequence of years with run size persistently larger than the other cycle lines. The sub-dominant line has moderate abundance, and off-year lines have extremely low abundance relative to the dominant and sub-dominant lines.

Despite 50 years of study, there is still no scientific consensus on the cause of cyclic patterns in the abundance of Fraser sockeye, but recent research points to a combination of biological mechanisms and past harvest patterns (Ward & Larkin 1964, Walters & Staley 1987, Cass & Wood 1994, Ricker 1997, DFO 2006b). Various ecological hypotheses have been proposed, including interactions with predators, diseases, or parasites. Marine influences have been discounted because it is unlikely they could generate cycles where some stocks are dominant one year, and some stocks are dominant the next. Reduced food availability imposed by dominant cycle lines on off-cycle years is also unlikely since growth rates of highly cyclic Fraser sockeye are highest in off-cycle lines. Human impacts can perpetuate or increase the cyclic pattern in abundance: In the past, off-cycles were consistently fished at higher relative rates than dominant and subdominant cycle lines. Some researchers have suggested that genetic factors, such as strongly inheritable age-at-maturity and age-dependent mortality, could maintain population cycles or at least slow the recovery of off-cycle lines, *in combination with high fishing mortality* (e.g. Walters and Woodey 1992).

In 2006, DFO hosted a technical workshop to assess alternative models for explaining the observed cyclic dynamics of some stocks (DFO 2006b). This workshop was a direct result of concerns raised by participants in the FRSSI process. The two main recommendations from the technical workshop were to change the escapement strategy to a fixed exploitation rate for run sizes above a certain threshold, and to use a more flexible model to calculate recruitment for all stocks based on the observed degree of interaction between cycle lines. Both of these recommendations have since been implemented in the simulation model.

Another on-going debate concerns potentially detrimental influences of large escapements (e.g. Walters et al. 2004, Clark et al 2007). The concern is that overall survival and growth of the offspring could be greatly reduced due to biological mechanisms such as competition (e.g. for spawning sites, prey, oxygen in the lake), disease outbreak, or increased predation. However, a broad review for Fraser sockeye found only declines in productivity at higher escapement levels, but no evidence of collapse, concluding that productive stocks should not suffer drastic reductions in recruitment as a result of management actions to protect weak stocks in mixed-stock fisheries (Walters et al. 2004). These conclusions were supported by observations in 2005 and 2006, when offspring from the 2001 and 2002 spawners returned in reduced, but substantial numbers despite an on-going decline in productivity. However, individual stocks may have suffered pronounced density effects. For example, sockeye smolts migrating out of Quesnel Lake in 2004 were the smallest on record, resulting in severely reduced marine survival. These were the offspring of spawners in 2002, facing high densities at early life stages, but the observation may be confounded by low food availability in the lake at the same period. The productive capacity of Fraser River sockeye stocks is limited in the freshwater environment, either by available spawning habitat or by available lake rearing habitat. Several approaches have been used to estimate productive capacity for individual sockeye stocks, including available spawning area, lake productivity, and numerical estimates of the capacity parameter from population models (FRAP-FMG 1995, Shortreed et al. 2000, Bodtker et al. 2007). This information can be used to shape prior assumptions about density-dependent parameters in the spawner-recruit model (Section 2.2.5)

Uncertainty around the effects of large escapements is closely linked to yearly variability in environmental, marine and freshwater conditions, as well as the large uncertainty in estimates of productive capacity for Fraser sockeye stocks. The current management approach is based on the assumption that occasional large escapements likely reduce the efficiency of sockeye production in that year (i.e. smaller number of recruits per spawner), but do not cause stock collapses. Potential benefits of escapement spikes include increased genetic diversity (e.g. Schindler et al. 2010) and transport of marine nutrients into distant watersheds (e.g. Naiman et al. 2002, Uchiyama et al. 2008, Hill et al. 2009, Adkison 2010).

Theoretically, substituting effective female spawners for total spawners in the stock-recruitment relationship reduces both uncertainty in parameter estimates and bias due to underestimating spawner potential for years with a low proportion of effective females. The problem with using effective female escapement instead of total spawners is that recruitment and spawners are in different units. As shown by Collie and Walters (1987), the spawner-recruitment parameters estimated using effective female spawners can be re-scaled to represent total sockeye in Eq. 1 and 3. However, we included the option to directly use parameters estimated for effective females by adding an extra step that accounts for sex ratio and spawning success (Figure 5).

The intent is to:

- Establish consistency with other work which is based on effective females (e.g. the forecasts developed by Grant et al. 2010).
- Maintain consistency with previous model versions, which are based on total spawners, to ensure we can compare the results.
- Encourage the planning process to explicitly consider assumptions about pre-spawn mortality, and set up the model to easily explore alternative future scenarios (e.g. increased PSM).
- Allow the planning process to explore the implications of basing decisions on one or the other approach. These implications range from technical aspects (e.g. What if different lag-terms appear significant? Are potential biases in SR data different if we use effective females?) to practical implementation (e.g. Should benchmarks be developed or redefined in terms of effective females? If so, what are the implications for setting management goals and annual implementation?).

We approximate the proportion of effective female spawners as the observed median % effective females in deterministic simulations, or sample from fitted beta distributions in stochastic simulations. Figure 14 shows observed and fitted distributions for the 19 stocks, based on maximum-likelihood fit to a beta distribution (using “fitdistr()” in R, Venables and Ripley 2002).

2.2.5 Bayesian parameter estimates

Bayesian methods explicitly characterize the uncertainty in estimated parameters in the form of a probability distribution. By framing parameters as a distribution, rather than a single estimate, we can evaluate the expected performance of management decisions across a wide spectrum of alternative scenarios. Box and Tiao (1973) discuss the theoretical foundation for Bayesian methods in great detail. Theoretical aspects of Bayesian methods continue to be debated (e.g. Efron 1986, Gelman 1998, Bayarri and Berger 2004).

Bayesian methods have been widely applied in fisheries models. Punt and Hilborn (1997) provide a step-by-step description and review fisheries applications. Hilborn and Mangel (1997) discuss practical considerations for implementation. Recent applications include Schnute and Kronlund (2002), Gibson and Myers (2004), Su et al. (2004), Michielsens and Mcallister (2004), and Grant et al (2010).

One way to think of Bayesian estimates is that they first specify a range of hypothetically possible values and narrow it down to a range of plausible values using observed data. Specifically, we confront a prior assumption about some parameter (e.g. could be any number between 0 and 100) with some observed data (e.g. fifteen observations falling between 20 and 30) to arrive at a posterior distribution (e.g. could be any number between 0 and 100, but most likely falls between 20 and 30).

Each component of this analysis needs to be carefully considered. For example, bounds on the prior assumption define the range of parameter values that is considered hypothetically possible, and no amount of evidence in the form of observed data can push the resulting estimate outside of these bounds. Prior assumptions are often designed to be uninformative, such that they don’t cut off any information contained in the observed data. Alternatively, prior assumptions can bring in information from other sources (e.g. using estimate of lake productivity to shape estimates of a capacity parameter for a salmon stock, as in Bodtker et al. 2007).

To estimate stock-specific parameters for the spawner-recruit models in Eq. 1 and Eq. 3 we applied the Bayes inference Markov Chain Monte Carlo methodology described in Cass et al. (2004), which was adapted from Schnute et al. (2000). However, we have changed the computational implementation from the commercial software S-Plus to a combination of freeware programs: the statistics package R (R Development Core Team 2008) in combination with WinBUGS (Lunn et al. 2000), which uses a Gibbs sampler to approximate posterior distributions.

Appendix 1 documents the WinBUGS code used to derive the parameter estimates.

For forward simulations in the FRSSI model, 1,000 sets of stock-recruit parameters were sub-sampled from the Bayesian posterior distribution (55,000 total samples, not including 5,000 "burn-in"). All results were visually examined for convergence and checked for auto-correlation. For the purpose of assessing model parsimony, a sub-sample of 20,000 MCMC samples from a total of 150,000 total samples (not including 10,000 "burn-in") was used.

2.2.6 Prior assumptions about the productivity parameter α

Estimates of the productivity parameter α use a uniform prior, such that all values within a plausible range are considered equally likely at the start. The intent is to keep the prior uninformative, and to choose bounds on the uniform prior that do not cut off any part of the range indicated by the observed data. We chose alpha ~N(0,σ) as the prior for all 19 stocks, with σ = 31.6 to get a precision of $1/\sigma^2$=0.001 in WinBugs (Table 3) .

2.2.7 Prior assumptions about the capacity parameter β_0

Prior assumptions about the capacity parameter β_0 are shaped by assumptions about the value of S_{max}, the spawning abundance that maximizes production, as specified in Eq. 2.

In previous versions of this model (Cass et al. 2004), S_{max} was set to a uniform prior bounded by 0 and 100.

This approach has been modified to a lognormal prior distribution with the mean of S_{max} at S_{high} and upper bound of 3 S_{high} (Table 3), where S_{high} is the largest observed abundance. This informative prior is based on two considerations:

- Lognormal distribution allows for possibility of higher carrying capacities, but doesn't put equal weight on the high end of the distribution.
- Use the existing data to mildly inform the prior for each stock.

While the true current capacity of a stock may not have been fully reached within the available data set (e.g. Harrison), we consider it implausible that current S_{max} would be greater than three times the largest spawner abundance recorded since the 1940s. Posterior estimates of β_0 fell clearly within these bounds for the majority of stocks.

Further work is planned to explore how high the upper constraint needs to be to not constrain the estimates for populations like Early Stuart and Cultus, and to link these priors to biological analysis of each system's capacity (Section 4.3).

2.2.8 Prior assumptions about the cycle-interaction parameters β_1, β_2, and β_3

Estimates of cycle-interaction parameters β_1, β_2, and β_3 use positive uniform priors between 0 and 100, to reflect the assumption that all lag terms have either no effect or some negative effect on future survival within the 4 year cycle (Table 3).

2.2.9 Assumptions about random variation

The standard approach is to use log-normal errors (Hilborn and Walters 1992), such that

$$\log(R_{BY} / S_{BY}) = \alpha - \beta\ S_{BY} + \varepsilon \quad \text{Eq. 4}$$

where ε is normally distributed with a mean of 0, resulting in a log-normally distributed residuals on R_{BY}. Two concerns with log-normal errors were debated during the review of this paper.

One participant suggested that an assumption of log-normal error gives more weight to lower observations, and that the resulting model fits therefore do not reflect the population dynamics of dominant years in highly cyclic populations.

In forward simulations, a large positive residual can be randomly sampled for a year where spawner abundance is already large, leading to a very large spike in modeled recruitment, which may bias the performance measures. In the observed data, however, recruitment residuals are inversely proportional to spawner abundance (see plots of observed residuals in Appendix 4).

An alternative assumption is to use a additive errors such that

$$R_{BY} = \alpha S_{BY} \exp(\beta S_{BY}) + \varepsilon \quad \text{Eq. 5}$$

where ε is normally distributed with a mean of 0.

We explored both error structures in model fitting (Section 3.2.2), but only show forward simulations based on log-normal residuals in this paper.

2.2.10 Comparing alternative spawner-recruit model forms

We explored 8 variations of spawner-recruit models:

- Ricker model (Eq. 2)
- Full Larkin model with three lag terms, where production from a brood year is influenced by the abundance in each of the three previous years (Eq. 3)
- Larkin with two lag terms, where production from a brood year is influenced by the abundance in the two previous years (β_1, β_2,)
- Larkin with 1 lag term (β_1)
- Larkin with lag 2 only (β_2)
- Larkin with lag 3 only (β_3)
- Larkin with lag 1 & 3 (β_1, β_3)
- Larkin with lag 2 & 3 (β_2, β_3)

We also repeated all of the above assuming an additive error structure, rather than a log-normal error structure (Section 2.2.9)

We compare model fits using the Deviance Information Critieria (DIC) as described by Spiegelhalter et al. (2002) and implemented by Michielsens and McAllister (2004). The DIC accounts for the number of parameters being estimated, and thereby addresses concerns related to over-fitting. Without this aspect of the comparison, the Larkin model might appear to fit the data better simply due to the flexibility introduced by 3 additional parameters.

The intent of this comparison is not to choose a single “best” model on which to base planning decisions, but to investigate the relative weight of evidence for or against alternative assumptions. In practice, none of these alternative SR models can be completely eliminated from consideration, and we need to evaluate how sensitive alternative management strategies are to the range of most likely alternatives (Section 2.4.4). This approach is consistent with the recommendation by Spiegelhalter et al. (2002) that model selection should be part of a larger process considering the "robustness of its conclusions and its inherent plausibility", rather than relying solely on a statistical criterion.

The model fitting analysis presented in this paper is using the effective female dataset only. This is in keeping with the dataset used to forecast Fraser River Sockeye run sizes (Grant et al. 2010). We assume for the purposes of this paper that the model selection using total spawners would give the same set of candidate models as the analyses using effective females. This assumption should be explored in more detail at a later time.

In this paper, we illustrate the effect of some of these model variations (Section 3.4.2).

2.2.11 En-Route mortality

Since the early 1990s there have been some notable differences between estimates (DBE) of sockeye in the lower Fraser River measured at the hydro-acoustic site at Mission, B.C. and estimates of the population at the spawning sites plus in-river catch above Mission (Banneheka et al., 1995). The discrepancies potentially arise from a number of different sources, including: estimation error, unreported catch, and en-route mortality from adverse environmental conditions (MacDonald 2000, MacDonald et al. 2000, Patterson and Hague 2007, Macdonald et al 2010). Discrepancies are evaluated post-season, and if they are concluded to be due to mortalities (as opposed to biases in estimation techniques at either site), the DBE is incorporated into the recruitment data used in the spawner-recruit dataset (Section 2.2.3).

We use observed DBE data provided by Ian Guthrie (PSC) to approximate en-route mortality in the forward simulations. Positive DBEs, where upstream estimates are larger than lower-river estimates are set to 0, assuming negligible en-route mortality that year (Table 2). Figure 15 shows observed patterns in DBE.

Our current approach evolved as follows: Early in the process, during the 2004/05 planning workshops, the definition of harvest control rules shifted from exploitation rate to allowable mortality rate. This shift was intended to increase clarity for implementation, because en-route mortalities have to be estimated and deducted each year. If control rules are expressed in terms of exploitation rate, and adjusted to account for long-term average en-route mortality, then annual implementation would not respond to changing patterns (e.g. periods of high en-route mortality). With the current approach (i.e. TAM rules shown Figure 19), annual variability in en-route mortality is mostly absorbed by changing the exploitation rate, keeping the total mortality at the target level, and stabilizing the target level of spawner abundance for a given run size.

Note that we treat en-route mortality as distinct and independent from pre-spawn mortality (see discussion of effective female spawners at the end of Section 2.2.4).

As part of the methods review for this paper, we updated and re-examined the DBE data, and looked at incorporating a more explicit environmental component. However, we decided against the added complexity of an environmental sub-model, and ended up with four alternative options for DBE in forward simulations (Figure 16). The base case samples from the observed distribution of % DBE, with the alternative option to only sample from the worse half of the observations to account for the potential effects of climate change (Merran Hague, pers. Comm.). To reflect the possibility that harvest patterns influence the future distribution of % DBE, two additional options are included based on the linear and log-linear simple regressions of actual vs. potential escapement.

In summary, en-route mortality can either be independent of abundance, or have a feedback loop with management through the abundance that passes into the river. If it is independent of abundance, it can be "like the past" or "like the worse half of the past". We expect that these four options are reasonable bookends for exploring the sensitivity of alternative strategies to en-route mortality assumptions.

Two of the three types of escapement strategy included in the model adjust the annual target exploitation rate based on % DBE (Section 2.3).

2.2.12 Productivity scenarios

A recurring concern raised by participants in the FRSSI workshops relates to assumptions about future productivity of Fraser sockeye stocks. Any forward simulation using parameters estimated from observed data implies that the range of future outcomes (e.g. recruits per spawner at a given abundance of spawners) resembles the range observed in the past (Figure 6). However, this does not capture how productivity changes over time (Figure 7).

We include two options for exploring assumptions about future productivity. An abrupt and persistent loss of productivity across all stocks can be included by specifying a scaling parameter z_R for the recruits calculated based on Eq. 1 or Eq. 3, such that:

$$R_{BY} = z_R \ S_{BY} \ (R_{BY} \ / \ S_{BY}) \quad \text{Eq. 4}$$

with $0 \le z_R \le 1$ and R_{BY}/S_{BY} is calculated from Eq. 1 or Eq. 3.

Proposed patterns in productivity over time and across stocks can be specified as a grid of scalars for each year and stock (Figure 17).

On-going work (Sue Grant, pers. comm.) is exploring the use of a Kalman filter (Dorner et al. 2008) to identify past patterns in productivity (i.e. estimating changes over time in the *α* parameter of Eq. 1 and Eq. 3).

Once these analyses are complete for all 19 stocks, the identified patterns can be fed directly into the FRSSI model by converting the each year's scalar on the α parameter into a scalar z_R for use in Eq. 4:

$$z_R = \frac{\exp(\alpha \ z_\alpha)}{\exp(\alpha)} \quad \text{Eq. 5}$$

Note that z_R and z_α are intended to be equivalent, but serve a slightly different purpose. In previous years' planning processes we included z_R as a straight-forward scalar that is directly meaningful to workshop participants (i.e. 0.5 means half the recruits). We are now expecting the results of a more comprehensive analysis, which will produce trajectories of α parameters. For programming simplicity, we implement those patterns using the existing code, and Eq. 5 is intended to show that a pattern of z_α can be easily converted into a pattern of z_R.

2.2.13 Depensatory mortality and quasi-extinction thresholds

A number of factors could result in depensatory mortality. For example, inbreeding may occur and result in increased mortality, spawner densities may be so low that fish cannot easily find mates, and predation may result in higher proportions of fish killed when densities are low. Depensatory mortality will accelerate population declines and increase their probability of extinction (McElhany et al. 2000).

Several approaches have been used to incorporate possible depensatory effects in the analysis of spawner-recruit data. Hilborn and Walters (1992) recommended including a power term in the Beverton-Holt model to represent the effects of predators. Liermann and Hilborn (1997) used a Bayesian hierarchical model to estimate the distribution describing the variability of depensation within various taxa. Routledge and Irvine (1999) introduced a cut-off value to allow for the effects of possible depensation at low abundance. Frank and Brickman (2000) were the first to introduce a S-R model that incorporated Allee effects by permitting a non-zero intercept representing recruitment failure. Chen et al. (2002) extended the standard Ricker function by incorporating an additional parameter and estimating the value of non-zero intercepts using S-R data. They found evidence for significant depensatory mortality in a northern BC coho population but not for Chilko sockeye.

Our purpose here is not to estimate depensatory mortality, but to include the option of simulating potential implications on the performance of alternative escapement strategies. If spawner abundance S falls below a critically low value S_c, users can specify an associated proportional reduction in recruitment. This is equivalent to a recent application for Cultus sockeye, which re-scales the Ricker curve if spawner abundance falls below a benchmark determined based on expert judgment (Bradford et al. 2011).

For forward simulations we chose an arbitrary value for S_c recognizing the difficulty in estimating it reliably and consistently for all 19 of the modelled stocks. As a base case, we set S_c to the lowest S value observed in the SR data set, because stocks were able to recover to much greater levels of abundance, at least given survival conditions at the time. We also explored larger Sc up to the low escapement benchmark (Section 2.4.3), and the combined effect of depensation with reduced productivity and increased en-route mortality.
Table 1 lists lowest observed spawner abundances and benchmarks for the 19 stocks.
Finally, we also added the option of quasi-extinction thresholds to the model in response to reviewer's comments. While computationally equivalent to our implementation of the depensation threshold, we included it as a separate mechanism to allow for reinforcing: depensation increases the frequency of crossing the quasi-extinction threshold.

2.3 HARVEST SUB-MODEL

2.3.1 Escapement strategies

The purpose of this model is to explore the expected long-term performance of different escapement strategies for Fraser sockeye under a wide range of alternative assumptions (e.g. population dynamics, future changes in productivity). During the annual management cycle, escapement strategies guide the annual balance sought between catch and abundance of spawners as run sizes vary from one year to the next and among stocks. In the model, these strategies are specified as quantitative control rules that prescribe a target level of exploitation rate for each management group.

Three types of escapement strategies are currently available in the model:

- Fixed escapement

- Fixed exploitation rate
- Target rate of allowable mortality that changes with run size (i.e. TAM rules).

Figure 18 shows the sequence of choices necessary to define a specific escapement strategy for each of these types.

TAM rules are designed around three fundamental considerations (Figure 19):

- Cap on total allowable mortality rate at larger run sizes to ensure robustness against uncertainty in population dynamics (e.g. capacity estimate), changing in-season information, and differing productivity among component stocks.
- Fixed escapement at low run sizes to protect the stocks and reduce process-related challenges at this critical stage (e.g. uncertain run size).
- ER floor at very low run size (e.g. for test fishing).

These TAM rules are consistent with the minimal requirements for harvest strategies to be compliant with the Precautionary Approach (DFO 2006a). Specifically, the target mortality is reduced as abundance drops from a healthy to a cautious zone, and target mortality is minimal if abundance is critically low.

The model runs on an annual time step for all three escapement strategies, and the resulting exploitation rate for each management group is applied without distinguishing fishery locations or open times (i.e. apply total exploitation rate to total run size, as illustrated in Figure 11).

Exploitation rate is applied without implementation error (i.e. target ER = actual ER), based on three considerations:

- Holt and Peterman (2008) compared target harvest rules and realized harvest rules for the 4 management groups of Fraser River sockeye from 1986 to 2003. They found that average discrepancies were small for 3 of the 4 management groups, and that annual discrepancies were correlated with environmentally-driven en-route mortality.
- TAM rules account for en-route mortality when converting TAM to a target ER, and can account for uncertainty by adjusting the cap on TAM. The model includes the option to explore outcome error (Holt and Peterman 2008) in total mortality by drawing independent samples for predicted en-route mortality, used to determine exploitation rate, and actual en-route mortality used to calculate spawner abundance.
- Finally, there have been changes in fishing patterns (e.g. terminal-areas demonstration fisheries) and new developments in in-season assessment (e.g. DIDSON, genetic stock identification), which will likely affect the pattern of implementation error in the future.

2.3.2 <u>Constraints imposed by run timing</u>

During the 2006 workshop series, participants requested to incorporate constraints imposed by timing overlap. The intent was to approximate the effect of choosing strategies that result in very different average exploitation rates for the 4 management groups. For example, participants pointed out that simulated long-term performance for individual management groups cannot be realized if strategies result in an average exploitation rate of 5-10% for Early Summers (after accounting for average observed en-route mortality, Section 2.2.11) and an average exploitation rate of 55-60% on Summers (with much smaller average observed en-route mortality).

To approximate this, we included a step in the model that generates average timing curves on a daily time step, then calculates the realizable exploitation rates for each aggregate given two alternative types of overlap constraint. This approximated realizable ER is then applied at the annual time step. Note that this step is trying to approximate the overall effect of overlap on different combinations of control rules for the 4 management groups.

Timing overlap is approximated based on long-term average migration timing through Area 20 (i.e. in a mixed-stock fishing area). Two alternative approaches for approximating the constraints imposed by timing overlap are included in the model:

- *Abundance*: Mixed-stock exploitation rate for each day is constrained by the smallest exploitation rate among those timing groups that contribute more than a user-specified percentage of the abundance (e.g. 10%), and realizable catch in mixed-stock fisheries is calculated based on these revised exploitation rates.
- *Window*: Mixed-stock exploitation rate for each day is constrained by the smallest exploitation rate among those timing group that are present that day based on a time window that captures a user-specified portion of each run centered around the peak. Realizable catch in mixed-stock fisheries is calculated based on these revised exploitation rates.

The extent to which timing overlap constrains realizable harvest depends on the differences in target exploitation rate. If the same fixed exploitation rate were chosen for all management groups, there would be no overlap constraint. With a TAM rule, the difference in target ER is strongly influenced by assumptions about en-route mortality.

Figure 20 illustrates the difference between these two approaches. In both cases the intent is to reflect the implementation challenges introduced by management strategies that tend to result in widely differing target exploitation rates for the four management groups. The first option was chosen to approximate management practice at the time. During subsequent workshops, participants pointed out that a severely depleted management group would fail to act as a constraint if it never exceeds the user-specified % of daily abundance. The second option was added to address these concerns. The implications of alternative “overlap constraints” are substantial. Figure 20 illustrates the difference for 1 simulated year in 1 sample scenario. Section 3.3.7 summarizes some sensitivity analyses. Note, however, that the FRSSI model is not a spatial model, and so it doesn’t reflect TAC that could be available in more terminal areas (i.e. the overlap constraint reflects mixed-stock fisheries).

We explored other alternatives for approximating overlap constraints based on variable peak time and optimizing a sequence of daily exploitation rates. However, we chose not to include these analyses here, because the optimization found many different patterns of daily harvest rate that come very close to achieving the target ER on all management groups and result in minimal overlap constraints if the peak and spread of timing curves are perfectly known. Variability and uncertainty in run timing and spatial distinction in harvests goes beyond the scope of this model. Spatial and temporal variations in fishing patterns will be investigated as part of the new in-season model being developed (Section 2.1.1)

2.4 PERFORMANCE EVALUATION

2.4.1 <u>Forward Simulations</u>

We evaluate the expected performance of alternative escapement strategies over 48 years, seeding the simulations with the most recent available spawner abundances. All 19 stocks are projected forward concurrently, with some mechanisms applied to individual stocks (SR model, % effective females, Section 2.2.4) and others applied to management groups (% DBE – Section 2.2.11, TAM rule – Section 2.3.1). Forward simulations avoid potential artifacts in the observed sequence of data, which may introduce biases, and add flexibility for exploring effects of potential future patterns in productivity (Section 2.2.12), en-route mortality (Section 2.2.11) or pre-spawn mortality (Section 2.2.4)

The Bayesian approach for capturing parameter uncertainty and posterior sampling techniques, such as the MCMC approach of Gelman et al. (1995) used here, offer the advantage that complex parameter distributions can be naturally incorporated into policy analysis. To explicitly incorporate parameter uncertainty, a subsample of 1,000 stock-recruitment parameter sets for each stock was systematically subsampled from the original 55,000 MCMC samples (Section 2.2.5). For each parameter set sampled from the Bayes posterior distribution, the effect of applying an escapement strategy is simulated by generating trajectories of run size, catch, and spawner abundance in annual time steps.

2.4.2 Individual Stocks Vs. Management Groups

If escapement strategies are specified for management groups rather than individual stocks, the model reflects the complex interactions between individual stock dynamics and mixed-stock fisheries.

In single-stock fisheries there is a direct feedback between exploitation rate, future recruitment and ultimately the performance measures used to summarize conservation and socio-economic factors. Recruitment and performance in response to exploitation is only conditional on the underlying population dynamics of the stock.

A common exploitation rate applied to a stock mixture potentially affects future recruitment and performance of individual component stocks differently for a number of reasons. Productivity varies among stocks to the extent that a common harvest rule is not optimal for some or any of the stock components (Figure 6). This, of course, is the weak-stock challenge of mixed-stock fisheries. Differences in average productivity among stocks, as well as the stock-specific range of variation in productivity, are captured in the model through Bayesian statistical inference (Section 2.2.5). Stock-specific future patterns in productivity can also be explored (Section 2.2.12).

Mixed-stock fisheries models are more complex than single-stock models and the complexity increases with the number of stocks in the mixture given variations in timing among and within management groups, and the recruitment survival patterns among stocks. For example, Mueter et al. (2002) showed that correlations in survival patterns among Fraser sockeye stocks are weak, but significantly positive.

For simplicity, we assume that:

- Exploitation rates for each stock equal the exploitation rate applied to a management group, but stocks can be moved between management groups or treated as an individual management group.
- Temporal survival patterns between stocks are uncorrelated (i.e. stochastic residuals are sampled independently for each stock).

2.4.3 Performance Measures

The overarching goal of the FRSSI process is to seek a balance between the fundamental objectives of (1) meeting spawner abundance goals for individual stocks and (2) accessing the catch-related benefits from the management groups. However, there are many aspects to consider when interpreting the simulation results. Early on in the process, we moved away from optimizing a value function with user-supplied weightings to a more interactive exploration of alternative scenarios. Over the course of more than a dozen workshops the list of potentially interesting variations of performance measures, requested by participants, grew steadily to over 300. We use the following subset for the sample results in this Research Document:

- *Low escapement:* Proportion of simulated years where the 4yr running arithmetic average of spawner abundance falls below a stock-specific benchmark.
- *Low catch*: Proportion of simulated years where catch for an aggregate falls below a specified level.

The notions of low escapement and low catch can be quantified in many different ways, and even the *Wild Salmon Policy* offers a range of potential benchmark definitions that should be explored on a case-by-case basis (pages 17 and 18 of DFO 2005). Methods for determining WSP benchmarks for conservation units have been finalized (Holt et al. 2009, Holt 2009), but resulting benchmarks for the 19 stocks of Fraser sockeye are still under development (Grant et al. 2011).

Pending the completion of this work, we continue to use interim benchmarks developed during the 2006 planning process. Workshop participants reviewed alternative approaches for setting biological benchmarks and settled on a robust combination using the smallest and largest value resulting from 5 different definitions of low escapement (Table 1). These benchmarks are based on a combination of population dynamics (e.g. 20% of the escapement that maximizes run size) and past observations (e.g. smallest observed 4yr average escapement). Benchmarks for identifying low catch for each management group are based directly on feedback received from workshop participants: Early Stuart – 15,000; Early Summer – 100,000; Summer – 600,000; Late – 300,000

2.4.4 Sensitivity Analyses

The simulation model has accumulated many alternative options in response to participants' requests during the collaborative workshops. We categorize alternative settings into choices related to the management strategy (e.g. fixed exploitation rate or TAM rule? exploitation rate fixed at 20% or 70%?) and states of nature (e.g. cyclic interactions or not? en-route mortality average or worse than average?). Figure 10 visualizes these alternatives as a decision tree, with each path through the tree corresponding to one simulation scenario. The model lets us try out many alternative choices and confront them with a wide range of alternative states of nature (i.e. "what if?").

As an illustration, Figure 21 shows a decision tree for Early Stuart based on evaluating 2 options for each of the 3 types of escapement strategy under each of 8 different states of nature (i.e. sets of biological assumptions). The purpose of the planning process is to iteratively work through each of these steps and discuss the results with participants bringing different perspectives to the table. Given the intended use of this model in a collaborative planning process, we do not complete a full analysis along these lines in this Research Document. Rather, we illustrate the general properties of the model with three sets of results.

In the first set of results, we explore the following management choices for a base case of biological assumptions, which is summarized in Section 3.3.1 :

- Vary fixed exploitation rate from 5% to 90%
- Vary fixed escapement target for each stock from Benchmark 2 (Table 1) up to ten times BM 2. For each of the management groups, the lowest resulting exploitation rate is then applied (i.e. harvest driven by the component stock that is least abundant relative to its target)
- Same as previous, but largest resulting exploitation rate applied to all component stocks of a management group (i.e. harvest driven by most abundant stocks)

- Vary cut-back point in Summer TAM rule from 10,000 to 5 Million
- Vary the cap on total allowable mortality for all 4 management groups from 40% to 90%
- Vary the exploitation rate floor in TAM rules for all 4 management groups from 2% to 40%
- Compare 3 different assumptions about run timing overlap for the 2009 TAM rules.

The second set of results looks at the following alternative biological assumptions:

- Effect of reduced productivity on performance of the three different types of management strategy
- Effect of alternative SR models on the performance of the three types of management strategy
- Effect of en-route mortality assumptions on the performance of different fixed ER strategies
- Effect of depensation assumptions on the performance of different fixed ER strategies

The third set of results compares the range of outcomes for different management options under 4 alternative biological scenarios:

- Larkin model, average productivity
- Ricker model, average productivity
- Larkin model, half productivity
- Ricker model, half productivity

3 SAMPLE RESULTS

3.1 A NOTE ON INTERPRETATION

The results presented in this chapter are intended to illustrate the range of questions that can be explored with this model (i.e. some of the many possible paths through the decision tree in Figure 10). The intent here is not to choose a particular spawner-recruit model, future scenario, suite of assumptions, or recommended management strategy. That will take place through the planning process. Our approach is consistent with the structure and content of Cass et al. (2004).

The results presented here use the same base case as the Working Paper presented in May 2010, but have been expanded to address reviewer's comments.

3.2 BAYESIAN PARAMETER ESTIMATES

3.2.1 Model Selection

Table 4 summarizes the DIC comparison for 16 alternative model fits for each of the 19 stocks. Appendix 2 lists the detailed results. We use ΔDIC > 5 as a cut-off for a significant difference in model fit.

Spiegelhalter et al. (2002) suggest using Burnham and Anderson's (2002) AIC criteria for DIC (e.g. within 1-2 of "best" are not significantly different, whereas values within 3-7 have much less support), but the WinBugs FAQ (www.mrc-bsu.cam.ac.uk/bugs/winbugs/dicpage.shtml) suggests two breakpoints, which we have adopted. Model fits with:

- ΔDIC > 10 are significantly different

- ∆DIC of 5 to 10 are most likely different
- ∆DIC < 5 should be reported as candidate models.

For eight of the 19 stocks, the Ricker model with lognormal errors fits best, and the DIC does not identify any other plausible candidate models: Bowron , Raft, Cultus, Portage, Fennell, Gates, Nadina, and Harrison. For the remaining stocks, there are from 2 to 8 candidate models identified based on DIC. For only 4 of the 19 stocks the Ricker form can be rejected based on DIC: Late Shuswap, Early Stuart, Stellako, and Chilko. For all 19 stocks, the lognormal error models performed better than the normal error models.

3.2.2 Spawner-Recruit Parameter Estimates

Figure 22 to Figure 25 illustrate the sequence from spawner recruit data to the resulting Bayesian parameter estimates for Early Stuart. In this case, we chose the full Larkin model with 3 lag terms out of 4 Larkin variations with similar DIC values (Table 4).

Figure 22 shows the time series of total spawners, recruits, and recruits per spawner. The largest abundance of spawners and the largest recruitment were observed in the 1993 brood year, but productivity (i.e. recruits/spawner) was low that year, and even lower the year after (1994 brood year).

Figure 23 shows the resulting parameter estimates. The lag terms (β_1 to β_3) are of similar magnitude as the capacity constraint for the brood year (β_0), indicating strong cycle line interactions (i.e. strong reduction in recruits/spawner for larger spawner abundances in previous years). The middle panel shows that the fitted model predicts the dominant years (i.e. which years have a spike in total number of recruits), but also shows the large uncertainty associated with trying to predict just how large the recruitment is.

Figure 24 compares the fitted SR curves to observed data.

Figure 25 shows the implications of including lag-terms in the spawner-recruit model. The top row shows the recruitment curves for each year (i.e. modeled recruitment at different levels of spawner abundance). Recruitment curves shift depending on spawner abundance in the three previous years. The large spawner abundance in 1993, combined with the strong 1-year lag term (β_1), result in a recruitment curve that predicts very poor recruits/spawner for any level of spawner abundance in the 1994 brood year. Appendix 4 includes the same series of figures for the other 18 stocks.

Figure 26 to Figure 29 compare estimated spawner-recruit parameters across the 19 stocks, first using the full Larkin model with 3 lag terms for all stocks, and then using mixed model forms as marked in Table 4. Pending further analyses, we illustrate the effect of varying model form by stock using the following rationale:

- If DIC clearly favors one of the candidate models, use that model (i.e. use Ricker for the first 8 stocks listed in Table 4).
- If DIC identifies several plausible models, use the full Larkin whenever it is among the candidate models (i.e. for the remaining stocks, except one).
- Else use the Ricker model (i.e. for Weaver).

Figure 26 and Figure 28 highlight the challenge of mixed-stock management by identifying stocks with lower intrinsic productivity within a management group (top panel), with larger uncertainty in parameter estimates (middle panel), or larger capacity constraint (i.e. lower optimal spawner abundance in brood year).

Figure 27 and Figure 29 highlight stocks with strong lag-terms (relative to β_0).

3.3 EXPLORING ALTERNATIVE TYPES OF MANAGEMENT STRATEGIES

3.3.1 Base-Case Scenario

The following assumptions are used throughout all of the results shown, except for the explicitly-stated variation explored in a particular section:

- Use full Larkin models with three lag terms and parameter estimates based on total spawners (Section 2.2.5).
- En-route mortality sampled from past observations (Section 2.2.11).
- No patterns in productivity (Section 2.2.12).
- No depensation (Section 2.2.13).
- No overlap constraint due to run-timing (Section 2.3.2).
- Random variation in recruitment and en-route mortality.

As the base case for this Research Document, we chose priors that were mostly uninformative in order to maintain a consistent approach for all 19 stocks and explore the implications of different data availability (Appendix 3). The same reasoning also applies to alternative assumptions about cycle-line interactions. For the base case, we start with the assumption that there is a potential interaction between cycle lines, and estimate the strength of that interaction based on observed data (i.e. Larkin model in Eq. 3). As a variation, we set the interaction parameters to 0 (i.e. Ricker model in Eq. 1) to see whether this influences estimates of the remaining parameters (i.e. α for productivity and β_0 for capacity).

Sections 2.2.6 to 2.2.8 describe base case assumptions for each of the parameters in Eq. 3.

3.3.2 Changing Fixed Exploitation Rates

Figure 30 shows the expected effect of applying fixed exploitation rates ranging from 5% to 90%.

Stock-specific differences in productivity (α) are reflected in the exploitation rate at which each stock approaches a high probability of low spawner abundances. Relative patterns can be directly compared across stocks (i.e. at which point does it hit a rapid change in performance), but comparisons of absolute values are confounded by cyclic patterns (i.e. off-cycle effect on performance measure) and choice of benchmark. Careful review on a case-by-case basis is necessary, but beyond the scope of this paper.

Broadly, Figure 30 shows that:

- Summer run stocks respond similarly to increasing exploitation rates, as is expected given their similarity in estimated productivity (Figure 26). Component stocks in the Early Summer and Late management groups exhibit a wider range of productivities, resulting in different levels of resilience to changes in exploitation rate.
- Probabilities of low escapement tend to sharply increase at exploitation rates somewhere between 40% to 70% (top panels), which is also the range that stabilizes catch (i.e. minimizes the probability of low catch) for each of the management groups (bottom left panel).
- Higher exploitation rates around 75-80% maximize long-term median catch for all 4 management groups, but median catch is highly sensitive to hitting the peak exactly (i.e. steep degradation in median catch if optimal exploitation rate is slightly exceeded.

3.3.3 Changing Fixed Escapement Targets

Figure 31 and Figure 32 summarize the performance of alternative fixed escapement targets for each stock, expressed as multiples of Benchmark 2 (Table 1). Performance depends on the relative productivity of component stocks as well as the management approach: If each stock is managed to its own target, risk comes only from how closely the management target is set to the benchmark. Performance in terms of escapement stabilizes at roughly 2-4 times BM 2, depending on the stock (Figure 31). If, however, aggregates are managed based on the strongest component (i.e. max ER based on harvesting all fish over over the escapement target), then stock-specific differences in productivity are picked up strongly, because productive stocks tend to have more fish available for harvest over the escapement target, resulting in higher exploitation rate (Figure 32).

If stocks are managed individually, catches tend to be largest for escapement targets set to about double BM2, but increasingly stable as targets are reduced (Figure 31). If aggregates are managed to strongest component, Summer catches tend to be largest for triple BM2 (Figure 32).

3.3.4 Changing Cut-Back Point On TAM Rule – Summer

Figure 33 shows the effect of changing the cut-back point of the TAM Rule for the Summer management group (see Figure 19 for definition of TAM rules).

For this scenario, timing overlap does not impose a constraint, so the performance of the other 3 management groups is not influenced by changes in the Summer TAM rule (i.e. horizontal lines).

Probability of low escapement for Summer stocks is highly robust to changes in cut-back point, with only small changes in performance for large changes in cut-back point (e.g. 1 Million vs. 3 Million). Some of the results appear counter-intuitive at first, with one of the stocks worsening slightly as the cut-back point is pushed higher. However, this is due to the feedback between aggregate management and individual stock characteristics. As the cut-back point increases, aggregate abundance increases, raising aggregate exploitation rates, which in turn affects the least productive stocks in the mix.

Cut-back points below about 1.5 Million are expected to stabilize catch for the aggregate, while median catch is highly robust to different cut-back points up to about 3 Million. Compare this to the highly sensitive response of median catch to changes in fixed exploitation rate (Figure 30).

3.3.5 Changing Cap On TAM Rule – All 4 Management Groups

Figure 34 shows the effect of changing the cap on TAM rules. Performance is more sensitive to changing the cap than to changing the cut-back points (Figure 33). The response pattern for each stock is similar to the effect of increasing fixed exploitation rates (Figure 30), but buffered by the consideration of en-route mortality and the reduced ER in low-abundance years.

3.3.6 Changing Exploitation Rate Floor On TAM Rule – All 4 Management Groups

Figure 35 shows the effect changing the exploitation rate floor. Performance with respect to stock-specific escapement is quite robust, but shows a gradual worsening (i.e. higher probability of low escapement) as the floor is pushed up. This is consistent with the results for the lower end of fixed exploitation rates explored above (Figure 30).

3.3.7 Effect Of Constraints Due To Overlap In Run-Timing

Figure 36 shows the effect of 2 alternative approximations for the constraints imposed by overlap in run timing, as described in Section 2.3.2. This particular example uses the 2009 TAM rule with either (1) no overlap, (2) 90% window for each timing group, and (3) 10% daily abundance. Timing overlap, as defined here, has little effect on the frequency of low escapement, but results in a drastic reduction in median catch from the Summer group. The effect on escapement patterns of component stocks is more pronounced under other assumptions (e.g. shorten the protected timing window, in combination with reduced productivity)

3.4 SENSITIVITY TO ALTERNATIVE BIOLOGICAL ASSUMPTIONS

3.4.1 Productivity Scenarios

Figure 37 to Figure 45 illustrate the effect of reduced productivity assumptions on various performance evaluations. All scenarios use the "immediate and permanent" option for including reduced productivity. More complex patterns will be explored as part of future FRSSI workshops.

Figure 37 shows how the expected performance of the 2009 TAM rule degrades as productivity decreases. Most stocks are resilient to some loss of productivity (i.e. up to about half), because the reduced productivity is absorbed by catch reductions up to that point (i.e. bottom right panel).

Figure 38 illustrates another way of taking productivity scenarios into account. The scenario is the same as in Figure 30, except with productivity set to half. The general patterns from the base case are retained, but shifted towards lower exploitation rates. For example, the fixed exploitation rate that maximizes median catch shifts from about 80% to about 60%.

Figure 39 applies the same approach to exploring the effect of changing the cap on TAM rules. The scenario is the same as in Figure 34, except with productivity set to half. The general patterns from the base case are maintained, but more pronounced.

Section 3.5 includes a more-detailed side-by-side comparison of average productivity versus half productivity.

3.4.2 Alternative Spawner-Recruit Models

Assumptions about delayed density effects (i.e. cycle interactions) have potentially important implications for shaping escapement strategies.

Figure 40 to Figure 42 illustrate the difference for Quesnel sockeye, using a simplified scenario with 30% fixed exploitation rate, without en-route mortality, and without random variation. The Larkin model with 3 lag terms creates strong and persistent cyclic patterns in escapement (Figure 40), while the Ricker model stabilizes abundance quickly as "off-cycle" lines rebuild (Figure 41). Figure 42 summarizes across the trajectories in Figure 40 and Figure 41. However, increased mortality on stock with Ricker-type dynamics can create strong cyclic patterns as well (e.g. 60% fixed ER plus median en-route mortality, Figure 43, also without random variation). Figure 44 illustrates the effect of adding random variation to the Larkin trajectories shown in Figure 40.

This illustration emphasises the importance of improving estimates of lag-terms are for each stock (Section 2.2.5) and highlights the difficulty in trying to determine where a stock falls at any given point in time: Larkin-type or Ricker-type with harvest rates perpetuating cycles?

Figure 45 and Figure 46 show the expected performance of 2009 TAM rules under half productivity, using 2 different spawner-recruit models. Both can be compared to the corresponding base case (Figure 37).

3.4.3 Assumptions About En-Route Mortality

Figure 47 shows the effect of alternative assumptions about en-route mortality if the harvest strategy is a fixed exploitation rate of 60%. Four alternatives are included, as described in Section 2.2.11. These are (1) none, (2) sampling from observed, (3) linear regression, (4) log-linear regression.

Including ERM based on resampling (Option 2) has pronounced effects on probability of low escapement for Early Stuart, and lower productivity components of the Early Summer and Late groups. The Summer group has experienced low levels of ERM (Figure 15), and therefore including it has little influence of expected performance.

Note that this example emphasizes the effect of ERM, because harvests are not adjusted in response to ERM, as they would be under a TAM rule.

3.4.4 Assumptions About Depensatory Mortality

Figure 48 shows the effect of depensatory mortality assumptions. To illustrate the potential implications, this example uses BM 2 as the trigger point, which is typically much higher than the lowest observed escapement (Table 1).

Even with this trigger point, the level of depensatory mortality needs to exceed 30-40% for the lower productivity stocks to affect long-term performance. However, under reduced productivity scenarios the effect of depensation becomes more pronounced.

3.5 SUMMARY ACROSS SENSITIVITY ANALYSES

Figure 49 to Figure 56 summarize the range of outcomes for several harvest rule variations, described in Section 3.3, under four different biological assumptions (2 alternative spawner-recruit models, 2 alternative productivity assumptions).

Each bar in these figures corresponds to one of the lines in the earlier figures. For example, the first bar in the top left panel of Figure 49 summarizes the information from the first panel of Figure 30 (i.e. Early Stuart, Changing fixed ER, Larkin SR model, average productivity).

To interpret these figures, note that:

- If a bar covers a wider range, then simulated long-term performance is more sensitive to changes in that aspect of a harvest strategy.
- If dark bars and light bars are very different, then simulated long-term performance is highly sensitive to assumptions about delayed-density effects (i.e. Larkin vs. Ricker).
- If the two panels in a row are very different, then simulated long-term performance is highly sensitive to assumptions about productivity.

Figure 49 summarizes sensitivity analyses for Early Stuart. Briefly:

- Fixed escapement policies and TAM rules are more robust in terms of avoiding low spawner abundances than fixed exploitation rate policies (top row). However, variations of these strategies have a much more pronounced effect on expected performance under a reduced productivity scenario (top left panel vs. top right panel).

- Median long-term catch is highly sensitive to variations in all 3 types of harvest strategies (bottom row), and is strongly affected by productivity assumptions (bottom left vs. bottom right). The highest median catch achievable under any of the alternative strategies is reduced by about 80% if productivity is reduced by 50%.
- For all three types of harvest strategies, the median catch can be higher under the Ricker SR model than under the Larkin SR model, if productivity is average (white bars reach up higher in bottom left panel). However, the reverse happens under a reduced productivity scenario (bottom right panel). Under average productivity, the delayed-density effects reduce available harvest. However, delayed-density effects become less pronounced under a reduced productivity scenario, because there are fewer years with large escapements (i.e. reduce α parameter without changing capacity parameters β_0, β_1, β_2, β_3), and estimates of intrinsic productivity tend to be higher for Larkin fits (Section 3.2.2).

These observations hold generally true for the other stocks and management groups, but vary in the details due to differences in estimates productivity and capacity, and the mixture of stocks in a group:

- Stocks with lower estimates of intrinsic productivity (i.e. smaller α in Figure 26) tend to be more sensitive to reduced productivity scenarios (e.g. Raft and Upper Pitt in Figure 51, Cultus in Figure 54)
- Stocks with stronger estimated lag terms (i.e. larger β_1, β_2, or β_3 in Figure 27) tend to show a more pronounced difference in performance when comparing the Ricker and Larkin SR models (dark bars vs. light bars). These differences also tend to be more pronounced under reduced productivity assumptions (e.g. Early Stuart in Figure 49, Scotch Creek in Figure 51, Late Shuswap in Figure 53)

Figure 57 compares the response of median annual catch to changes in fixed exploitation rate under four different biological assumptions. The results for Larkin fits are the same as shown the bottom right panels of Figure 30 (average productivity) and Figure 38 (half productivity). Also note that the first set of bars for each panel in Figure 56 corresponds to the vertical range of the curves in Figure 57. The patterns are similar for all 4 management groups. Specifically:

- Under average productivity, the highest achievable median catches are larger with the Ricker model (i.e. without cycle interactions) than with the Larkin model, but occur at a lower fixed exploitation rate.
- Under half productivity, the highest achievable median catches are much lower, and occur at lower exploitation rates.
- The fixed exploitation rate that maximizes median annual catch can differ as much or more between SR models than among productivity assumptions for the same SR model. This is particularly pronounced for Lates.

4 DISCUSSION

4.1 ALTERNATIVE SPAWNER-RECRUIT MODELS

Spawner-recruit dynamics for Fraser sockeye have been intensively studied, but as yet there is no agreement on whether populations are intrinsically cyclic or not, and whether harvesting could initiate cycles or is a perpetuating mechanism (Larkin & Hourston 1964, Walters & Staley

1987, Cass & Wood 1994, DFO 2006b, Myers et al. 1998, Ward & Larkin 1964, Martell et al. 2008)

In addition to uncertainty in the form of the underlying dynamics, there is also substantial uncertainty in the parameter estimates for each model form. We account for this uncertainty by sampling from the Bayesian posterior distributions rather than using a best estimate (Section 2.2.5).

One approach proposed during the CSAP review is to use the full Larkin model for all stocks and "let the data speak" regarding the relative importance of cycle-line interactions (DFO 2011a). We use this as the base case for the sample results presented in Sections 3.3 and 3.4. However, a more detailed stock-by-stock review of spawner-recruit dynamics should be completed, because the extra terms in the Larkin model increase concerns related to over-fitting and parameter estimates may change as statistically insignificant terms are dropped. One approach proposed during the CSAP review is to estimate Larkin model lag-terms from different subsets of the spawner-recruit data to check which are persistently significant. We recommend this as a priority for future work, concentrating on the models that were identified as being most parsimonious by the DIC results (Section 4.3).

4.2 USE OF THE FRSSI MODEL

The model presented in this Research Document, as well as the planning process it supports, focuses on long-term strategies and doesn't attempt to capture all of the operational complexities of in-season management. The model assumes that one strategy is going to be adopted and applied for 48 years, which is not likely in practice. However, previous versions of this model have proven sufficient to explore and illustrate the long-term differences between major categories of escapement strategies applied to the 4 management groups of Fraser sockeye. For example, during previous planning processes the model showed advantages of a strategy that responds to run size compared to fixed escapement strategies or fixed exploitation rate strategies (Section 3.5).

The particular choices made in the initial scoping of the FRSSI model were shaped by the existing decision process for Fraser sockeye. Revisions and extensions over the years mirrored the progression of debate among participants at various levels of the process (Steering Committee, Working Group, Workshops, annual review of draft IFMP, Fraser Panel)

Discussions around annual model revisions helped with highlighting alternative hypotheses and brought practical considerations into the analytical work. For example, the TAM rule was adapted to specify a fixed escapement in the middle range (bottom panel of Figure 19), rather than a linear reduction in allowable mortality rate (top panel of Figure 19).

The model has now gone through 4 incarnations in 3 different programming languages over the course of 8 years, and has been adapted to support discussions during the pre-season planning process. For example, the approach of optimizing a value function based on multi-attribute weightings elicited from workshop participants has shifted towards a collaborative exploration of alternative scenarios. Essentially, use of the FRSSI model moved from the approach exemplified by Hilborn and Walters (1977) towards the process envisioned by Schnute and Richards (2001) through sustained interaction with a fairly stable group of workshop participants, greatly expanding the scope of alternative assumptions along the way.

In terms of scope, the FRSSI model went through the following major changes:

- Added 7 more stocks with shorter data sets (for a total of 19)
- Added alternative population models (Cycle-Aggregate model, Larkin model)

- Added alternative types of harvest strategies (TAM rules)
- Switch from optimizing a harvest strategy based on a value function to collaborative evaluation of different strategies across a range of contingencies
- Added options for approximations of timing overlap between management groups
- Added options for stock-specific patterns in productivity
- Added options for en-route mortality, pre-spawn mortality, depensatory mortality, and quasi-extinction thresholds.

Table 5 compares the current scope of the FRSSI model to six other published models used to evaluate harvest strategies for Fraser River sockeye salmon. The FRSSI model includes more stocks and more alternatives for biological mechanisms than these six other analyses. This broader scope is a direct result of the multi-year workshop series, where participants identified a prioritized list of model extensions each year and then reviewed the implementation the following year.

The model offers many options (Figure 10), which present a challenge for communication. However, these options simply reflect the many questions being asked about alternative strategies for the management of Fraser River sockeye fisheries, and the model helps us explore expected implications in a collaborative process. Based on the options developed through this process (Pestal et al. 2008), revised harvest strategies have been implemented since the 2006 brood year. Fundamental changes from the previous management approach include:

- Escapement strategies for a given year are based on a target mortality rate, not on a fixed escapement target. Estimates of spawning capacity are highly uncertain for some stocks, and harvest strategies based on target mortality rates should be more robust to this uncertainty.
- Escapement strategies respond to run size, but do not change for different cycle years. Under the 1987 Rebuilding Plan, a different interim escapement goal was identified for each cycle line. Under the Spawning Initiative, off-cycle years in cyclic stocks are simply treated as an instance of low abundance, with the target mortality rate based on the shape of the escapement strategy.
- Escapement strategies specify target levels of total mortality rates. When put into practice, these strategies need to take into account en-route mortality. The proportion of each run available for harvest, the target exploitation rate, is determined by deducting projected en-route mortalities from the allowable total mortality.
- The requirement to stay above brood year escapement was removed to account for the fluctuating productivity of many stocks; and
- Escapement strategies are explicitly based on simulated long-term performance relative to explicitly stated management objectives (e.g. keep 4 yr average above benchmark)

Despite new data and new analyses, future planning processes will always have to rely on the approach of testing alternative strategies against multiple working hypotheses (e.g. Hilborn and Mangel 1997, Hilborn 1997, Francis 1997, Schnute and Richards 2001), such as the illustration for Early Stuart in Figure 21.

In an ideal setting we would be able to identify a type of strategy with fairly robust performance across a balance of multiple objectives, even when confronted with multiple alternative working hypotheses about the biology of Fraser sockeye and a wide range of plausible future changes. In practice, however, we find that a strategy may perform very well in terms of one of the objectives for some stocks under one of the working hypotheses, but perform very poorly in terms of the other objectives for the remaining stocks. For example, a strategy that results in the highest average catches from productive stocks also tends to increase the year-to-year variability in catch and increase the probability of low escapements on less productive stocks. Similarly, a strategy that performs well under one working hypothesis may perform very poorly under an alternative working hypothesis that may be considered less likely, but is still plausible.

Balancing these considerations over the long-term, and finding approaches for dealing with annual variability and uncertainty, requires on-going constructive debate and collaboration.

Finally, workshop participants frequently requested a more extensive socio-economic analysis to provide additional context for the interpretation of simulated catch trajectories. A simplified sharing algorithm was used to roughly partition catch by sector (as described in Appendix 2 of Pestal et al. 2008). This rough catch partitioning was then used as the basis for a detailed economic comparison of three alternative management strategies in a pilot study (Gislason 2006). Future extensions of this work will require a process to review the details of the economic analysis that is analogous to the repeated science reviews of the biological model (Cass et al. 2004, Pestal et al. 2008, this Research Document).

4.3 NEXT STEPS

We identify seven priority areas for on-going work in support of future planning processes:

- Incorporate existing information on freshwater capacity into the beta priors.
- Explore risk management approaches to uncertainty in SR models and assess the risk of being wrong in assumptions about delayed-density effects (e.g. what if we manage a Ricker-type stock based on Larkin model assumptions?).
- Revise the performance measures and modeled stocks used in the FRSSI model (Section 2.4.3) to be consistent with status metrics and CUs being developed under the WSP (Holt et al. 2009, Grant et al. 2011).
- Explore alternative approaches for random variation in forward simulations. For example, should there be a constraint on the multiplicative error, or on calculated recruitment? A constraint on simulated recruits could be based on observed recruitment (e.g. 2 or 3 times largest observed), or some multiple of what's been modelled in the previous two cycles in the simulation.

Several work-intensive analyses were debated during the review process. While these go beyond the scope of the current Research Document, it may be appropriate to initiate requests for science advice to address them in detail. These analyses include:

- Updated estimates of productive capacity for Fraser sockeye salmon lakes. This is important for some stocks where the stock-recruit data is insufficient for purposes of estimating reliable stock-recruit parameters.
- Develop a plausible suite of stock-specific future patterns in productivity and alternative sample distributions for en-route mortality (e.g. based on climate scenarios). These would inform FRSSI model simulations as well as other planning processes (e.g. Fraser Panel).
- Further analyses of alternative spawner-recruit models and the implications of using them in forward simulations to represent the dynamics of individual stocks. These would inform FRSSI model simulations as well as Fraser sockeye forecasts and WSP BM.
- Full forward evaluation of 2010 TAM rules under all combinations of assumptions in the updated model (e.g. all identified variations of spawner-recruit models).

- Retrospective analysis of FRSSI TAM rule performance ("What would have likely happened if 2010 TAM rules had been used since 1987, given observed recruitment patterns"). This work would expand upon the review by Martell et al. (2008) with additional stocks, uncertainty in capacity, new data, and the added objective of avoiding low escapement on any component stocks.

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TABLES AND FIGURES

Table 1: Summary of spawner abundance and low escapement benchmarks for 19 stocks of Fraser River sockeye salmon.
*Note the wide range of observed spawner abundances and skewed distribution for stocks with pronounced 4-year cycles in abundance (e.g. compare median to largest 10% for Quesnel and Late Shuswap). Appendix 3 lists all of the included data (up to 2008), and Appendix 4 includes time-series plots of spawner abundance. The * denotes the 12 stocks with long time-series of high-quality data that were used early in the model development. The remaining 7 stocks were added in response to participants' feedback (Section 2.2.1).*

				Observed Range of Total Spawners								Low Escapement BM (Compare to 4yr Avg)	
	Stock ID		Stock	# of Obs	Min	Lower 10th	Lower Quarter	**Median**	Upper Quarter	Upper 10th	Max	Lowest 4yr Avg	BM1	BM2
	1	*	E. Stuart	61	1,522	4,657	21,044	**38,807**	117,445	234,219	688,013	10,218	10,200	50,300
Early Summer	4	*	Bowron	61	836	1,501	2,560	**6,395**	12,780	25,205	35,000	1,514	1,500	4,900
Early Summer	14		Fennell	42	9	220	1,681	**5,709**	9,901	15,195	32,279	483	500	2,200
Early Summer	16		Gates	41	70	777	2,582	**7,181**	14,838	28,899	99,470	2,401	1,100	3,500
Early Summer	17		Nadina	36	1,625	2,179	3,665	**9,547**	22,952	55,253	194,381	9,094	2,000	9,100
Early Summer	18		Pitt	61	3,560	9,290	13,412	**18,673**	37,747	55,380	131,481	11,229	3,400	11,200
Early Summer	5	*	Raft	61	464	1,279	2,714	**6,244**	9,988	18,369	66,292	2,572	2,500	5,200
Early Summer	15		Scotch	29	107	605	2,156	**4,609**	14,772	75,222	144,199	2,186	900	4,000
Early Summer	8	*	Seymour	61	1,323	2,802	5,709	**11,971**	44,588	78,371	272,041	9,087	9,100	19,000
Summer	7	*	Chilko	61	17,308	55,675	120,104	**305,853**	544,364	825,837	1,037,737	164,485	66,400	164,500
Summer	2	*	Late Stuart	60	35	1,620	6,315	**25,562**	157,197	372,859	1,363,826	29,499	29,500	78,300
Summer	6	*	Quesnel	61	49	111	308	**10,222**	278,961	1,349,263	3,510,789	7,803	7,800	154,500
Summer	3	*	Stellako	61	15,763	36,700	42,099	**86,688**	138,794	185,641	371,604	37,018	22,700	45,400
Late	10	*	Birkenhead	61	11,905	18,213	30,656	**48,916**	83,787	189,445	335,630	23,175	19,700	39,300
Late	11	*	Cultus	61	52	418	1,227	**9,055**	16,919	25,922	47,779	1,053	1,000	7,300
Late	19		Harrison	61	313	2,202	4,239	**8,259**	19,717	33,044	388,605	3,555	2,000	4,100
Late	12	*	Portage	54	9	89	1,118	**3,724**	9,071	17,321	31,343	1,301	100	1,300
Late	13		Weaver	43	2,756	11,621	25,442	**42,002**	59,165	74,903	294,083	19,488	8,600	19,800
Late	9	*	L. Shuswap	61	164	1,395	3,606	**21,113**	1,144,115	2,026,693	5,532,263	320,500	111,100	320,500

Table 2: DBE and contribution of non-model stocks for 4 management groups.
Differences between estimates (DBE) of sockeye in the lower Fraser River and on the spawning grounds potentially arise from a number of different sources (Section 2.2.11). Discrepancies are evaluated post-season, and if they are concluded to be real, the DBE is incorporated into the recruitment data used in the spawner-recruit dataset (Section 2.2.3). We use observed DBE data (provided by the PSC) to approximate en-route mortality in the forward simulations. Positive DBEs, where upstream estimates are larger than lower-river estimates are excluded from the table and set to 0 for the calculation, assuming negligible en-route mortality that year. Figure 15 shows observed patterns in DBE. Contribution of non-model stocks is the % of annual abundance not attributed to one of the 19 stocks listed in Table 1.

<table>
<tr><th></th><th colspan="4">% Difference between estimates</th><th colspan="6">% Contribution of non-model stocks (| = 4%)</th></tr>
<tr><th></th><th></th><th></th><th></th><th></th><th colspan="2">Early Summer</th><th colspan="2">Late</th><th colspan="2">Total</th></tr>
<tr><th>Year</th><th>Early Stuart</th><th>Early Summer</th><th>Summer</th><th>Late</th><th>% of run</th><th>% of esc</th><th>% of run</th><th>% of esc</th><th>% of run</th><th>% of esc</th></tr>
<tr><td>1977</td><td>-</td><td>27%</td><td>0%</td><td>-</td><td>4%</td><td>3%</td><td>1%</td><td>1%</td><td>0%</td><td>0%</td></tr>
<tr><td>1978</td><td>41%</td><td>0%</td><td>14%</td><td>0%</td><td>4%</td><td>4%</td><td>1%</td><td>1%</td><td>1%</td><td>1%</td></tr>
<tr><td>1979</td><td>37%</td><td>19%</td><td>2%</td><td>-</td><td>2%</td><td>1%</td><td>0%</td><td>0%</td><td>0%</td><td>0%</td></tr>
<tr><td>1980</td><td>-</td><td>24%</td><td>7%</td><td>-</td><td>9%</td><td>8% ||</td><td>1%</td><td>1%</td><td>1%</td><td>1%</td></tr>
<tr><td>1981</td><td>31%</td><td>13%</td><td>12%</td><td>-</td><td>1%</td><td>1%</td><td>1%</td><td>1%</td><td>0%</td><td>0%</td></tr>
<tr><td>1982</td><td>-</td><td>16%</td><td>0%</td><td>1%</td><td>13%</td><td>14% |||</td><td>5%</td><td>6% |</td><td>5%</td><td>5% |</td></tr>
<tr><td>1983</td><td>54%</td><td>48%</td><td>0%</td><td>-</td><td>7%</td><td>6% |</td><td>0%</td><td>0%</td><td>1%</td><td>1%</td></tr>
<tr><td>1984</td><td>-</td><td>0%</td><td>19%</td><td>-</td><td>13%</td><td>11% ||</td><td>1%</td><td>1%</td><td>1%</td><td>2%</td></tr>
<tr><td>1985</td><td>0%</td><td>0%</td><td>0%</td><td>-</td><td>9%</td><td>7% |</td><td>1%</td><td>2%</td><td>0%</td><td>0%</td></tr>
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<tr><td>1987</td><td>4%</td><td>39%</td><td>0%</td><td>-</td><td>11%</td><td>11% ||</td><td>0%</td><td>0%</td><td>1%</td><td>1%</td></tr>
<tr><td>1988</td><td>0%</td><td>53%</td><td>0%</td><td>-</td><td>20%</td><td>22% |||||</td><td>1%</td><td>1%</td><td>3%</td><td>4%</td></tr>
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<tr><td>1993</td><td>0%</td><td>0%</td><td>0%</td><td>-</td><td>5%</td><td>4% |</td><td>0%</td><td>0%</td><td>0%</td><td>0%</td></tr>
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<tr><td>1997</td><td>70%</td><td>46%</td><td>2%</td><td>41%</td><td>10%</td><td>13% |||</td><td>1%</td><td>2%</td><td>0%</td><td>0%</td></tr>
<tr><td>1998</td><td>81%</td><td>54%</td><td>40%</td><td>43%</td><td>28%</td><td>21% |||||</td><td>0%</td><td>0%</td><td>2%</td><td>1%</td></tr>
<tr><td>1999</td><td>83%</td><td>65%</td><td>14%</td><td>59%</td><td>11%</td><td>10% ||</td><td>0%</td><td>0%</td><td>1%</td><td>1%</td></tr>
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<tr><td>2001</td><td>16%</td><td>13%</td><td>0%</td><td>76%</td><td>15%</td><td>16% |||</td><td>3%</td><td>12% |||</td><td>1%</td><td>1%</td></tr>
<tr><td>2002</td><td>56%</td><td>15%</td><td>-</td><td>8%</td><td>27%</td><td>25% ||||||</td><td>0%</td><td>1%</td><td>2%</td><td>1%</td></tr>
<tr><td>2003</td><td>54%</td><td>29%</td><td>22%</td><td>12%</td><td>27%</td><td>21% |||||</td><td>1%</td><td>2%</td><td>3%</td><td>3%</td></tr>
<tr><td>2004</td><td>90%</td><td>73%</td><td>70%</td><td>64%</td><td>31%</td><td>30% |||||||</td><td>14%</td><td>24% |||||</td><td>11%</td><td>13% |||</td></tr>
<tr><td>2005</td><td>50%</td><td>53%</td><td>37%</td><td>58%</td><td>45%</td><td>38% |||||||||</td><td>2%</td><td>1%</td><td>4%</td><td>3%</td></tr>
<tr><td>2006</td><td>22%</td><td>61%</td><td>29%</td><td>-</td><td>21%</td><td>18% ||||</td><td>1%</td><td>1%</td><td>3%</td><td>2%</td></tr>
<tr><td>2007</td><td>56%</td><td>8%</td><td>11%</td><td>48%</td><td>28%</td><td>25% ||||||</td><td>2%</td><td>2%</td><td>4%</td><td>4% |</td></tr>
<tr><td>2008</td><td>16%</td><td>43%</td><td>6%</td><td>85%</td><td>27%</td><td>40% |||||||||</td><td>3%</td><td>8% ||</td><td>7%</td><td>10% ||</td></tr>
<tr><td>2009</td><td>39%</td><td>49%</td><td>17%</td><td>31%</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2010</td><td>39%</td><td>20%</td><td>0</td><td>0</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Table 3: Summary of prior probability distributions used for estimates of spawner-recruit parameters.

All Stocks

Parameter	Median	95% Probability Interval		
Productivity (alpha)	0	-62	to	62
1 year lag term (beta1)	50	2.5	to	97.5
2 year lag term (beta2)	50	2.5	to	97.5
3 year lag term (beta2)	50	2.5	to	97.5

Stock-Specific Capacity Priors (Beta0)

	Uniform Prior			**Lognormal Prior**		
		95% Prob. Int			95% Prob. Int	
Stock	Median	2.50%	97.50%	Median	2.50%	97.50%
L. Shuswap	0.7	0.4	14	0.4	0.1	2.6
Quesnel	1.1	0.6	24	0.7	0.2	4.3
L. Stuart	1.7	0.9	35	1.0	0.3	6.3
Chilko	3.3	1.7	69	2.0	0.6	13
E. Stuart	5.2	2.7	106	3.1	0.9	19
Harrison	9.4	4.8	194	5.6	1.7	35
Stellako	10	5.1	204	5.9	1.8	37
Birkenhead	10	5.2	207	6.0	1.9	38
Weaver	17	8.9	356	10	3.2	65
Seymour	18	9.5	378	11	3.4	69
Upper Pitt	28	14	566	16	5.1	103
Nadina	31	16	626	18	5.6	114
Scotch	40	20	813	24	7.3	149
Cultus	67	34	1,372	40	12	251
Raft	72	37	1,480	43	13	271
Gates	112	58	2,296	67	21	420
Bowron	123	63	2,532	74	23	463
Portage	131	67	2,694	78	24	493
Fennell	131	68	2,695	78	24	493

Table 4: Comparison of alternative spawner-recruit model fits.
Eight alternative model forms were fitted under 2 different assumptions about random errors (Section 2.2.10). Model forms differ in the number of lag terms to capture delayed-density dependence. The Ricker model has no lag terms, the full Larkin model has 3 lag terms, and the Larkin model variations have one or two lag-terms, as labeled. The default assumption for random error is a lognormal distribution (L), but a normal error (N) distribution was also tested. Model comparisons are based on the difference in the Deviance Information Criterion (DIC). Models within 5 of the lowest DIC are considered plausible candidate models (Section 3.2.1), and are shaded in the table. Full results are included in Appendix 2. X marks the models used for the "Mixed Model" scenario in Section 3.4.2.

	Ricker		**Larkin**		**Larkin 1**		**Larkin 2**		**Larkin 3**		**Larkin 1,2**		**Larkin 2,3**		**Larkin 1,3**		**Number of**
	L	N	L	N	L	N	L	N	L	N	L	N	L	N	L	N	**Candidate Models**
Bowron	X																1
Raft	X																1
Cultus	X																1
Portage	X																1
Fennell	X																1
Gates	X																1
Nadina	X																1
Harrison	X																1
L. Shuswap			X														2
Scotch			X														2
Quesnel			X														3
Weaver	X																3
E. Stuart			X														4
Stellako			X														4
Chilko			X														5
Seymour			X														5
Upper Pitt			X														5
L. Stuart			X														8
Birkenhead			X														8

Table 5: Scope of some published simulation models for evaluating harvest strategies for Fraser River sockeye salmon.

	FRSSI Model	Collie et al. 1990	Korman & Grout 2009	Holt & Peterman 2008	Dorner et al. 2009	Martell et al. 2008	Marsden et al. 2009
General							
Population Unit	Stocks	Stocks	Stocks	Stocks	Stocks	Stocks	Stocks
Number	19	8 (+2)[e]	1	1	16	9	9
Biological Components							
Ricker model	Yes	Yes	Yes[f]	Yes	Yes	Yes	Yes
Larkin model	Yes	No	No	Yes	No	Yes	Yes
Productivity changes	Yes	No	Yes	No	Yes	No	No
En-route mortality	Yes	No	No	No	No	No	No
Pre-spawn mortality	Yes	No	Yes	No	No	No	No
Depensatory mortality	Yes	No	Yes	No	No	No	No
Management Options							
Fixed ER target	Yes	Yes	Yes	No	No	Yes	Yes
Fixed escapement target	Yes	No	Yes	No	Yes	Yes	No
Abundance-based rules	Yes	No	Yes	Yes	No	No	No
ER trajectories	No	Yes	Yes	No	No	No	No
Management groups	Yes	Yes	No	No	No	Yes	Yes
Overlap between groups	Yes	No	No	No	No	No	No
Hatchery Supplementation	No	No	Yes	No	No	No	No
Habitat Improvement	No	No	Yes	No	No	No	No
Performance Evaluation							
Optimization	No	Yes	No	No	No	Yes[a]	Yes[a]
Forward Sim	Yes	No	Yes	Yes	Yes	No	No
Retrospective Sim	Approx[d]	Yes	No	No	No	Yes	Yes
Allocation	No[c]	No	No	No	No	No	No[b]
Socio-economic	No[c]	No	No	No	No	No	Yes

a) Assuming perfect knowledge ahead of time
b) Based on past effort and estimates of catchability
c) Separate analysis based on simplified sharing algorithm (e.g. Gislason 2006)
d) Can specify pattern in productivity, but not specific sequence of anomalies
e) Includes 8 stocks and 2 miscellaneous groups
f) Uses Ricker model to predict juveniles, then marine mortality to get recruits

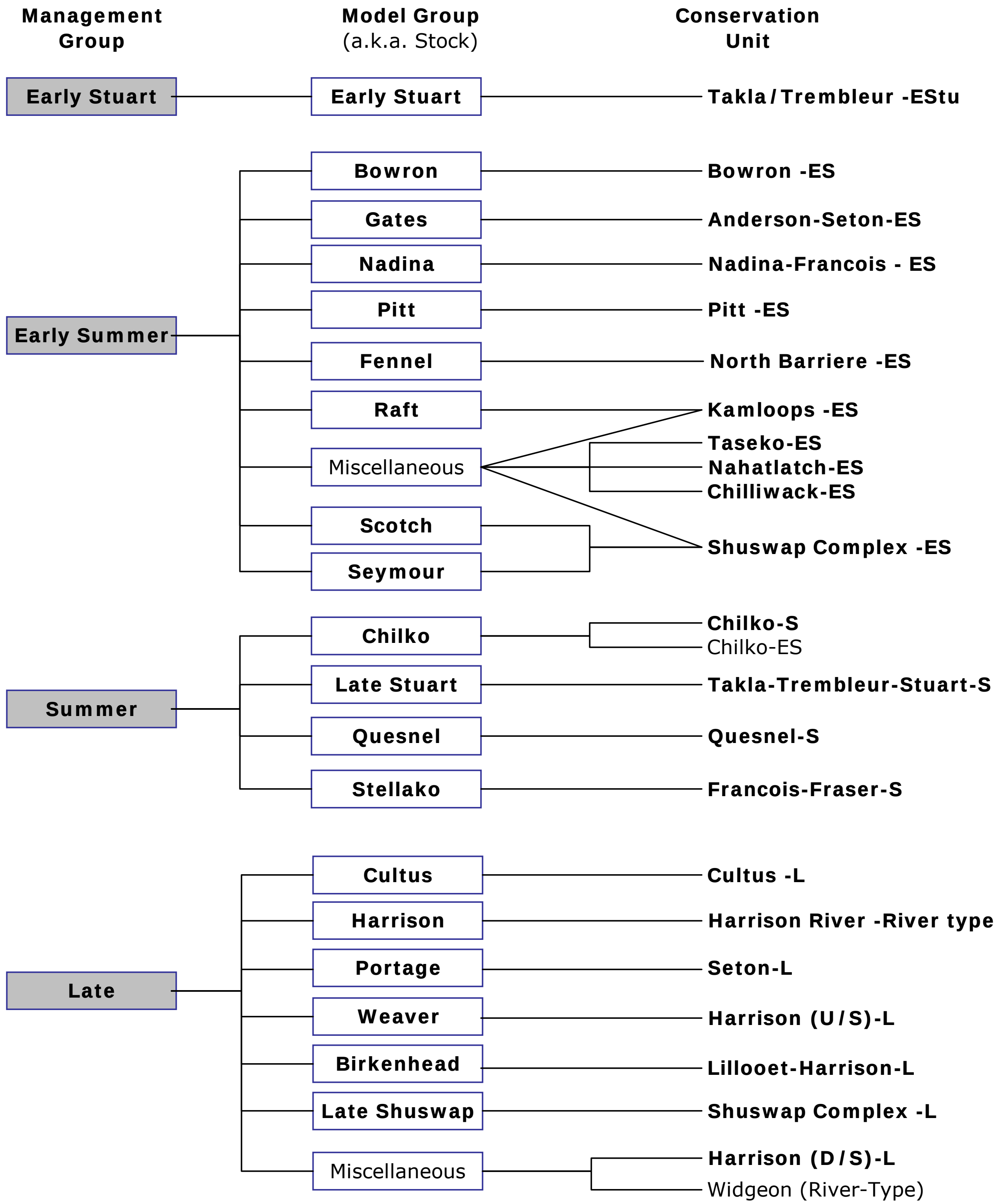


Figure 1: Matching stocks to conservation units.
Stocks included in the model are marked in bold. CUs which contribute a substantial share of a stock's abundance are also marked in bold. This figure is based on Grant et al. (2011), which provides an updated list of CUs and a summary of available data for each.

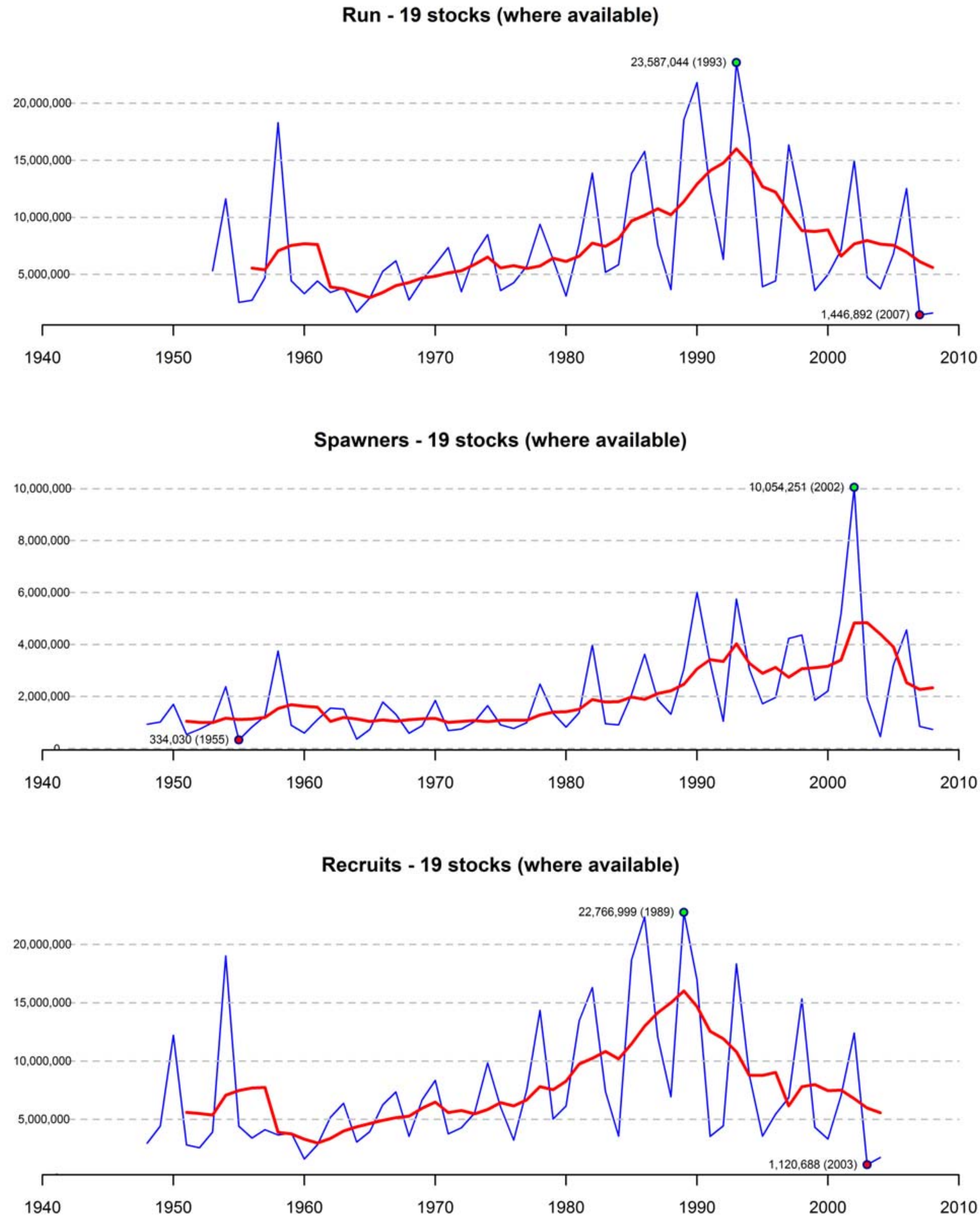


Figure 2: Total run, spawners, and recruitment for 19 stock of Fraser River sockeye salmon. *Note that run, spawners, and recruits are all for the same year (i.e. run returning that year, spawner abundance that year, and recruits produced by those spawners). Totals include all data available for a year, with more stocks included in the later part of the time series. Figure 3 extracts only those 12 stocks with long time series. Trend lines (in red) show 4-year running averages. Table 1 lists the component stocks, and Appendix 3 lists the available data for each stock.*

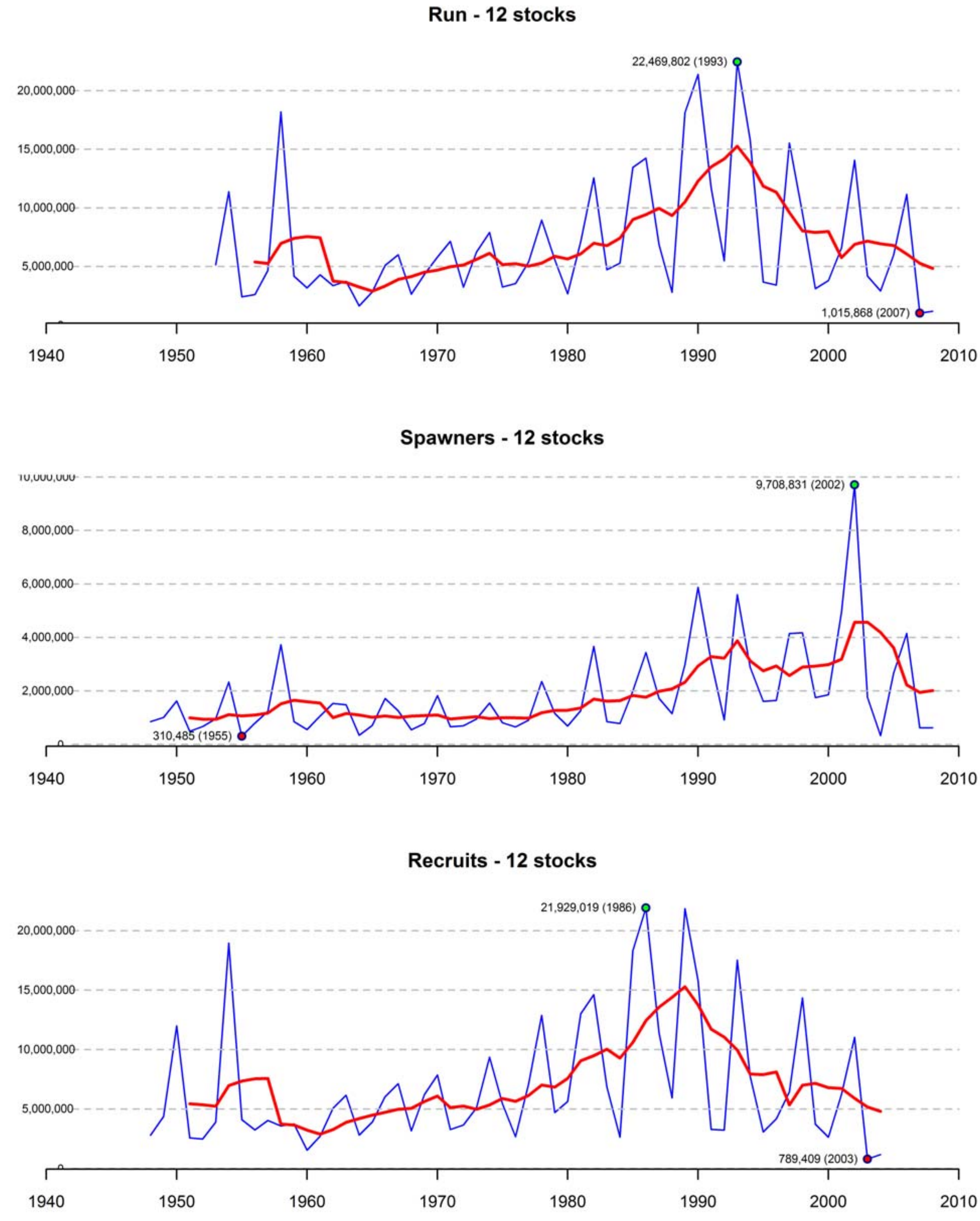


Figure 3: Total run, spawners, and recruitment for 12 stocks with long time series
*Note that run, spawners, and recruits are all for the same year (i.e. run returning that year, spawner abundance that year, and recruits produced by those spawners). Trend lines (in red) show 4-year running averages. Table 1 lists the component stocks (marked by *), and Appendix 3 lists the available data for each stock.*

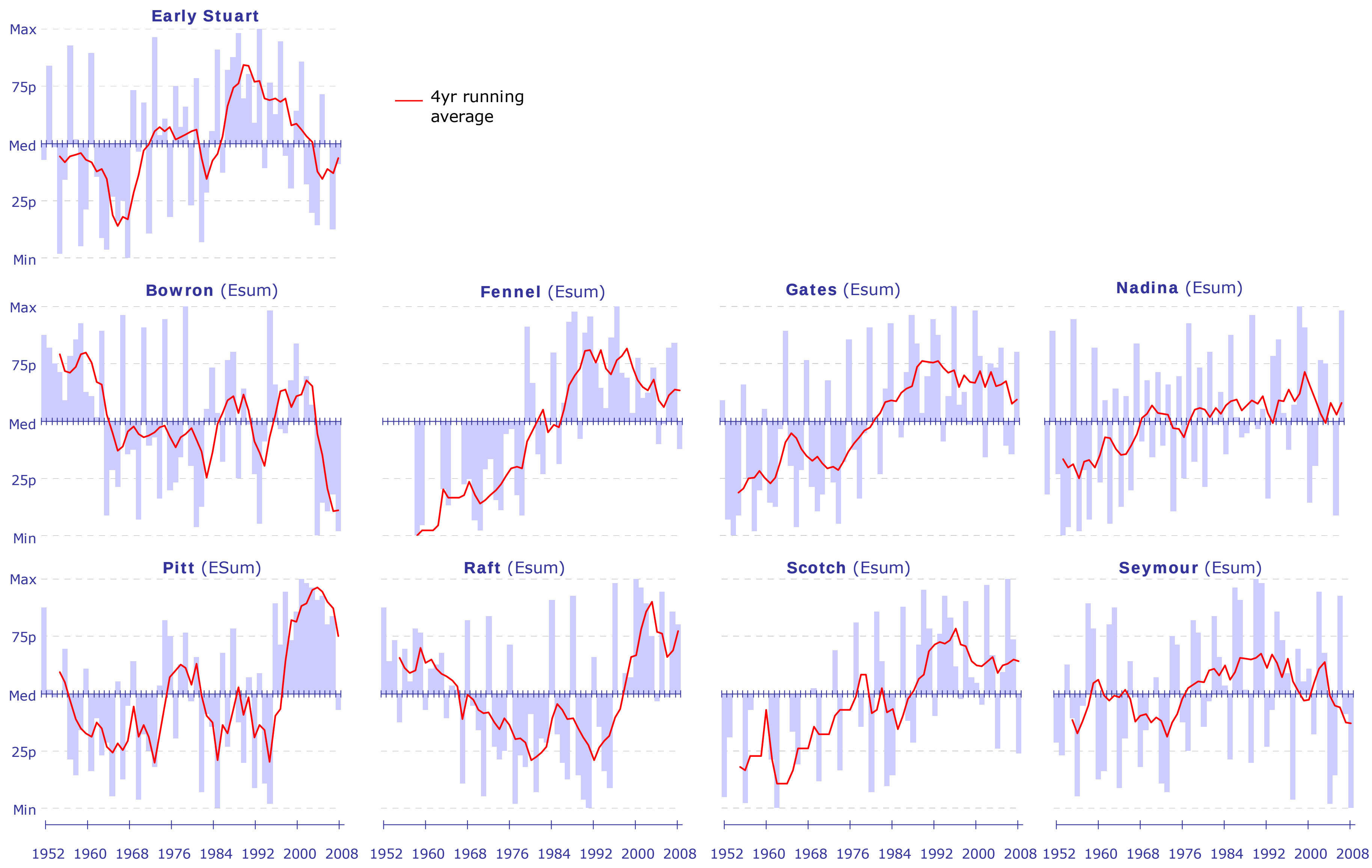


Figure 4: Stock-specific patterns in spawner abundance for Early Stuart and Early Summer
Each panel shows the observed pattern in total spawners, expressed as percent ranks to emphasize comparisons against the long-term median. The figures are analogous to a time series of log-scaled residuals, but with a more direct visual interpretation.

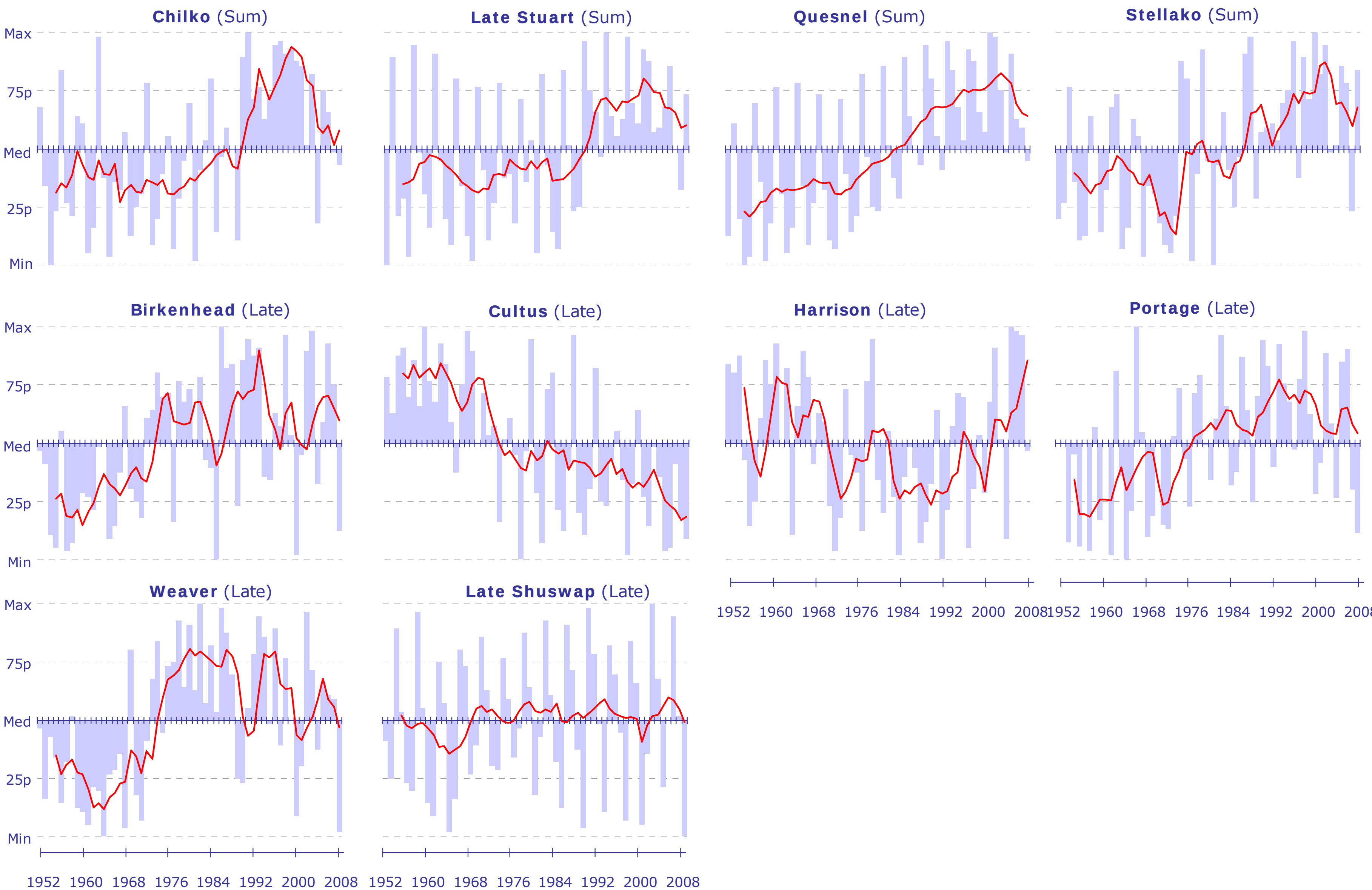


Figure 5: Stock-specific patterns in spawner abundance for Summer and Late run.
Each panel shows the observed pattern in total spawners, expressed as percent ranks to emphasize comparisons against the long-term median. The figures are analogous to a time series of log-scaled residuals, but with a more direct visual interpretation.

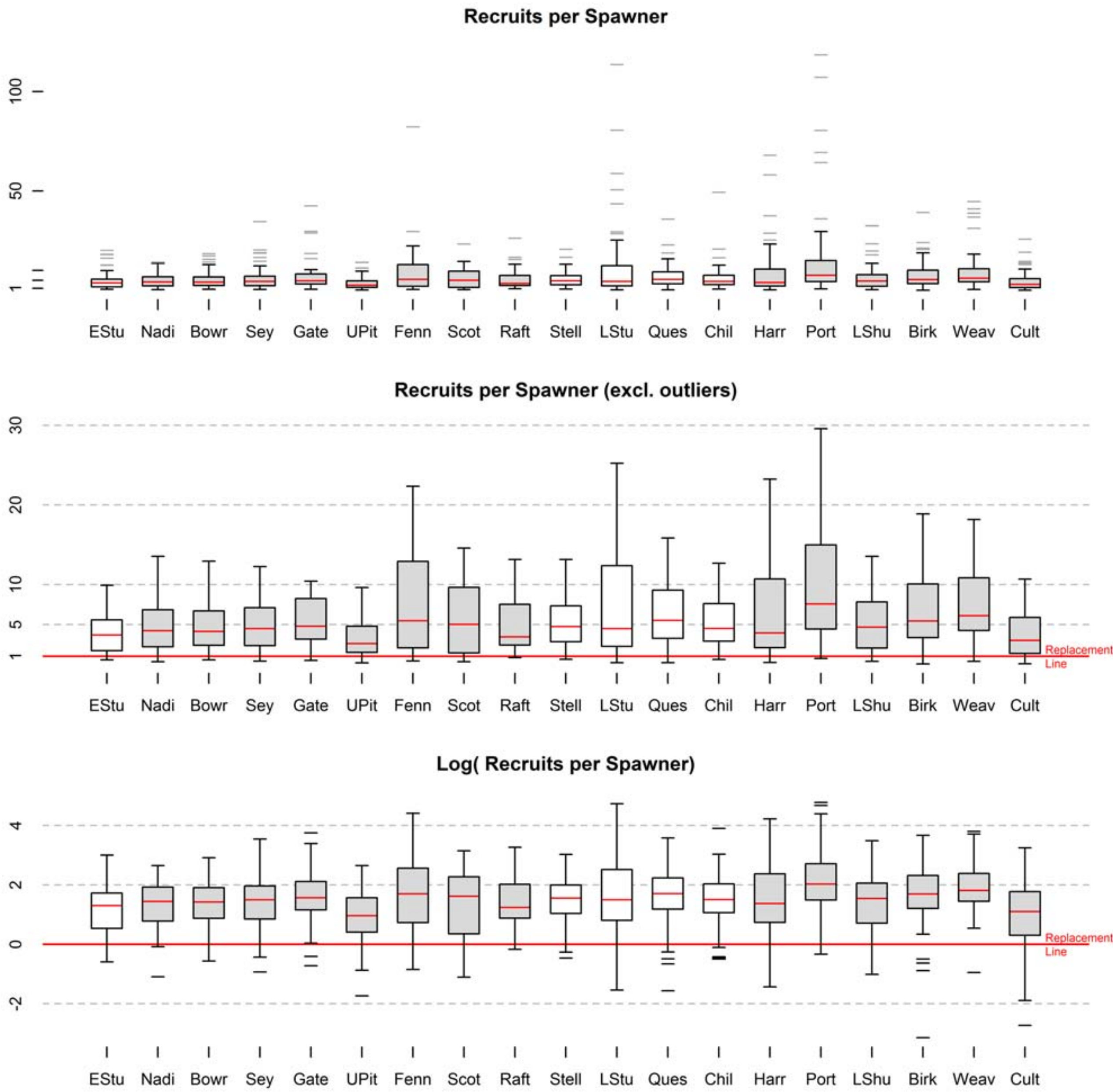


Figure 6: Distribution of observed productivity for 19 stocks of Fraser River sockeye salmon. *Boxes show the median and capture half of the observations. Whiskers mark the most extreme point within 1.5 box-lengths of the box. Stocks are sorted roughly in order of return timing. Management groups are marked by colour: Early Stuart (white), Early Summer (grey), Summer (white), Late (grey). Note that these ranges do not correct for density effects (i.e. SR fits).*

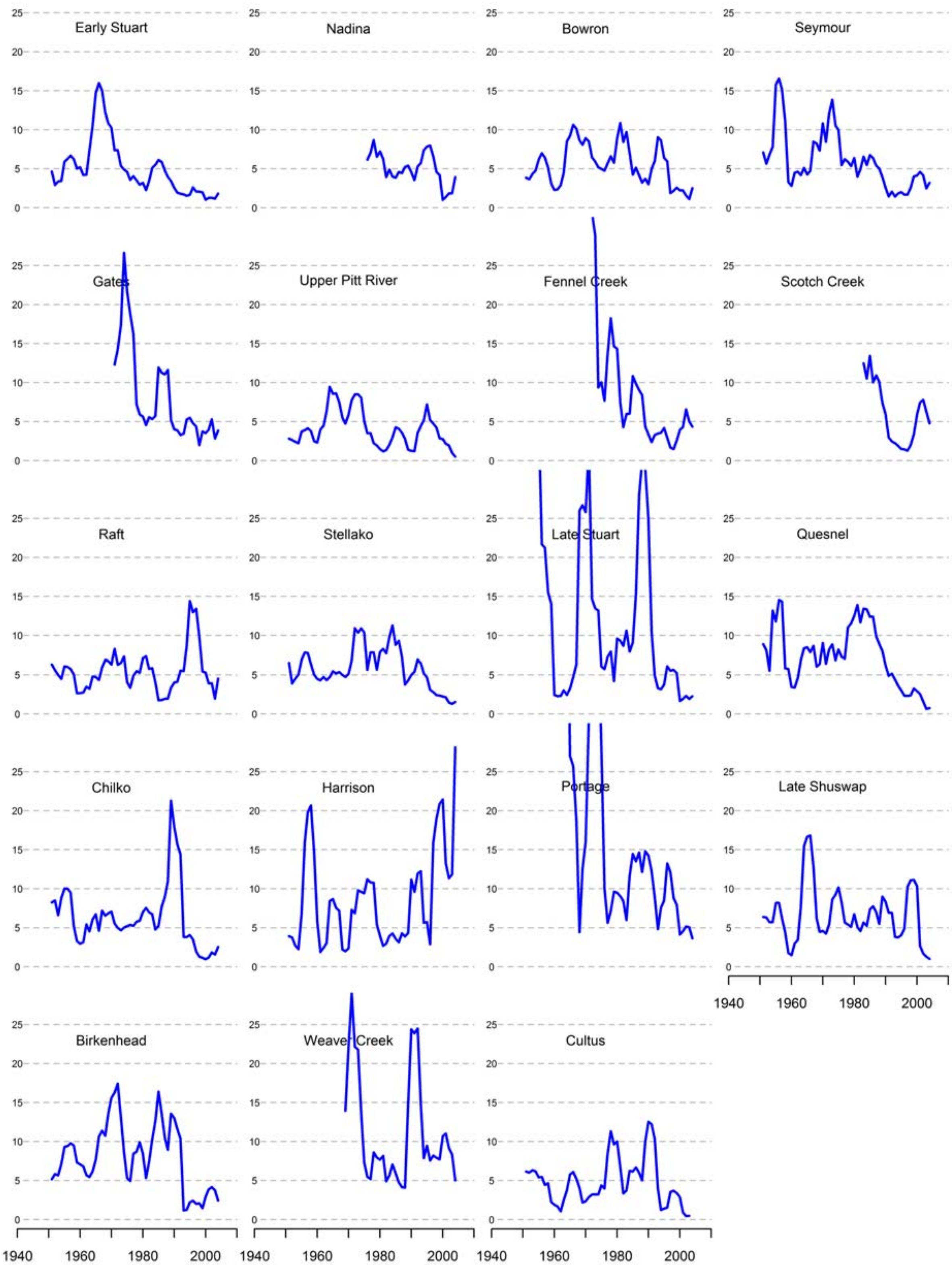


Figure 7: Stock-specific patterns in productivity for 19 stocks of Fraser River sockeye salmon. *Each panel shows the available estimates of 4-year running average of recruits/spawner from 1940 to 2010 (i.e. trend in generational average for the values in Figure 6). The most recent brood year in the data set is 2004. High outliers in the 4-year average are most likely due to estimation errors, and are cut off (Portage, Late Stuart). Note that individual outliers are not excluded from the calculation of 4-yr running average (e.g. early part of Fennel Creek time series pulled up by 1970 outlier). Appendix 4 shows the full time series for each stock. Note that these patterns do not separate out density effects (i.e. SR fits).*

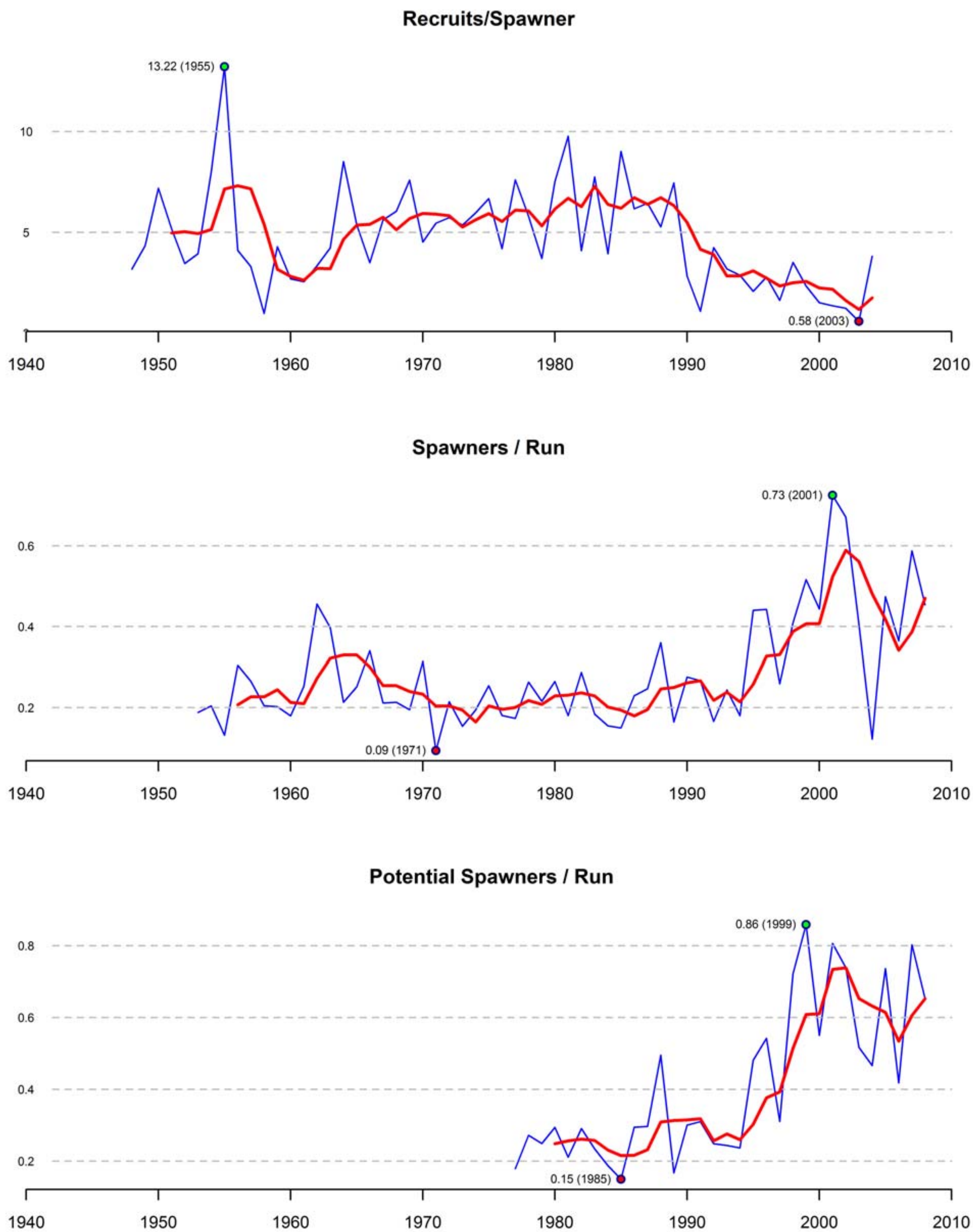


Figure 8: Aggregate patterns in productivity and harvest for Fraser River sockeye salmon. *Totals include all data available for a year, with more stocks included in the later part of the time series. Trend lines (in red) show 4-year running averages. Potential spawning escapement is reconstructed, based on estimated in-river mortality (Section 2.2.11). Note that the R/S pattern does not separate out density effects (i.e. SR fits).*

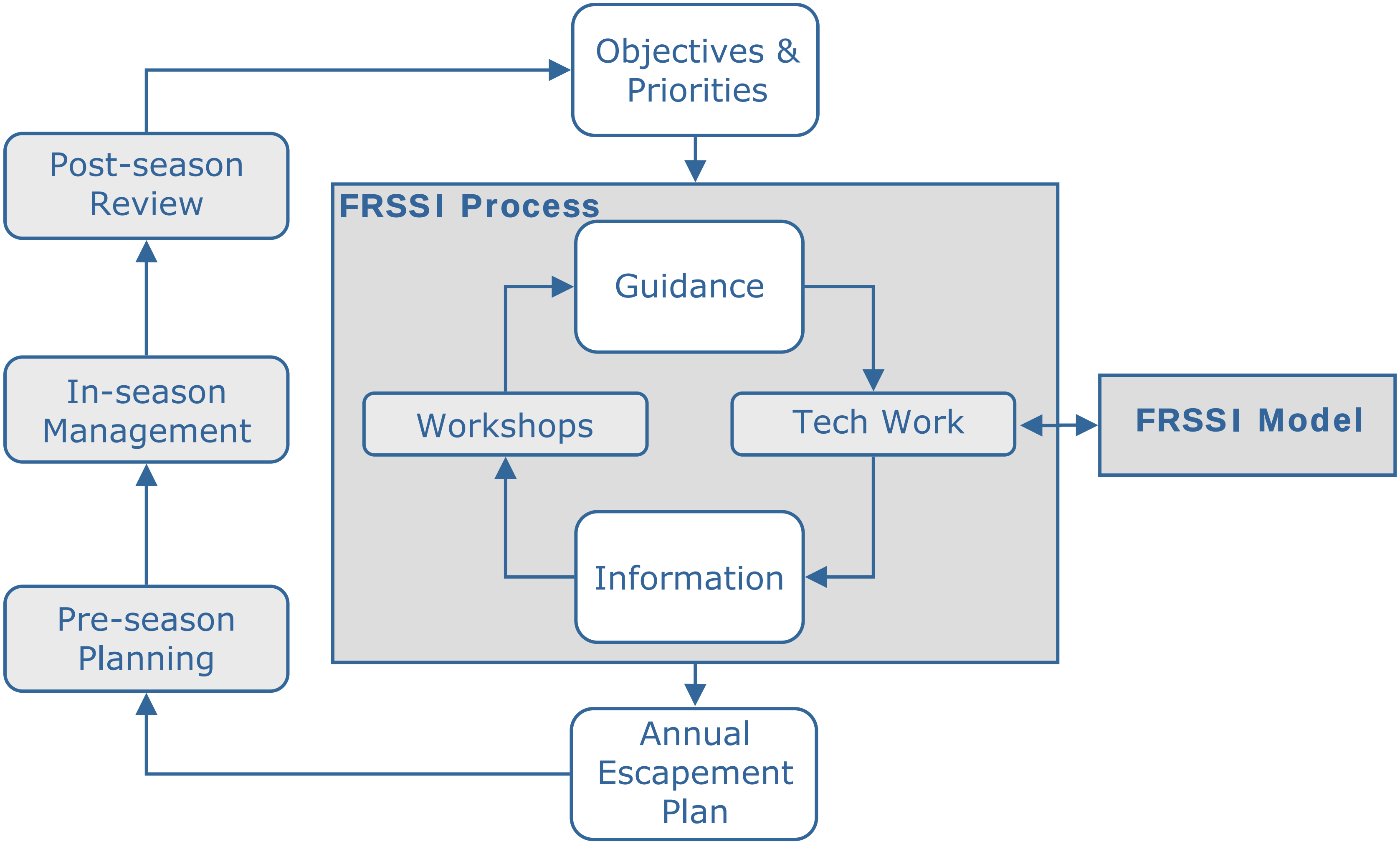


Figure 9: Flowchart of model contribution to annual planning process
The technical working group uses the FRSSI model to test alternative escapement strategies against a range of biological assumptions. The results support deliberations of workshop participants, which in turn help identify a suite of options for the annual escapement plan (Section 1.3). Note that the FRSSI model does not address annual implementation details, such as abundance estimates, migration conditions, or weekly fishing plans (Section 2.1.1)

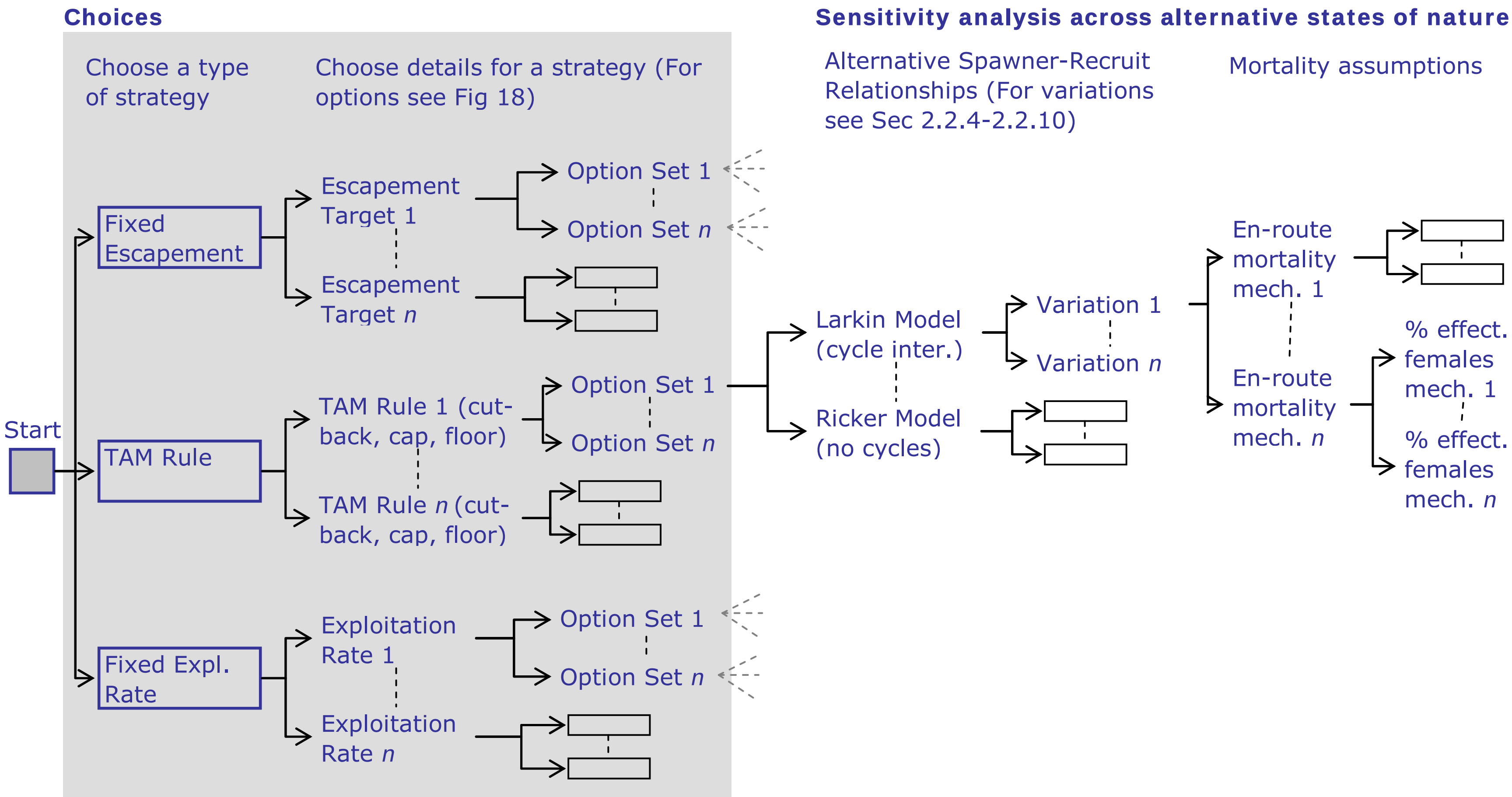


Figure 10: Overview of model options.

Alternative options in the model (i.e. user-specified settings) can be grouped into choices related to the management strategy (grey box) and assumptions about the high-level mechanisms intended to approximate major steps in the life history of Fraser sockeye (i.e. recruitment, en-route mortality, % effective females). Each path trough this decision tree constitutes one simulation scenario. At each fork in the path there are n possible variations (n varies; for example, fixed exploitation rate can be set to any number between 0% and 100%, but sample results in Section 3.3.2 are based on 5% increments up to 90%).

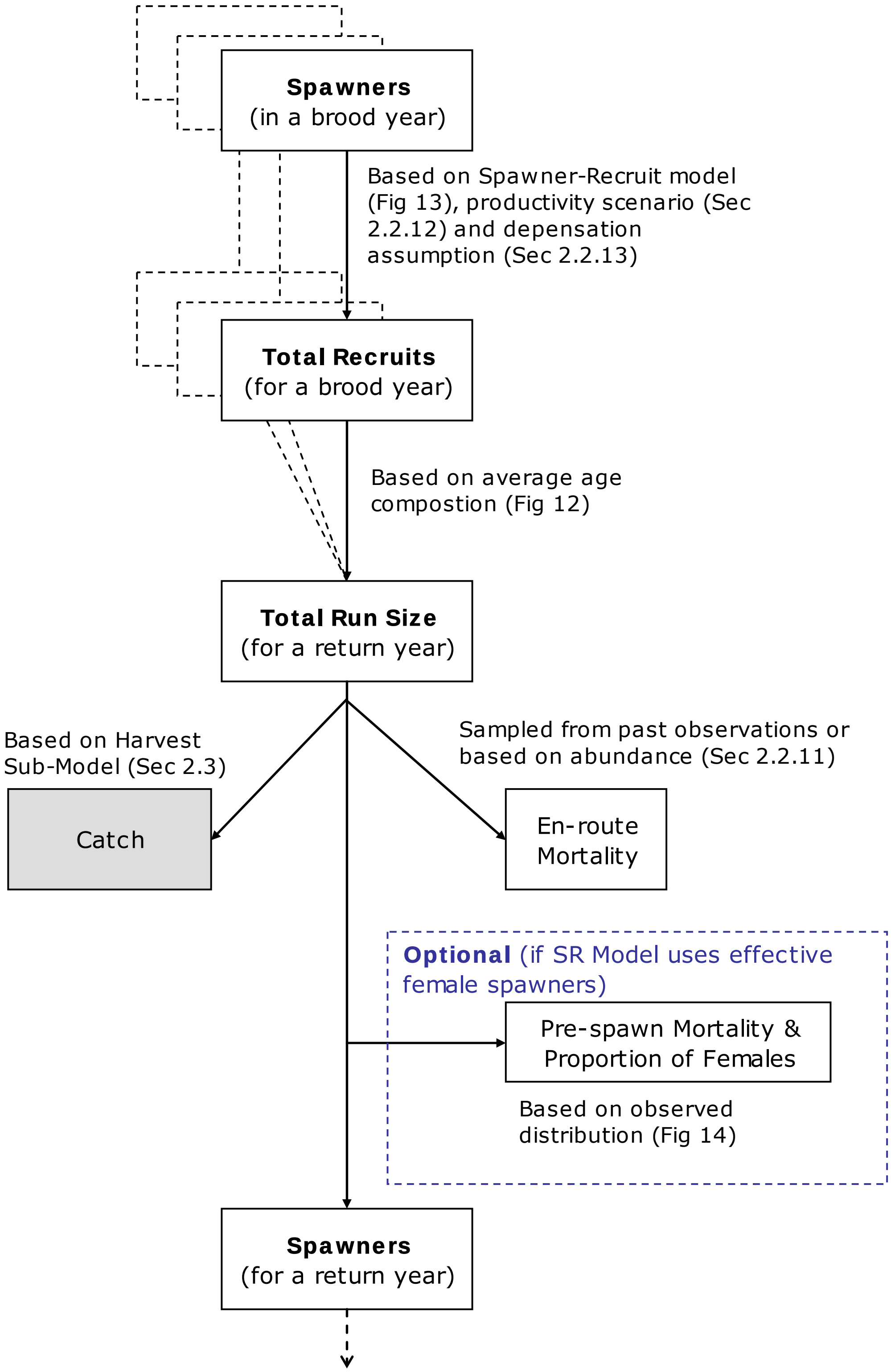


Figure 11: Overview of processes included in the model.

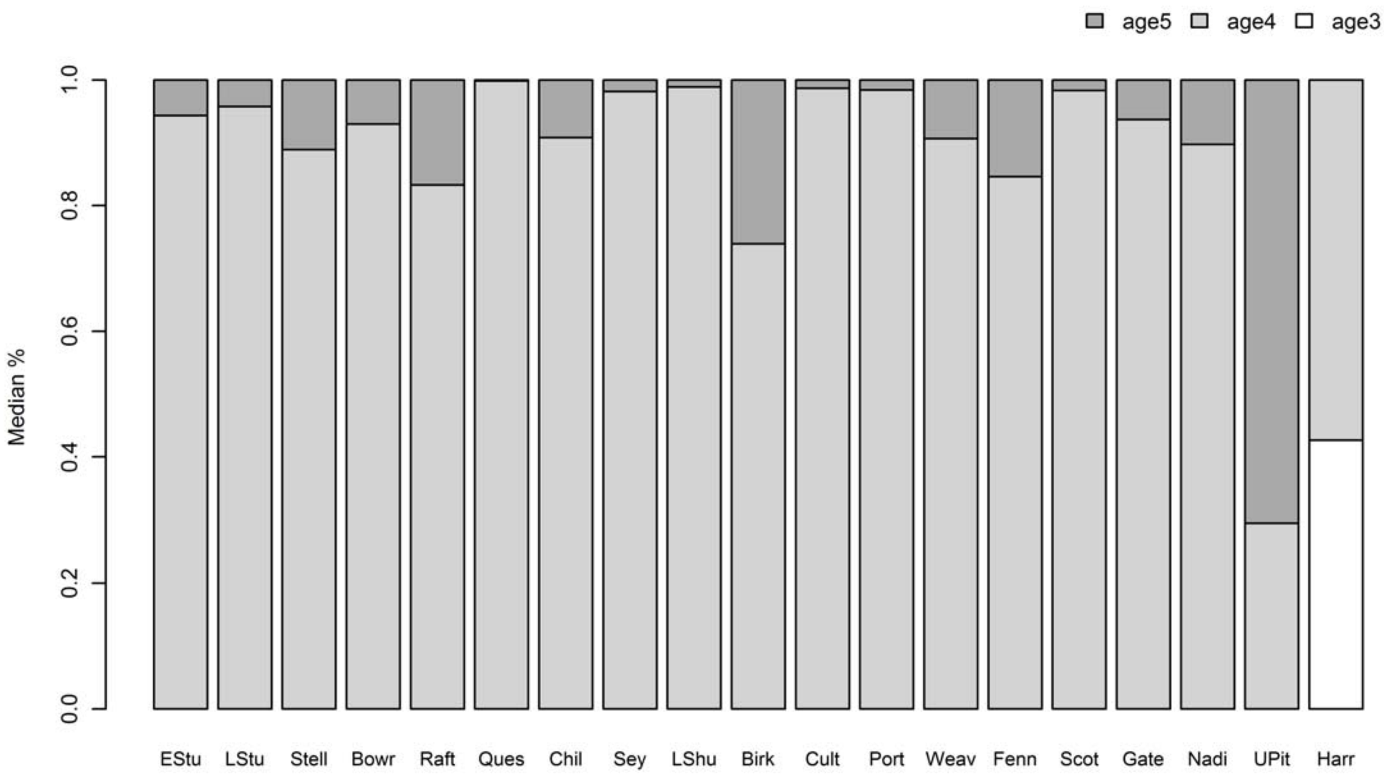
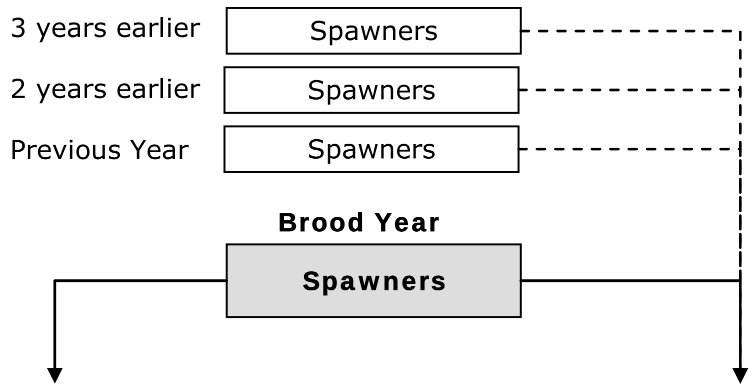


Figure 12: Age composition of recruitment for 19 stocks of Fraser River sockeye salmon.
Only the two predominant age classes are shown. Stocks are sorted by ID number (Table 1)



Ricker Model

<u>Characteristics:</u>
- steepest at origin ("intrinsic growth rate")
- dome shape (R/S declines at larger S)
- no effect of previous years' S

<u>Distinguishing feature:</u>
Assumes that all year lines have the same capacity and are independent of each other. Cyclic patterns were propagated by harvest patterns, and current off-cycles can rebuild.

<u>Need to estimate **2** parameters:</u>
- productivity at low run size(α)
- density effect in brood year (β0)

Larkin Model

<u>Characteristics:</u>
- steepest at origin ("intrinsic growth rate")
- dome shape (R/S declines at larger S)
- influenced by previous years' S

<u>Distinguishing feature:</u>
Assumes that year lines influence each other. Cyclic patterns can be due to lagged density effects, but can be exaggerated by harvest patterns.

<u>Need to estimate **up to 5** parameters:</u>
- productivity at low run size(α)
- density effect in brood year (β0)
- density effect - previous year (β1)
- density effect - 2 years ago (β2)
- density effect - 3 years ago (β3)

$$\underbrace{\overbrace{Log(R/S) = \alpha - \beta_0 S_0}^{\text{Ricker Model}} - \beta_1 S_{-1} - \beta_2 S_{-2} - \beta_3 S_{-3}}_{\text{Larkin Model}}$$

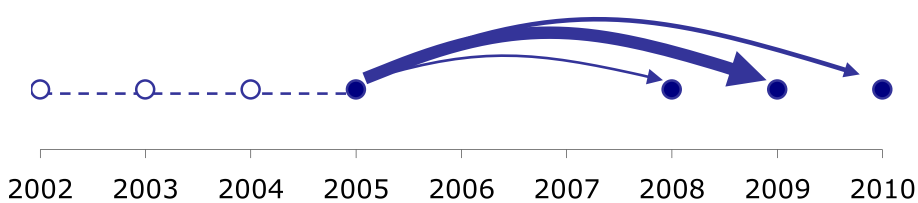


Figure 13: Comparison of spawner-recruit models currently available in the model.

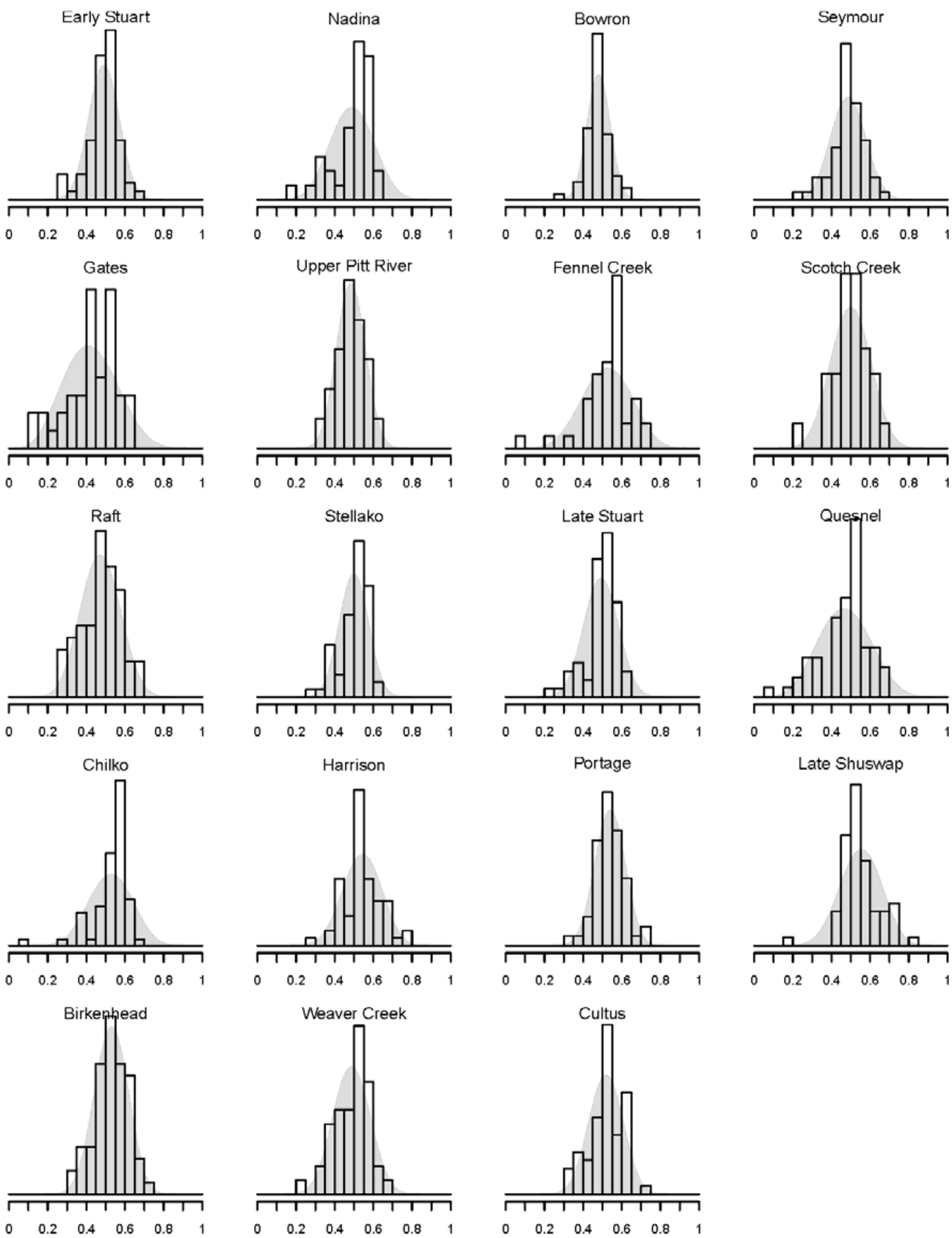


Figure 14: Observed and estimated distributions for proportion of effective female spawners.
Simulations use maximum-likelihood fit to beta distribution (Section 2.2.4)

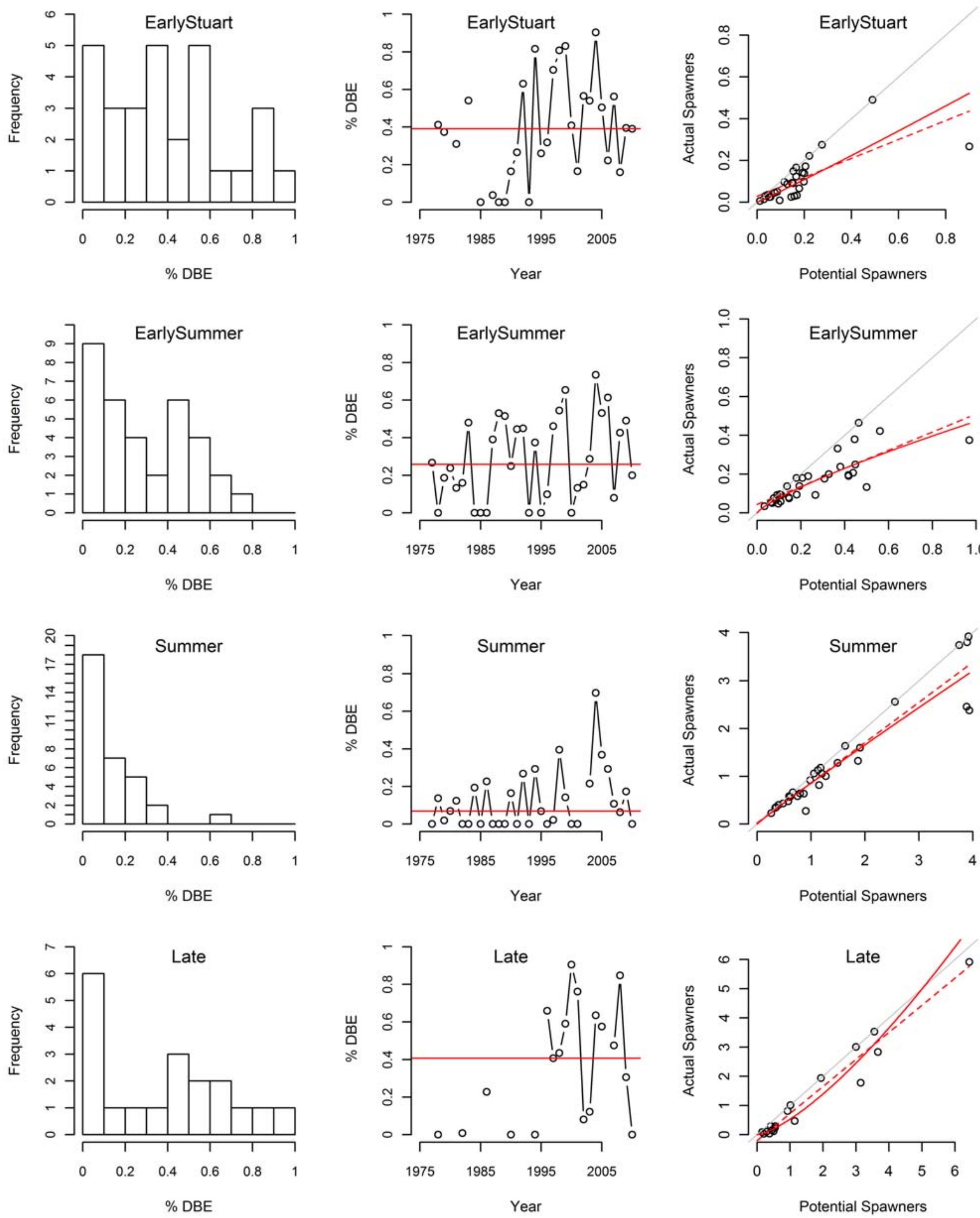


Figure 15: Patterns in difference between estimates (DBE) of potential and actual spawners.
The three panels for each management group show observed frequency (left) and time trend (middle) in observed % DBE, and a scatterplot (right) of actual vs. potential spawning escapement. Simple linear (dashed line) and log-linear (solid line) regression fits are included.

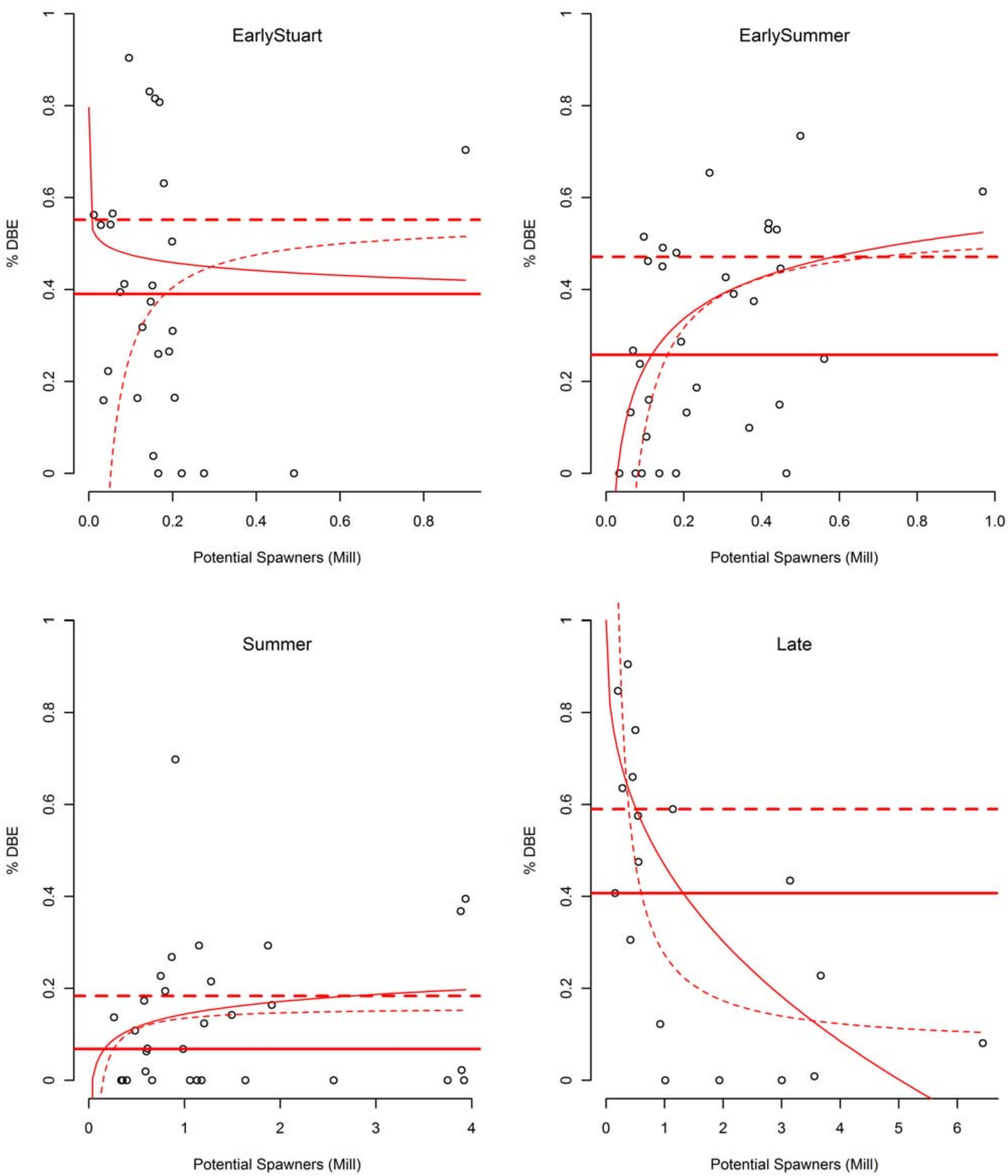


Figure 16: Four alternative assumptions about % DBE used in forward simulations.
The base case samples from the observed distribution of % DBE (median shown by thick solid line), with the alternative option to only sample from the worse half of the observations (median = thick dashed line). To reflect the possibility that harvest patterns influence the future distribution of % DBE, two additional options are included based on the linear (thin dashed line) and loglinear (thin solid line) fits shown Figure 15.

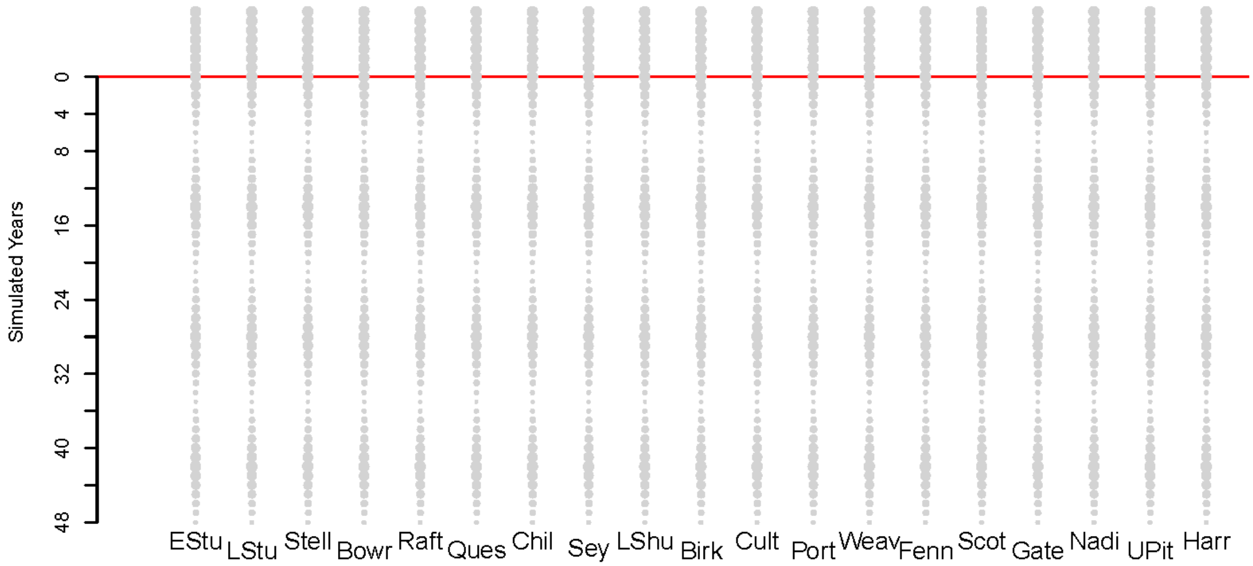


Figure 17: Sample pattern in productivity

The model allows users to specify hypothetical patterns of future productivity for each stock. One sample pattern with regular periods of reduced productivity is shown as an illustration. Larger dots indicate productivity closer to past observations. Initial seeding of forward simulations uses "like the past".

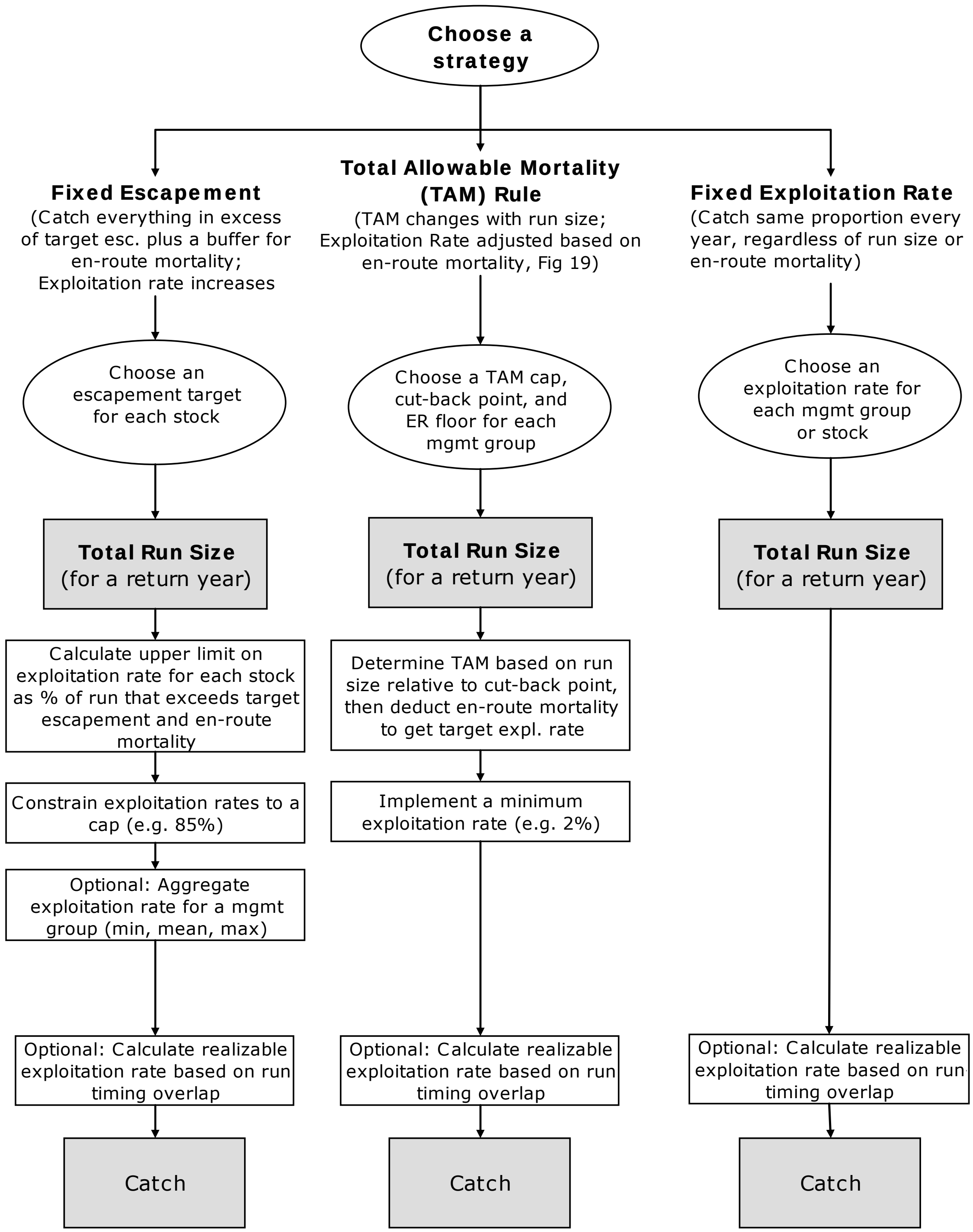


Figure 18: Flowchart of alternative management strategies.

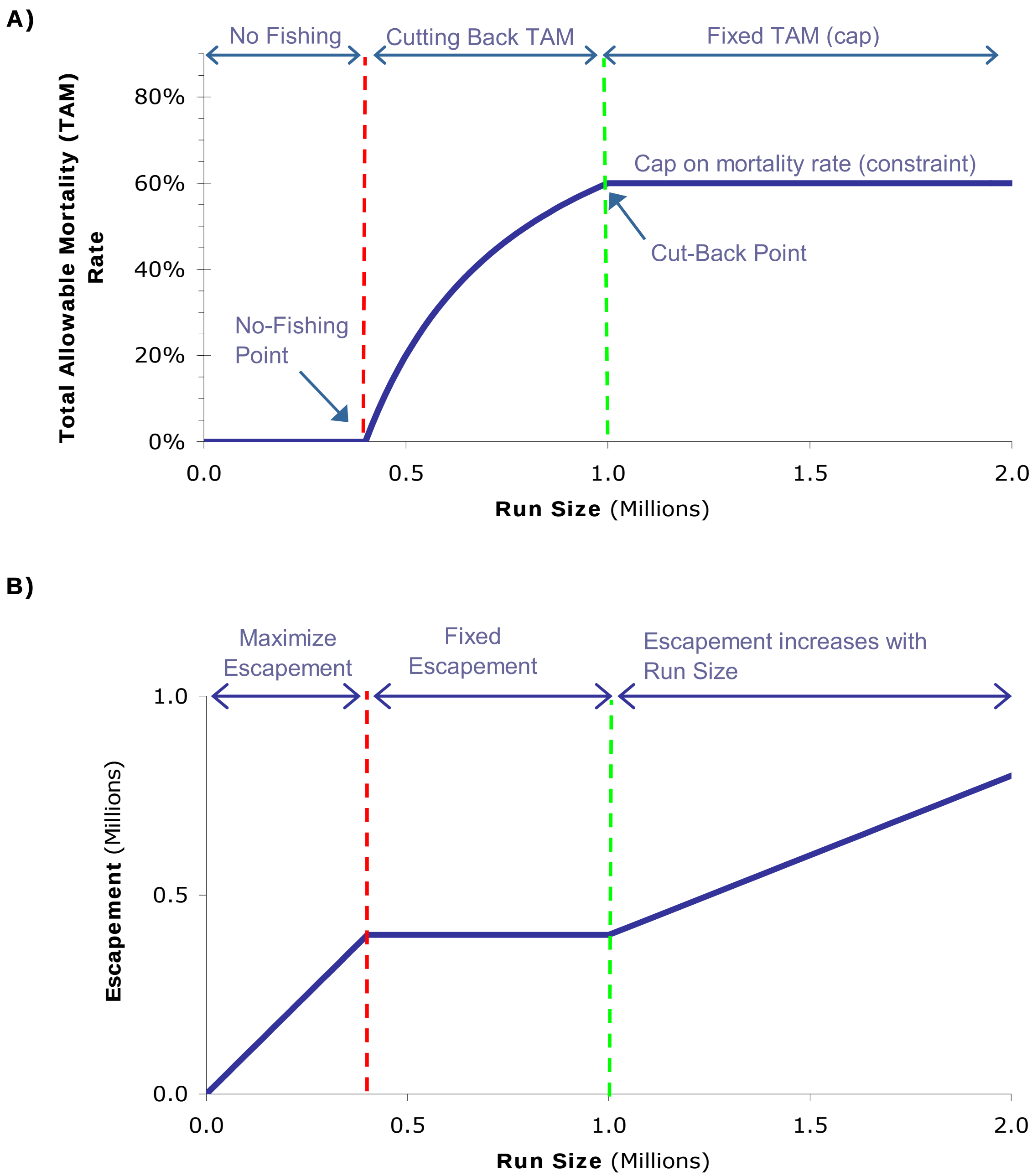


Figure 19: Shape of Total Allowable Mortality (TAM) rule.
Note: Optional floors on exploitation rate (e.g. 2%) are applied after the TAM rule, and are not shown on this figure.

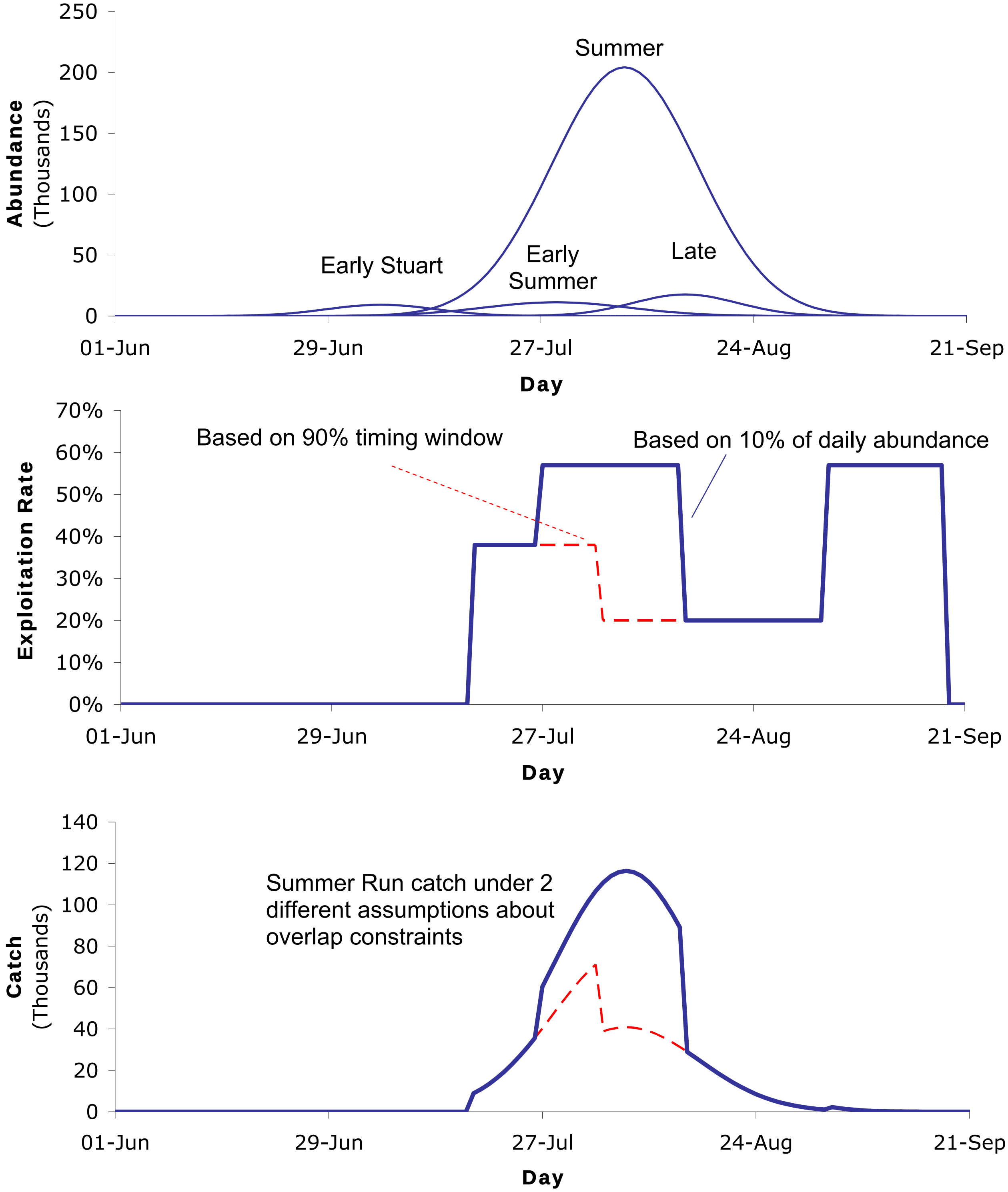


Figure 20: Two options for approximating the harvest constraint due to timing overlap.
The top panel shows simulated run sizes for the 4 management groups in one year in one of the simulation trajectories, converted to a timing curve based on average timing and spread in Area 20. The panels below show the realizable exploitation rate and catch under 2 alternatives for approximating overlap constraint (Section 2.3.2)

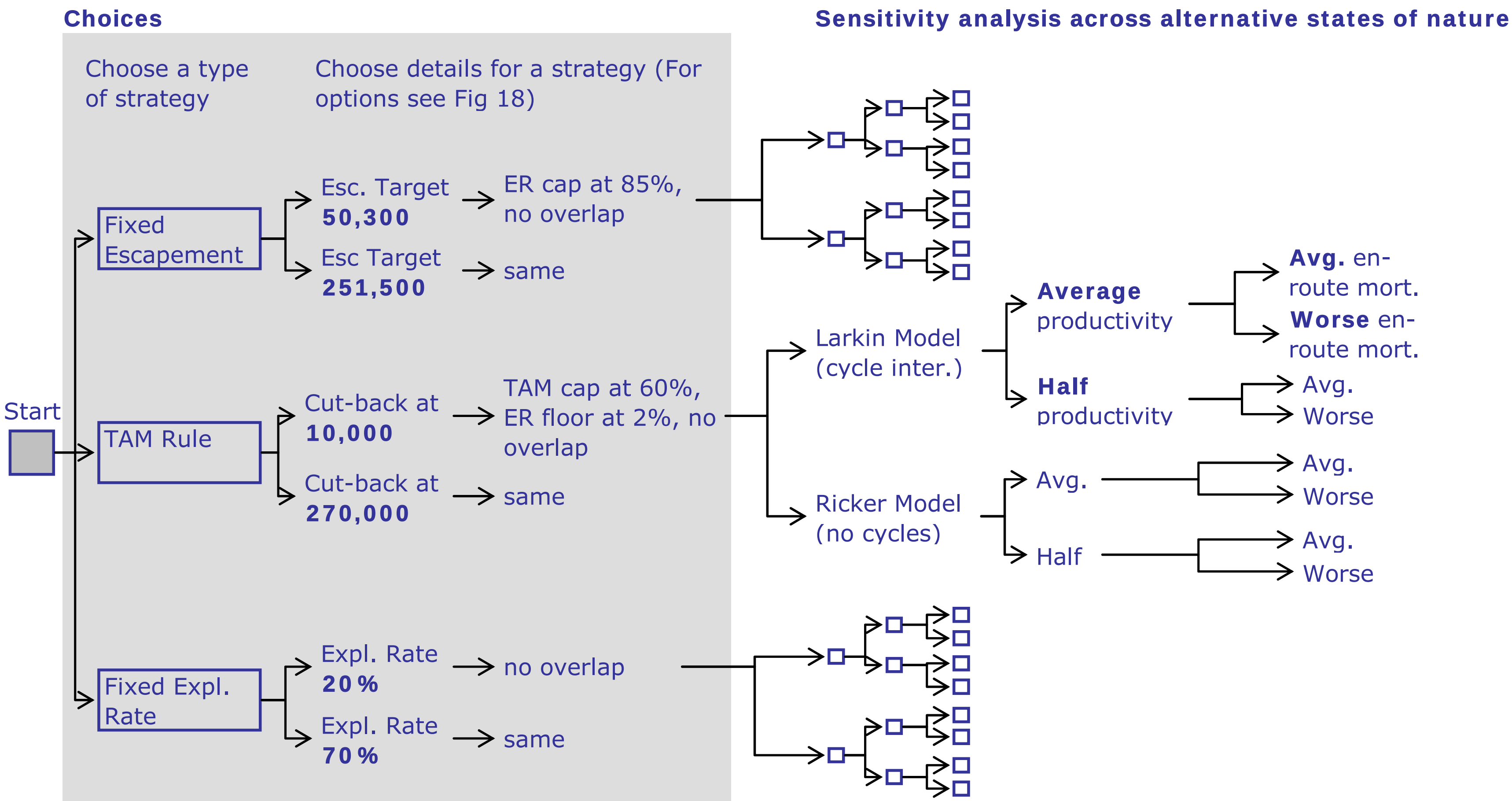


Figure 21: Sample decision tree for Early Stuart.
As an illustration, imagine that a multi-stakeholder working group has identified 2 options for each of the 3 types of escapement strategy under each of 8 different states of nature (i.e. sets of biological assumptions). Each scenario is evaluated in 1,000 forward simulations over 48 years using different spawner-recruit (SR) parameter estimates to capture uncertainty. Comparisons of simulated performance can then inform discussions among the working group about the merits and drawbacks of alternative choices.

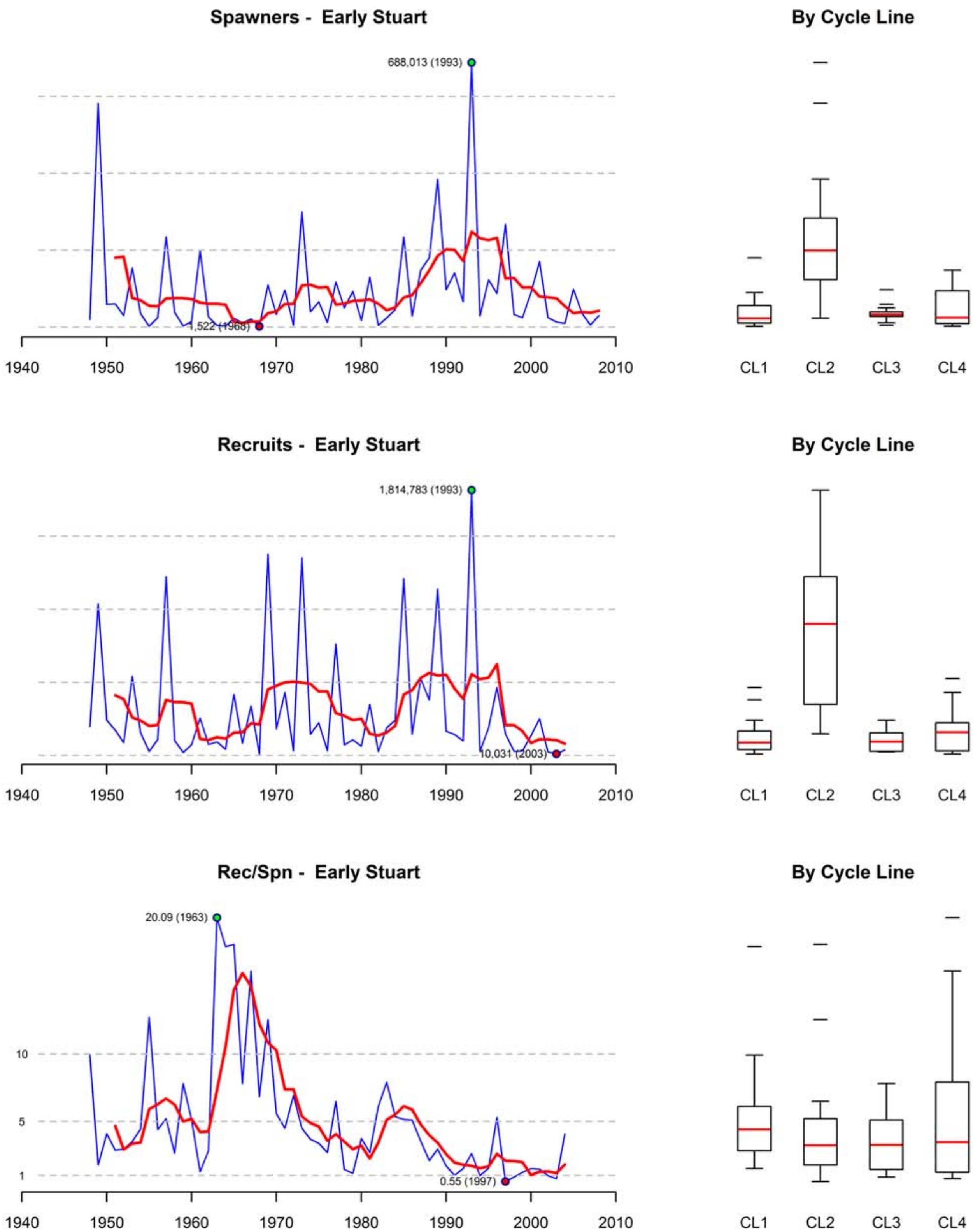


Figure 22: Early Stuart – Spawner-recruit data
Trend lines (in red) show 4yr running averages. Box plots show the range of observations for each 4yr cycle line. Appendix 3 lists the data. Appendix 4 includes the same figure for the other 18 stocks.

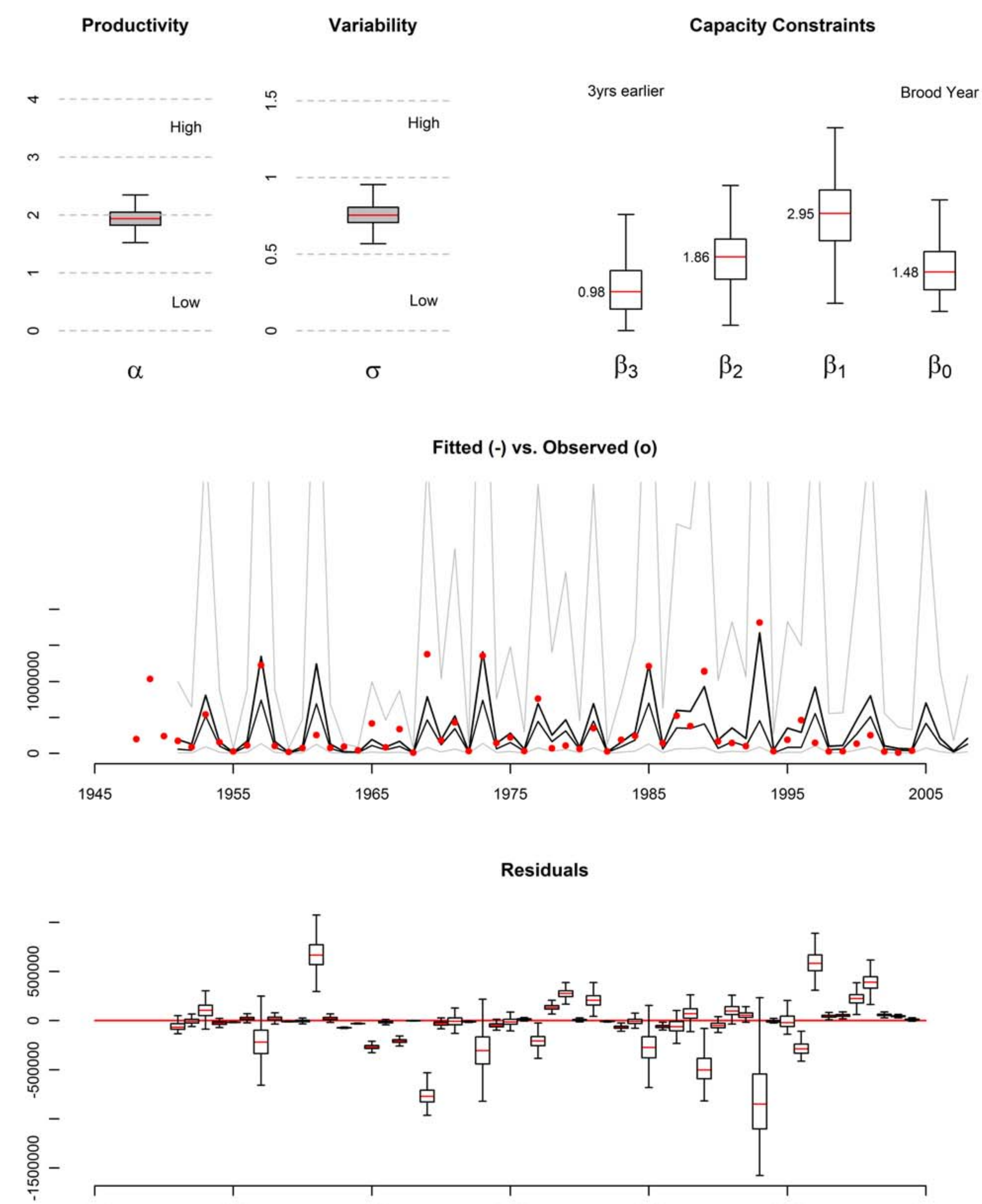


Figure 23: Early Stuart – Larkin fit parameters (3 lag terms)
Top row shows estimates for parameters in a full Larkin mode using total spawners. The middle panel shows observed recruitment (dots), recruitment modelled using alternative parameter estimates (thick lines) and uncertainty bands (thin lines). Bottom panel shows residuals (modelled – observed recruits).

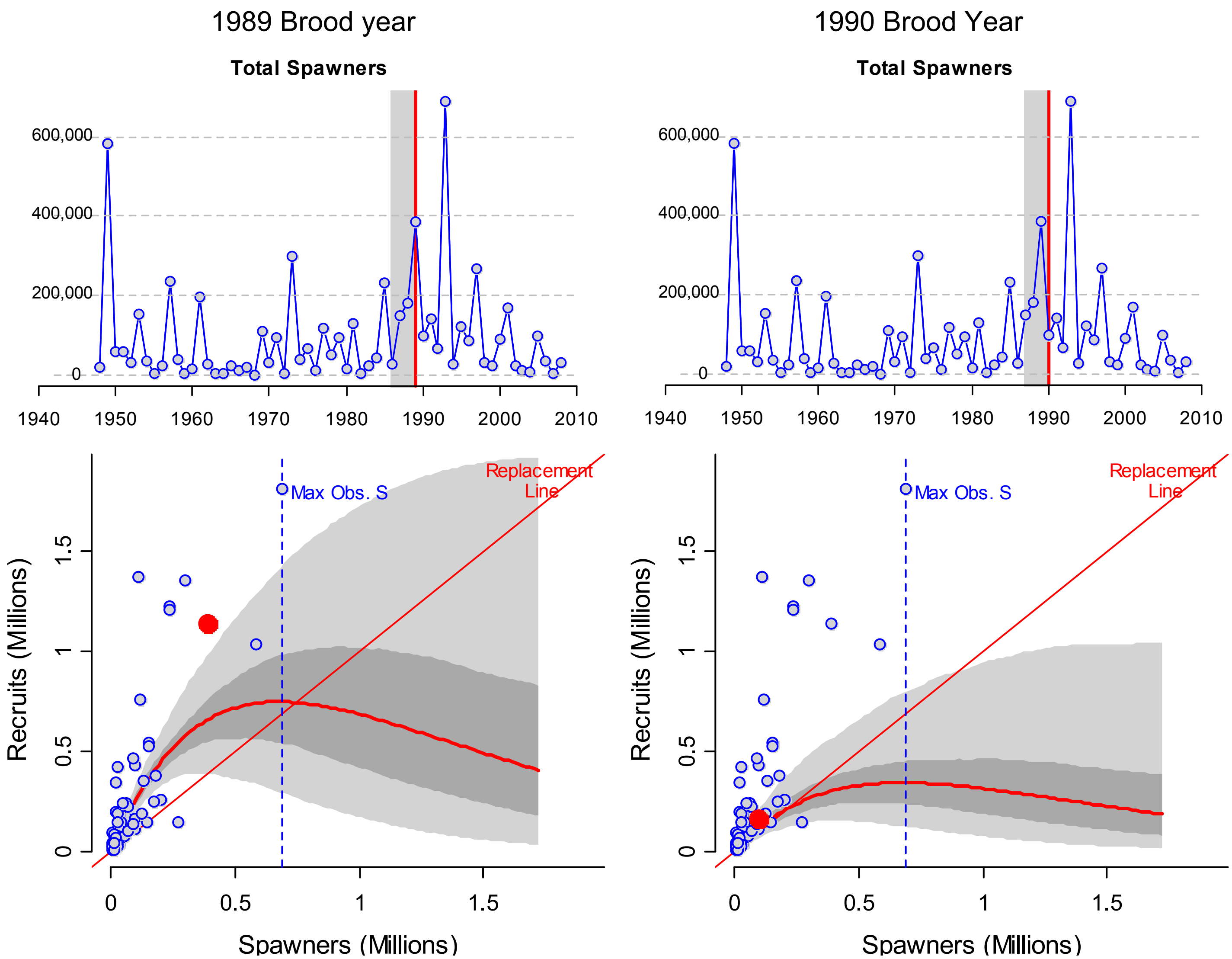


Figure 24: Early Stuart – Larkin fit recruitment curves (3 lag terms) for 2 brood years.
Recruitment curves in the bottom panels show the median (thick red line), 50% of the distribution (dark gray shading), and 90% of the distribution to capture uncertainty in parameter estimates. For context, the figures show observed data (red point in bottom panels, vertical lines in top panels), and a replacement line with 1 recruit / spawner. Recruitment curves shift depending on the spawner abundances observed in the 3 previous years (gray shading in top panels).

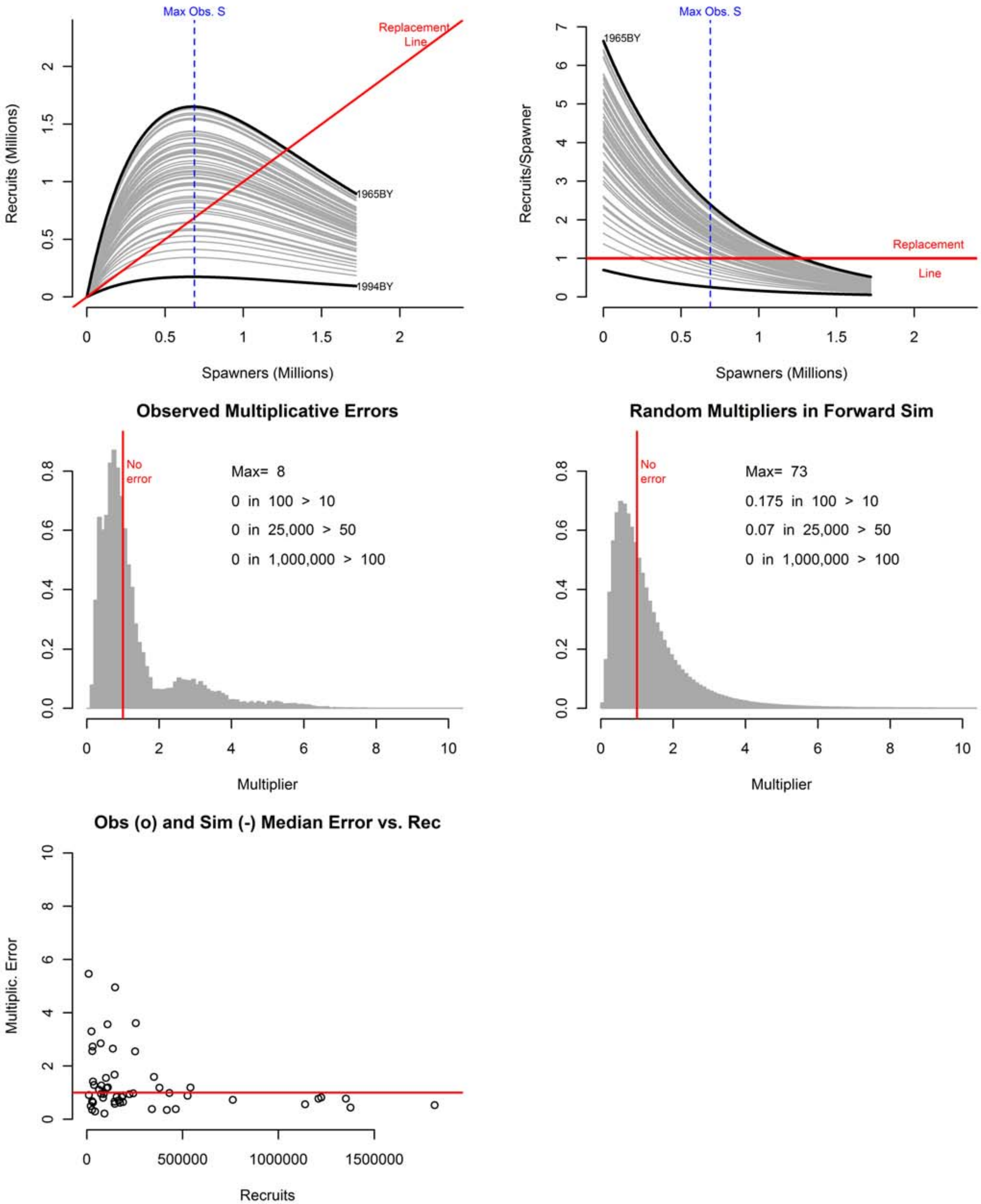


Figure 25: Early Stuart – Larkin fit diagnostics (3 lag terms)
Top row shows the recruitment curves for each year (i.e. modeled recruitment at different levels of spawner abundance). Recruitment curves shift depending on spawner abundance in the three previous years, as illustrated in Figure 24. Remaining diagnostics plots show error distributions. Note: Spawners = Total Spawners.

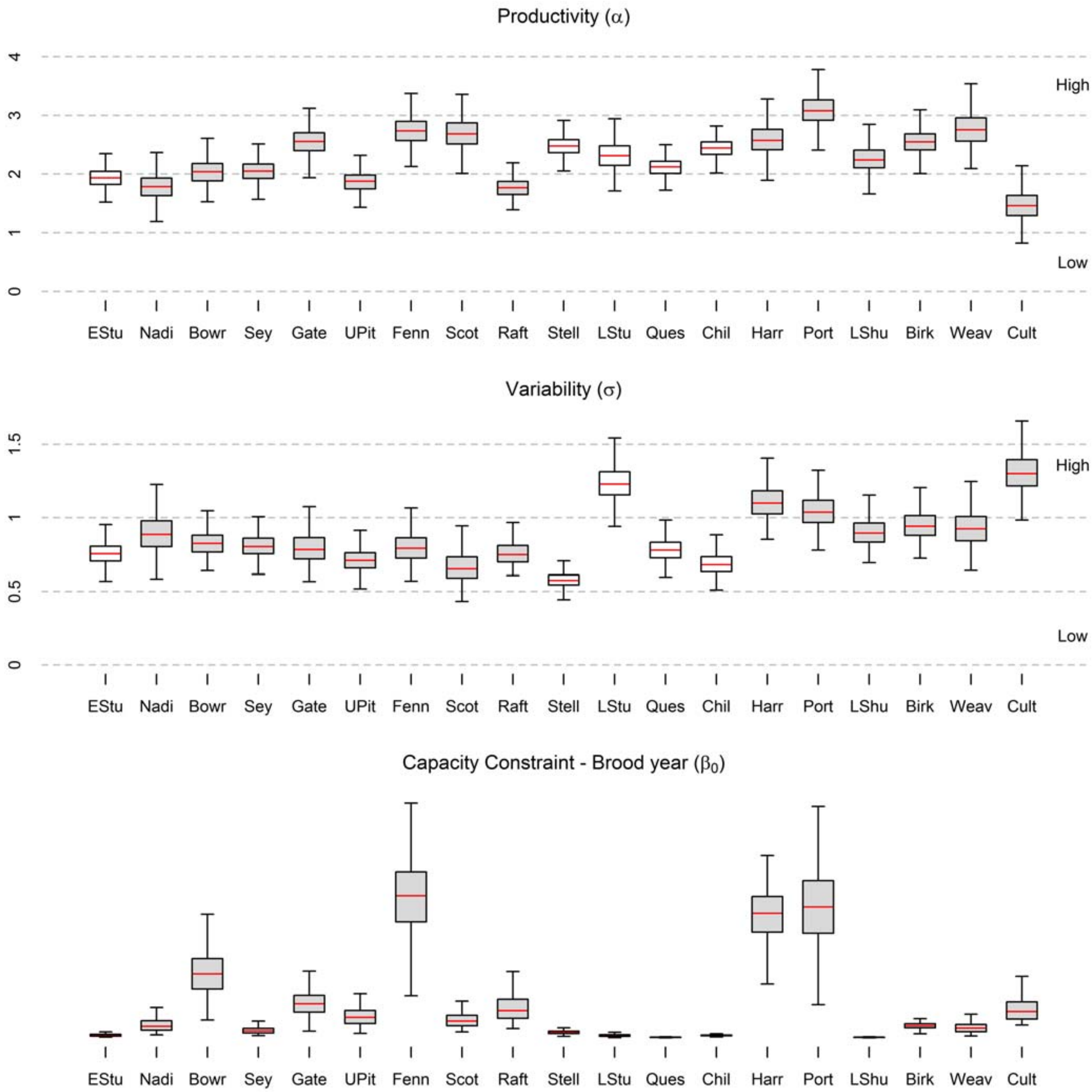


Figure 26: Parameter estimates for productivity, variability, and capacity – Larkin (3 lag terms)
Distributions show 500 parameter sets sampled from the Bayesian posterior distribution (Section 2.2.5), based on log-normal priors for β0 and uniform priors for the other β parameters. Boxes show the median and capture half of the sample. Whiskers mark the most extreme point within 1.5 box-lengths of the box. Stocks are sorted roughly in order of return timing. Management groups are marked by colour: Early Stuart (white), Early Summer (grey), Summer (white), Late (grey). All estimates using total spawner abundance.

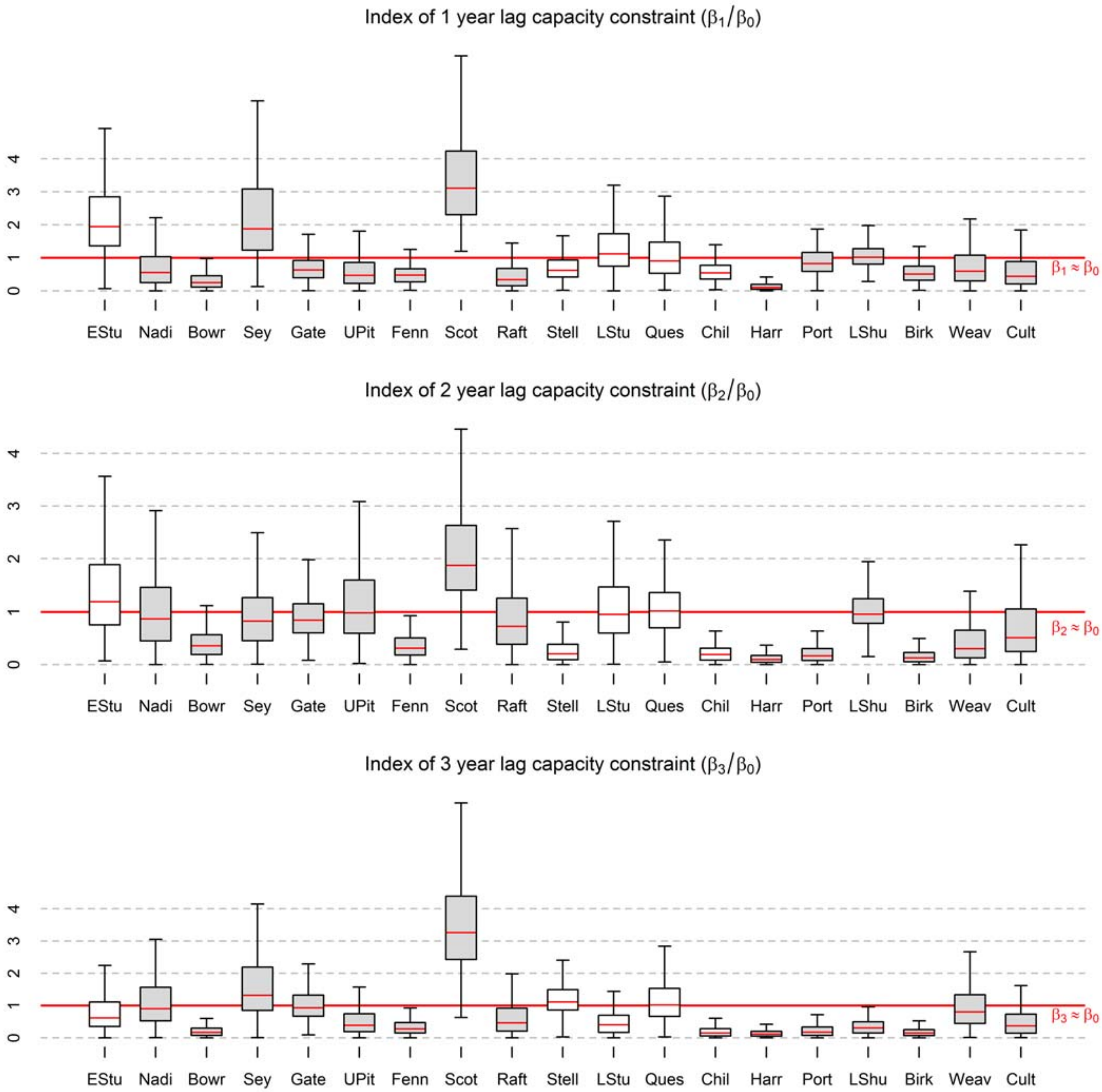


Figure 27: Parameter estimates for delayed-density effects - Larkin (3 lag terms)
Distributions show 500 parameter sets sampled from the Bayesian posterior distribution (Section 2.2.5), based on log-normal priors for β0 and uniform priors for the other β parameters. Lag terms are scaled relative to β0. Boxes show the median and capture half of the sample. Whiskers mark the most extreme point within 1.5 box-lengths of the box. Stocks are sorted roughly in order of return timing. Management groups are marked by colour: Early Stuart (white), Early Summer (grey), Summer (white), Late (grey). All estimates using total spawner abundance.

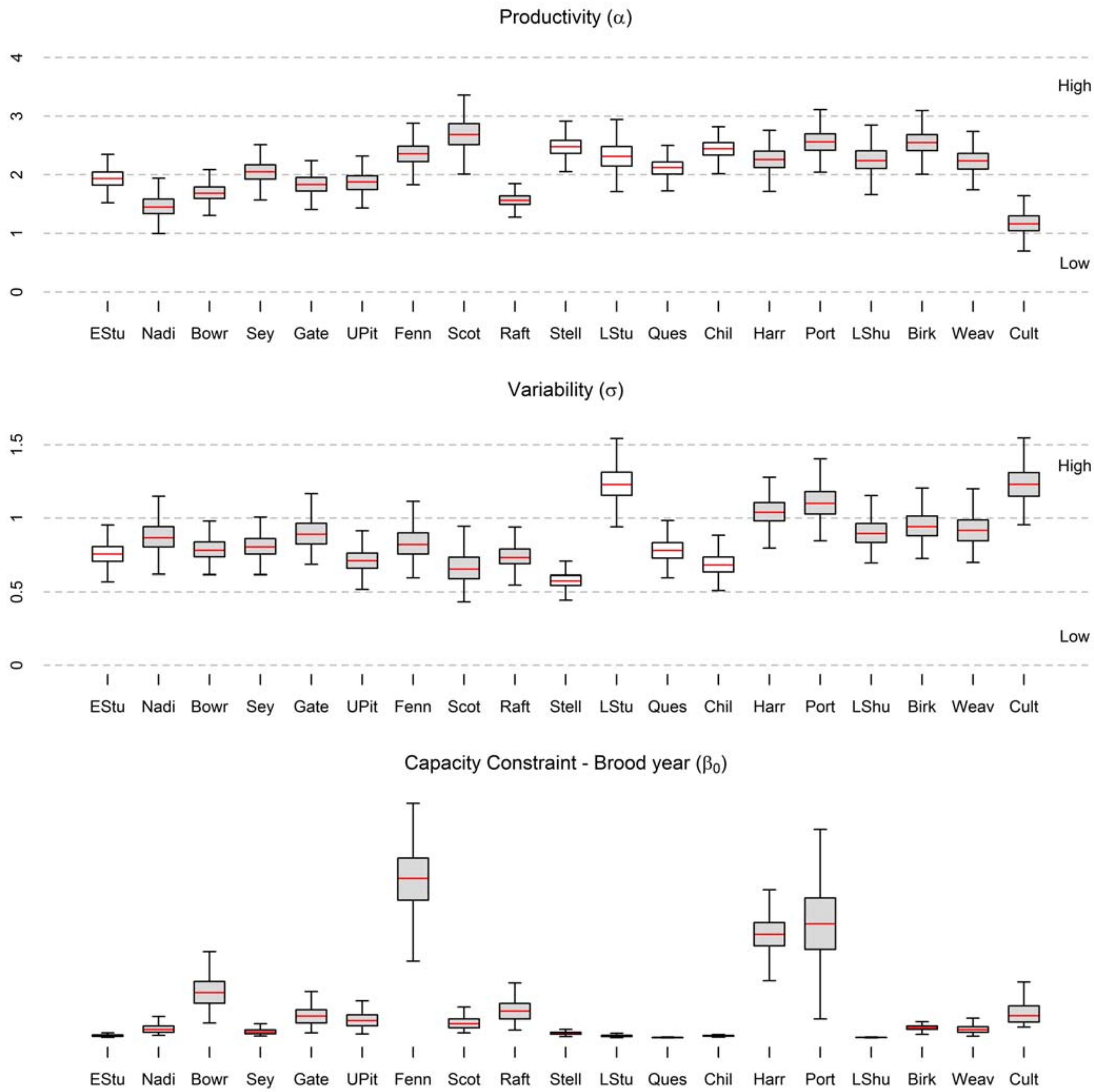


Figure 28: Parameter estimates for productivity, variability, and capacity – Mixed model forms
Distributions show 500 parameter sets sampled from the Bayesian posterior distribution (Section 2.2.5), based on log-normal priors for β0 and uniform priors for the other β parameters. Boxes show the median and capture half of the sample. Whiskers mark the most extreme point within 1.5 box-lengths of the box. Stocks are sorted roughly in order of return timing. Management groups are marked by colour: Early Stuart (white), Early Summer (grey), Summer (white), Late (grey). All estimates using total spawner abundance. Model forms as in Table 4.

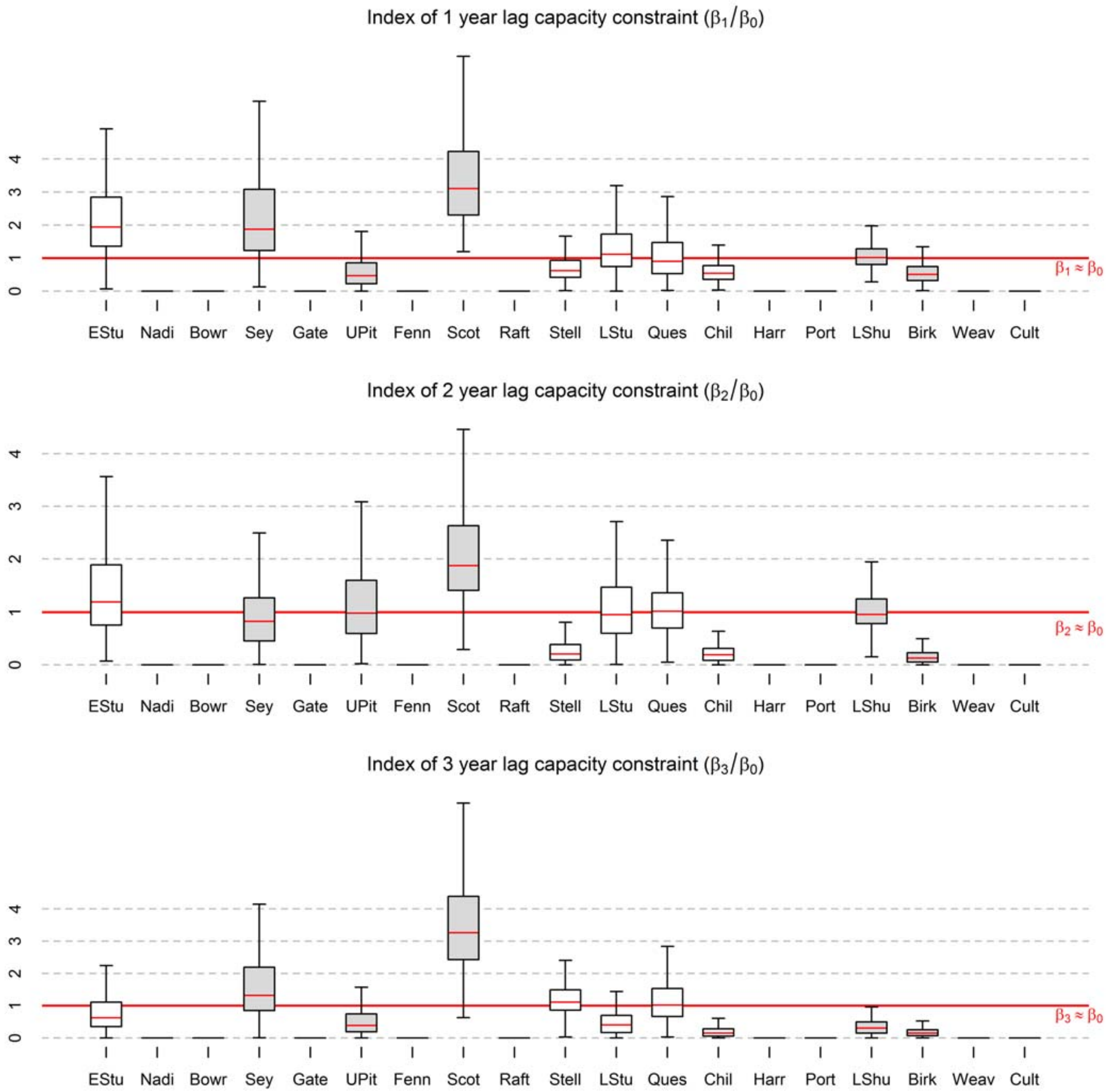


Figure 29: Parameter estimates for delayed-density effects – Mixed model forms

Distributions show 500 parameter sets sampled from the Bayesian posterior distribution (Section 2.2.5), based on log-normal priors for β0 and uniform priors for the other β parameters. Lag terms are scaled relative to β0. Boxes show the median and capture half of the sample. Whiskers mark the most extreme point within 1.5 box-lengths of the box. Stocks are sorted roughly in order of return timing. Management groups are marked by colour: Early Stuart (white), Early Summer (grey), Summer (white), Late (grey). All estimates using total spawner abundance. Model forms as in Table 4.

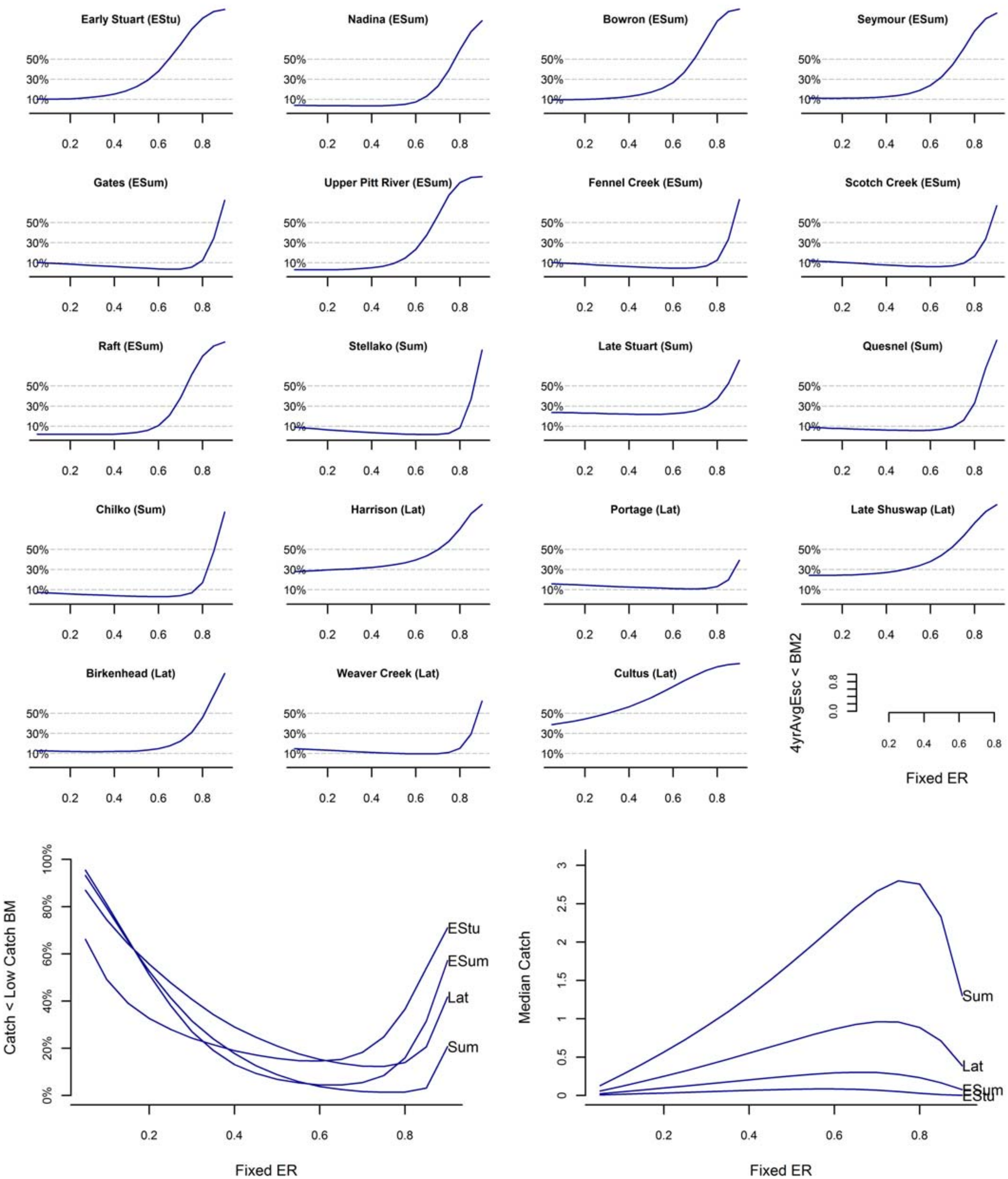


Figure 30: Changing fixed exploitation rates

The top five rows show Prob(4yr Avg Esc < BM2) for each stock, with BM 2 listed in Table 1. Bottom left panel show Prob(Catch < Low catch BM) for each management group, with low catch benchmarks listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1).

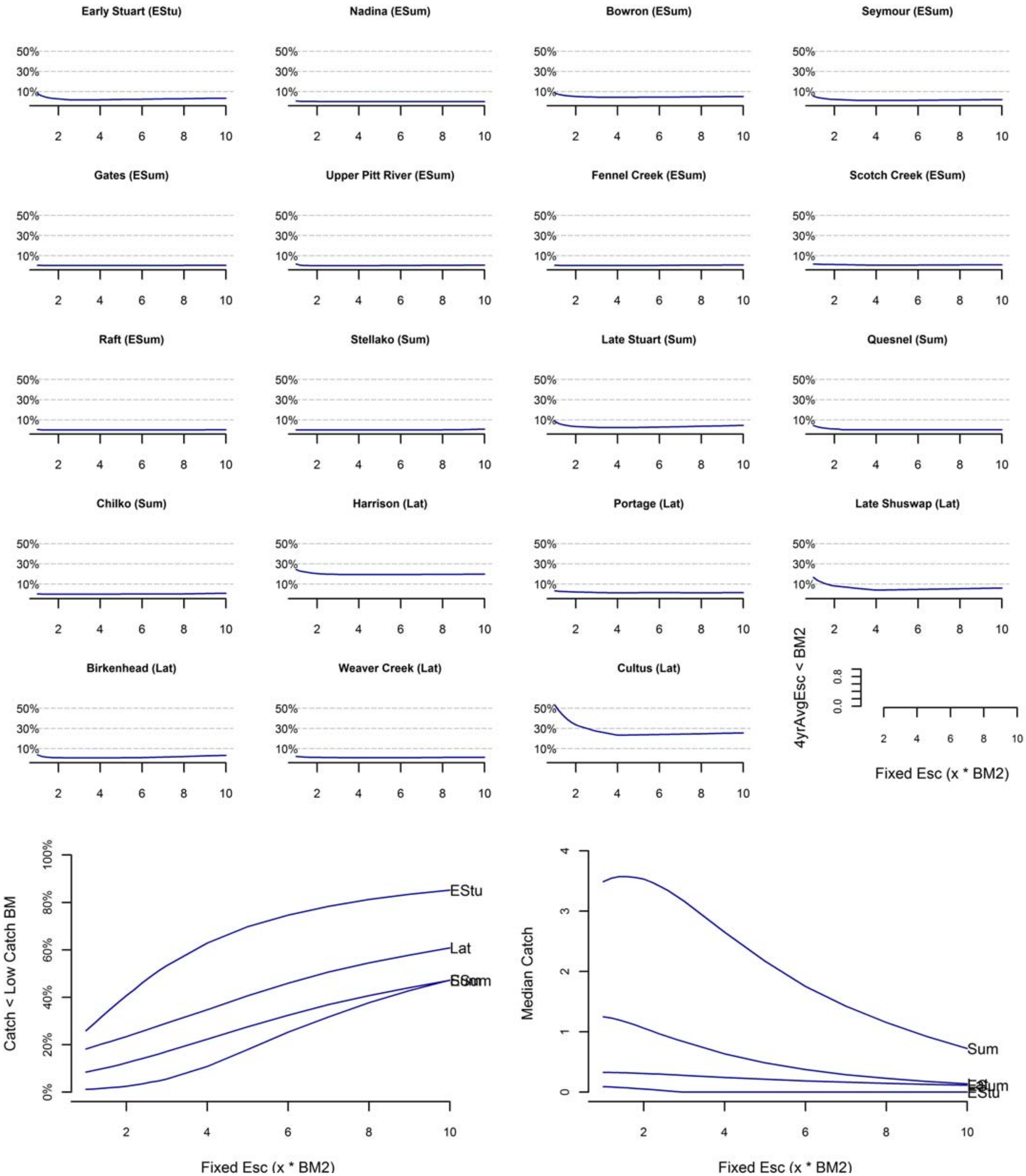


Figure 31: Changing fixed escapement targets – Manage individual stocks

Fixed escapement targets for each stock are expressed as multiples of BM2, listed in Table 1. The 5 top rows show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with low catch benchmarks listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1)

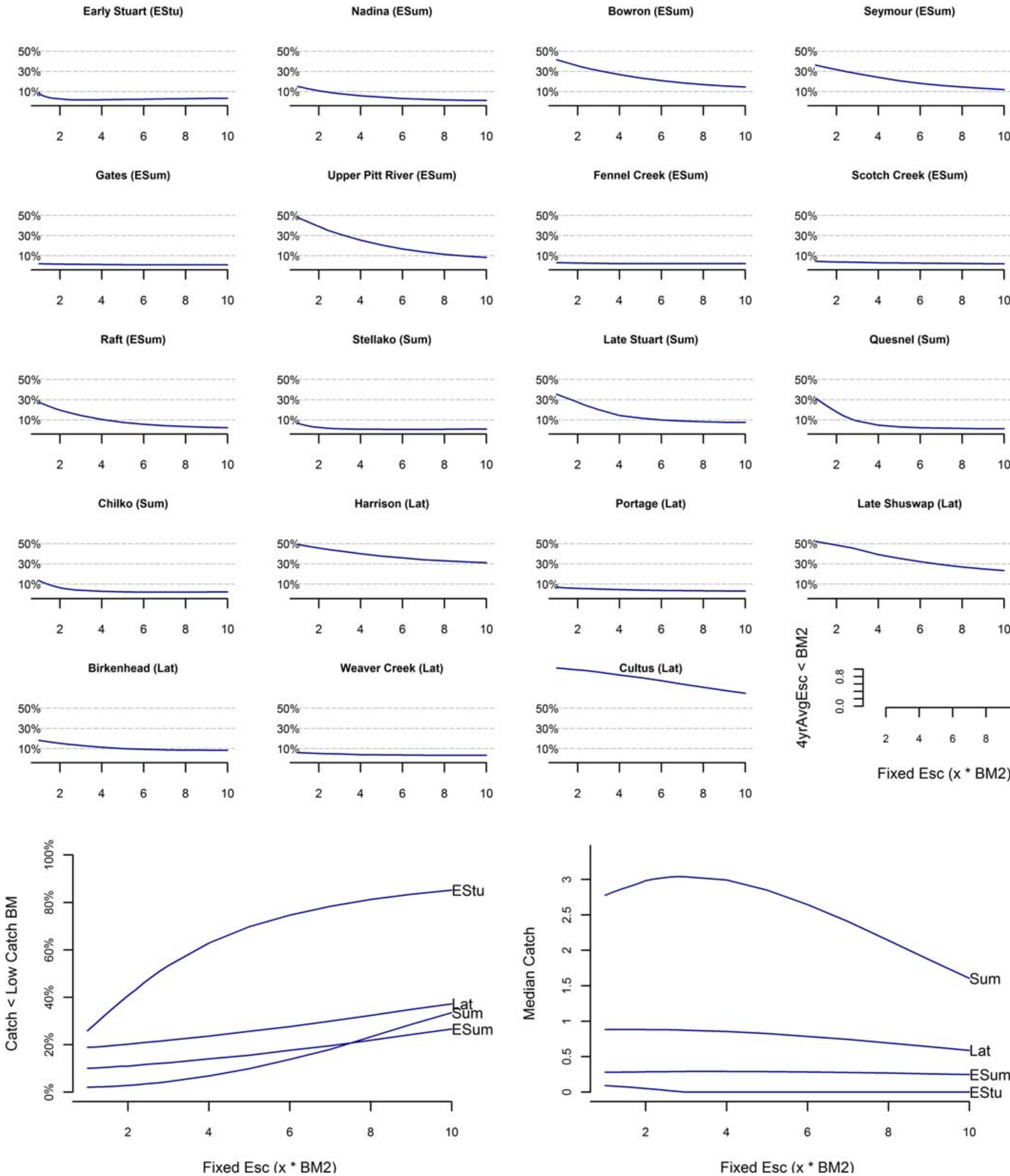


Figure 32: Changing fixed escapement targets – Manage to most productive stock in a group

Fixed escapement targets for each stock are expressed as multiples of BM2, listed in Table 1. The 5 top rows show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with low catch benchmarks listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1).

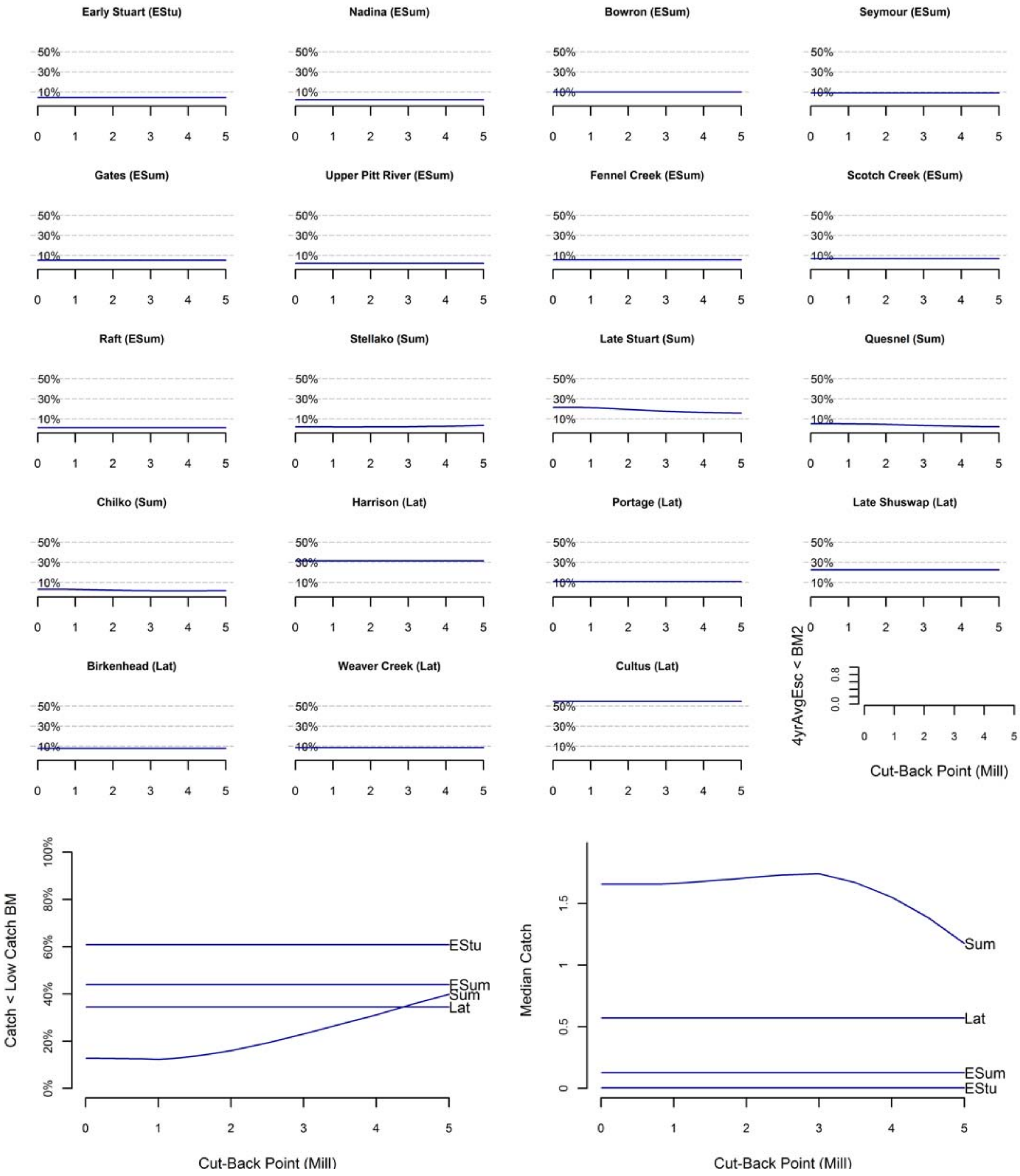


Figure 33: Changing cut-back point on Summer TAM rule.
Cut-back point is defined as in Figure 19.TAM rules for other management groups are as in 2009 management plan. The 5 top rows show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with BM listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1).

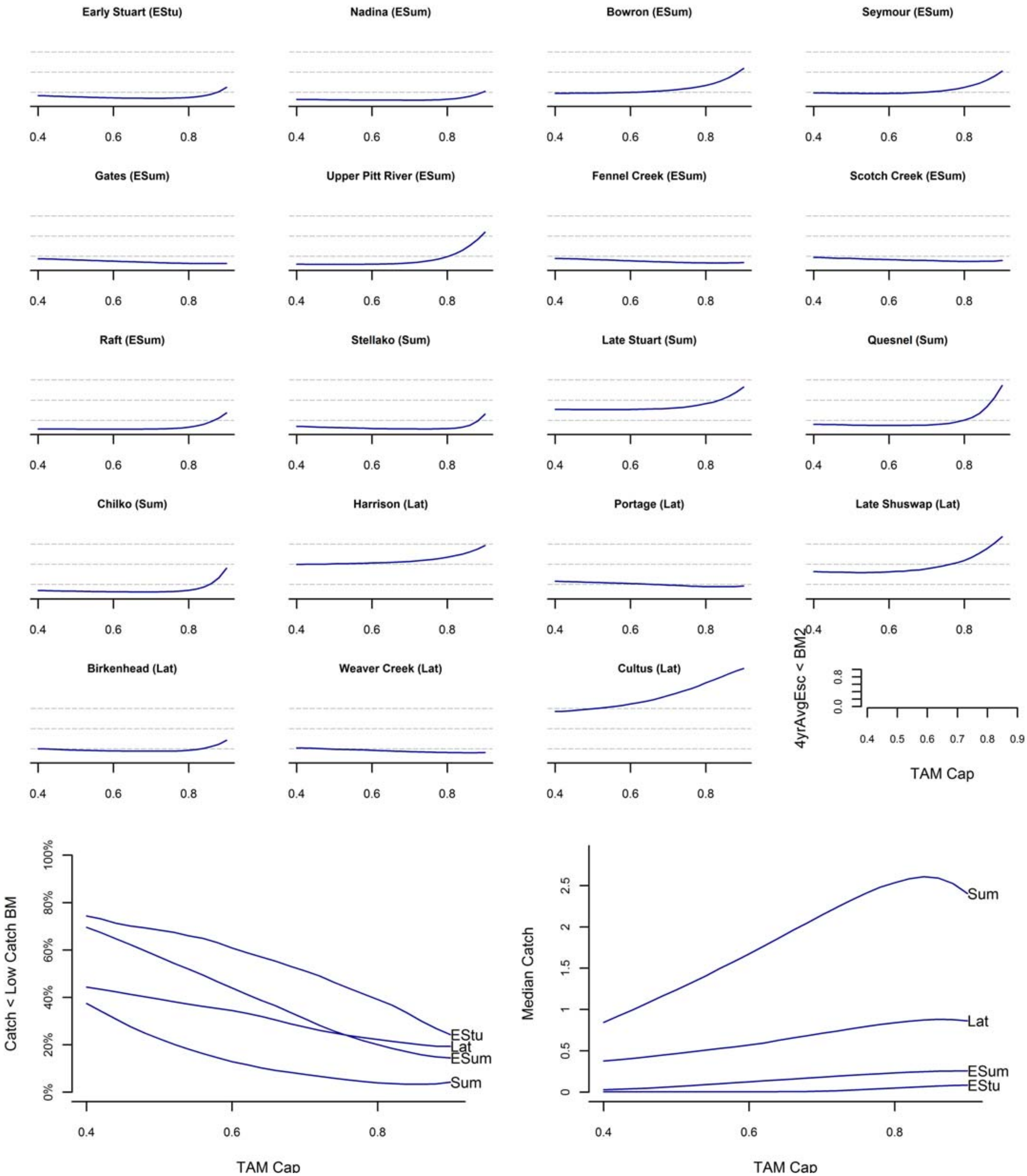


Figure 34: Changing cap on TAM rule

Cap is defined as in Figure 19. Cut-back points and ER floors are as in 2009 management plan. The five top rows show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with BM listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1).

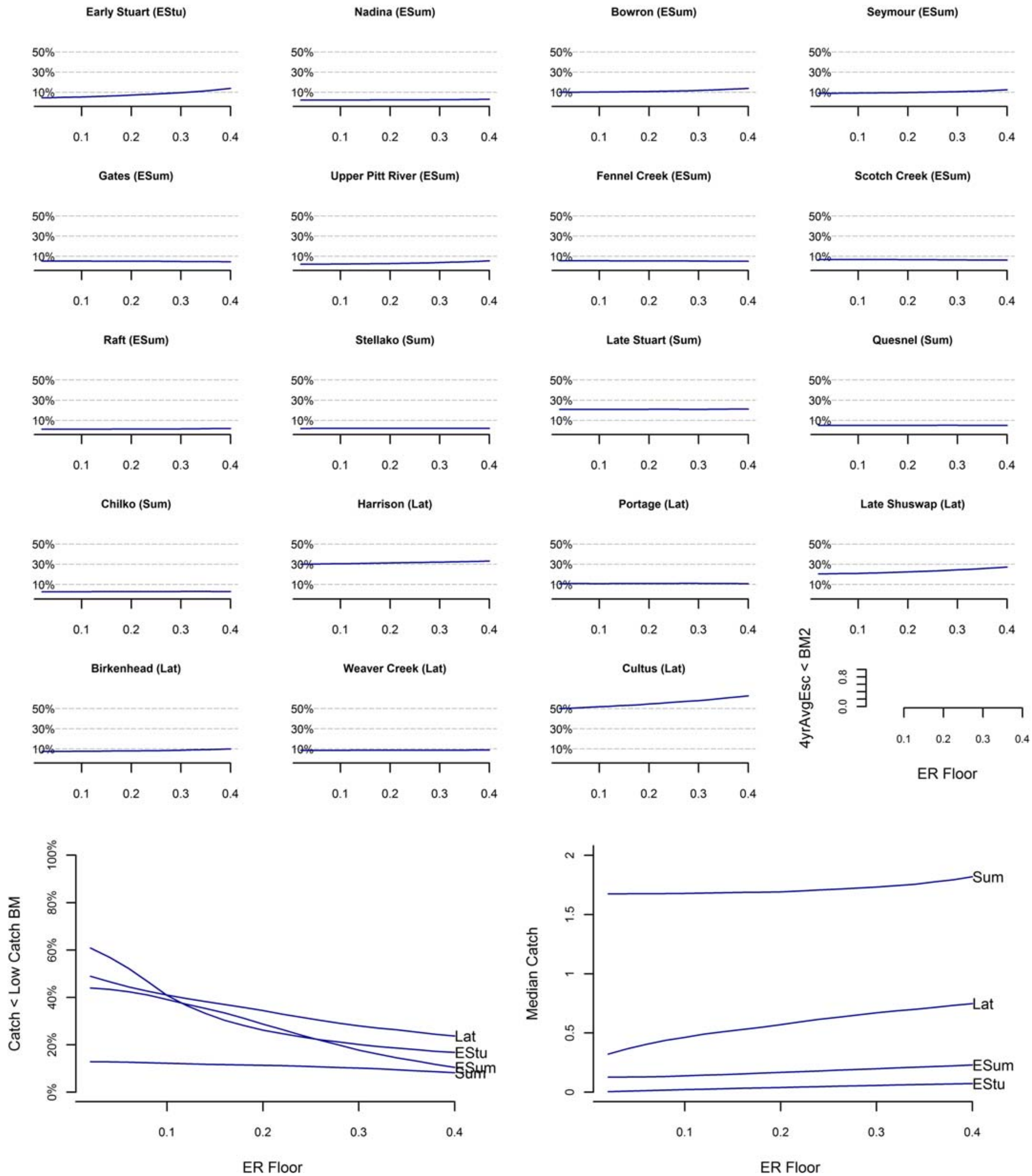


Figure 35: Changing exploitation rate floor on TAM rules
ER floor is defined as in Figure 19. Cut-back points and ER caps are as in 2009 management plan. The five top rows show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with BM listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1).

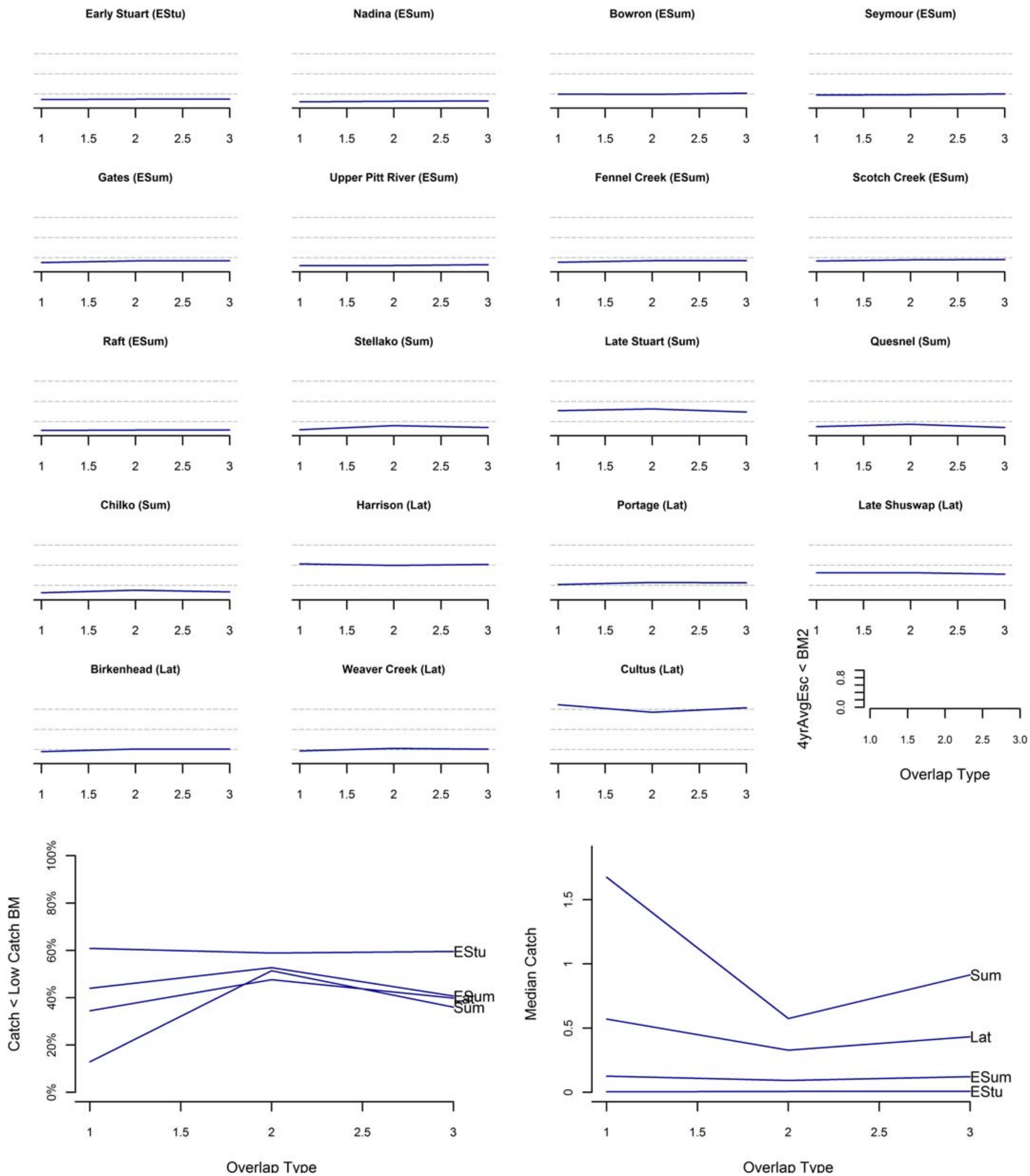


Figure 36: Alternative assumptions about timing overlap – 2009 TAM Rules
Overlap constraints are 1="none", 2="90% of migration window", 3="more than 10% of daily abundance"; as in Figure 20. TAM rules are as in 2009 management plan. The five top rows show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with BM listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1).

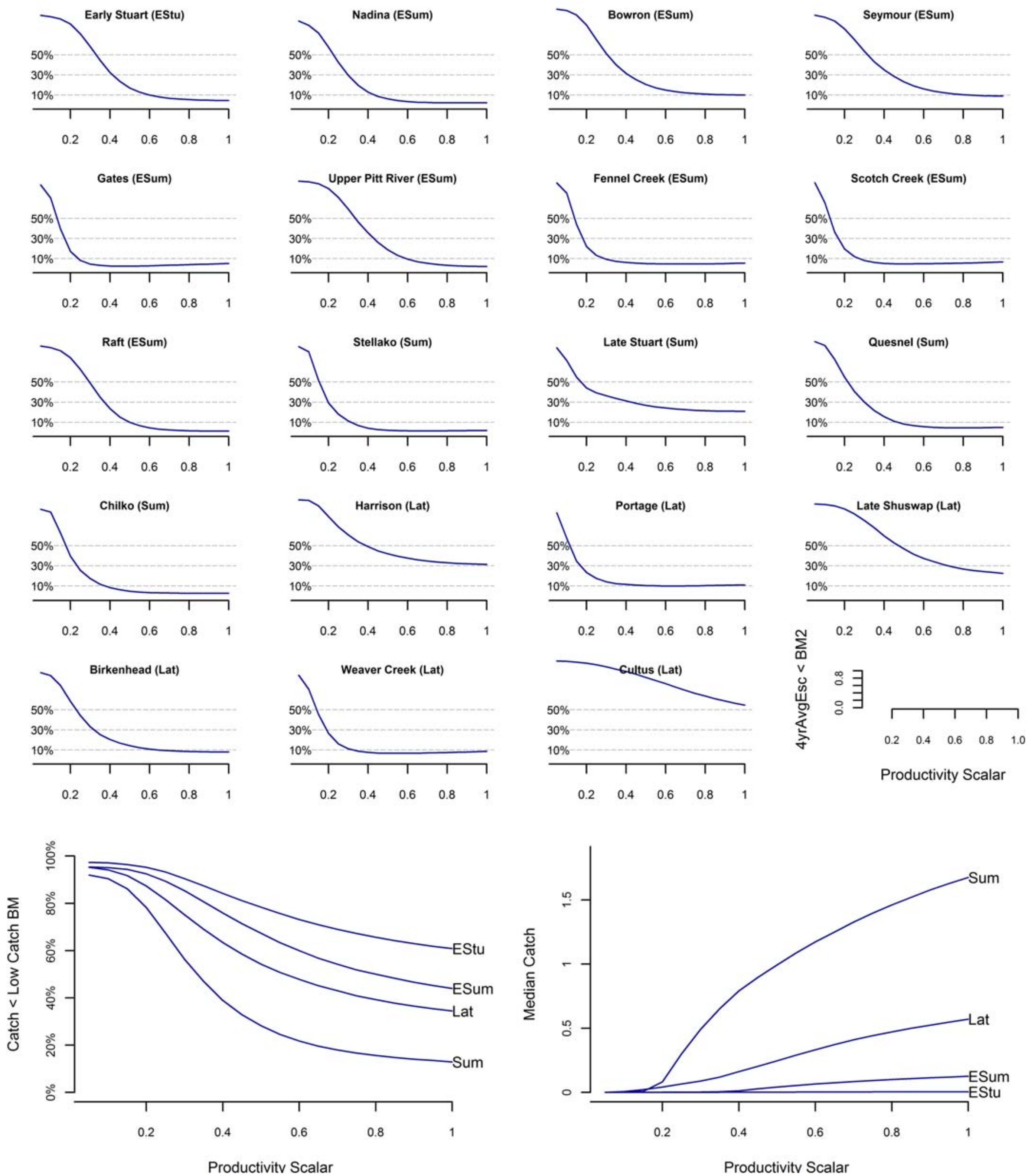


Figure 37: Reduced productivity scenarios – 2009 TAM Rules
The five top rows show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with BM listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1). Productivity ranges from "like the past" (scalar=1) to severe loss (scalar = 0.05, only 5% of modeled recruits actually return).

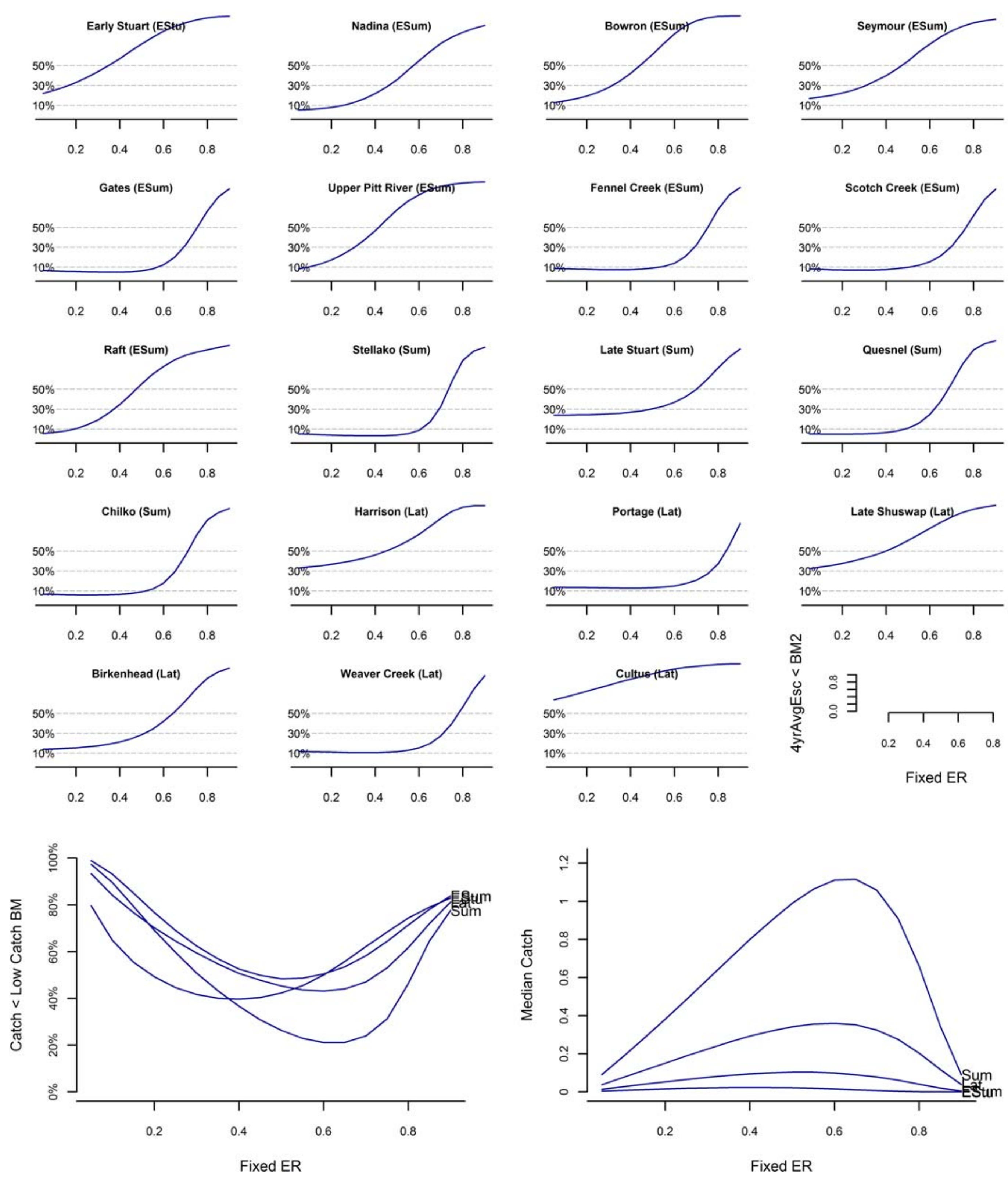


Figure 38: Reduced productivity scenarios – Changing fixed ER, half productivity

The five top panels show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with BM listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1).

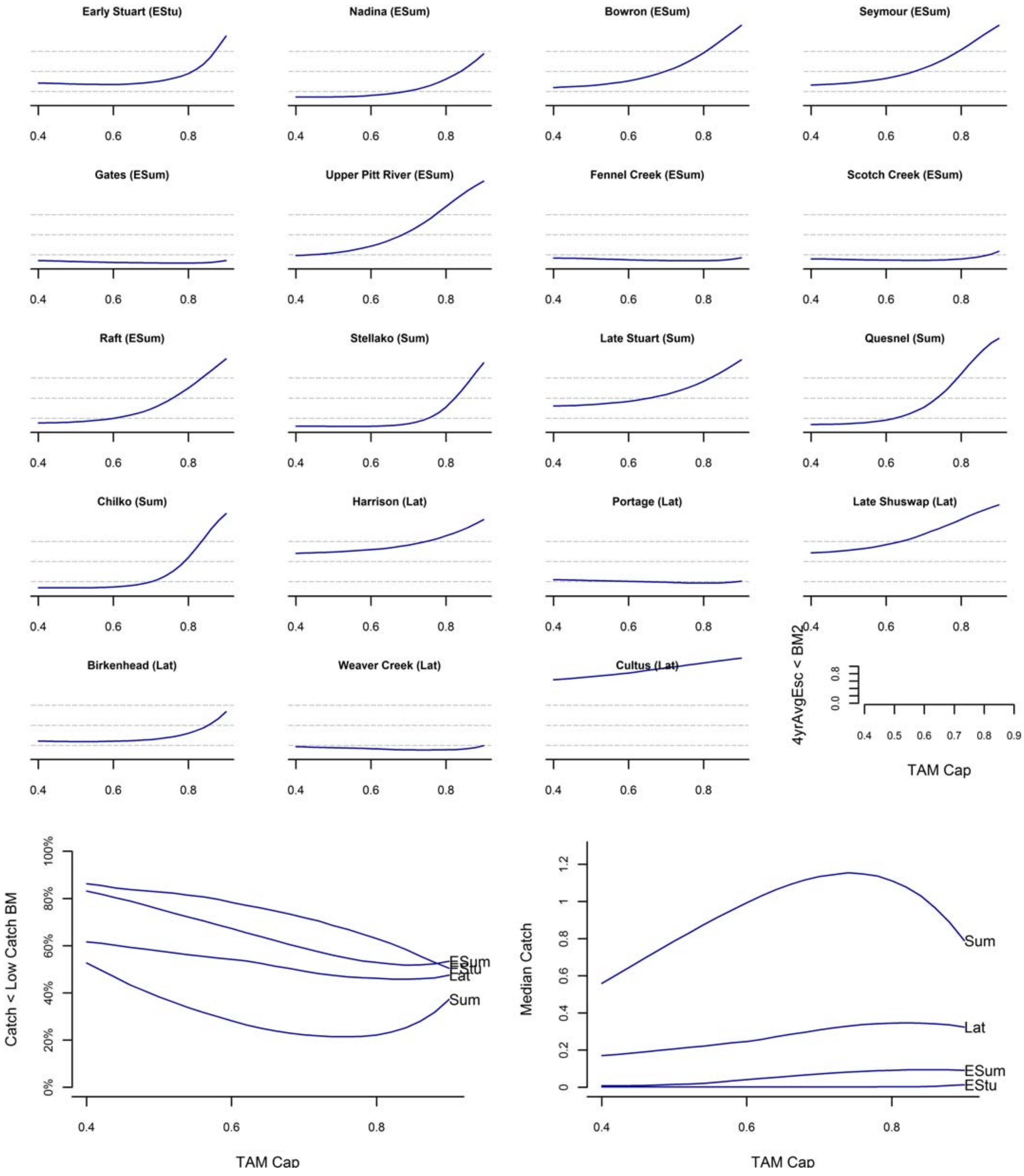


Figure 39: Reduced productivity scenarios – Changing TAM cap, half productivity
The four top panels show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with BM listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1).

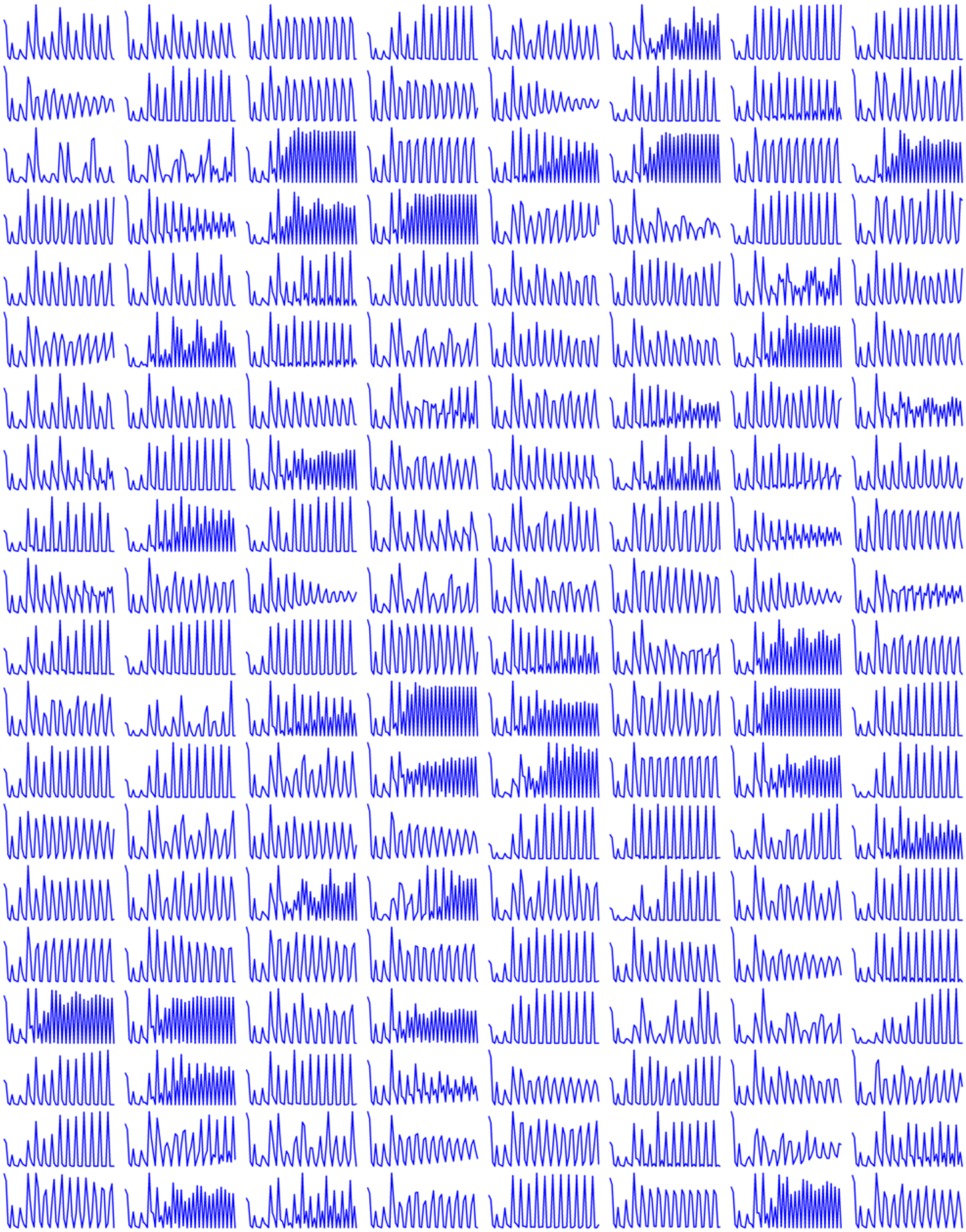


Figure 40: Larkin model illustration – Quesnel spawner trajectories with 30% fixed ER
The sparklines show 160 sample trajectories, each one for a different set of spawner-recruit parameters sampled from the Bayesian posterior distribution (no random variation).

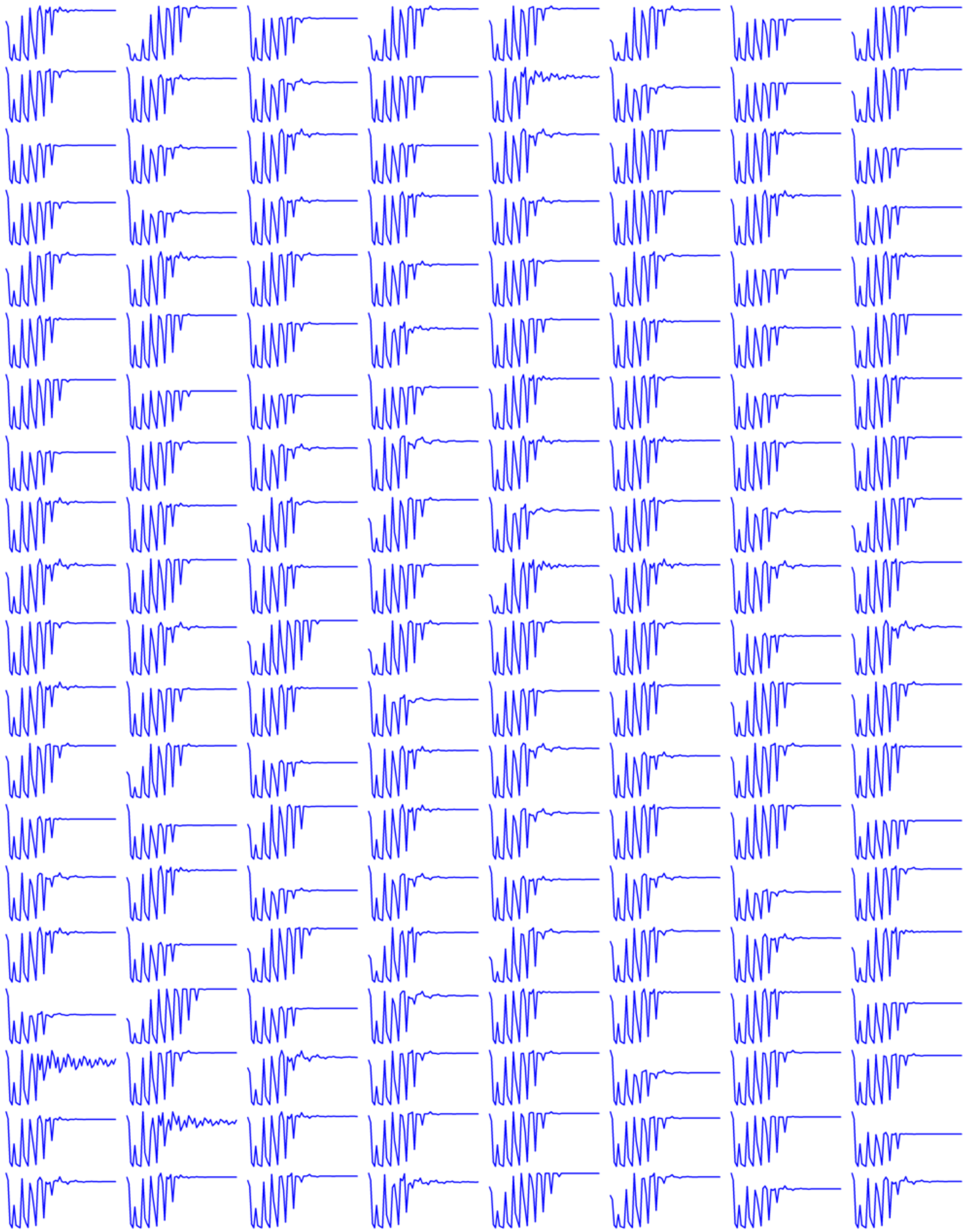


Figure 41: Ricker model illustration – Quesnel spawner trajectories with 30% fixed ER
The sparklines show 160 sample trajectories, each one for a different set of spawner-recruit parameters sampled from the Bayesian posterior distribution (no random variation).

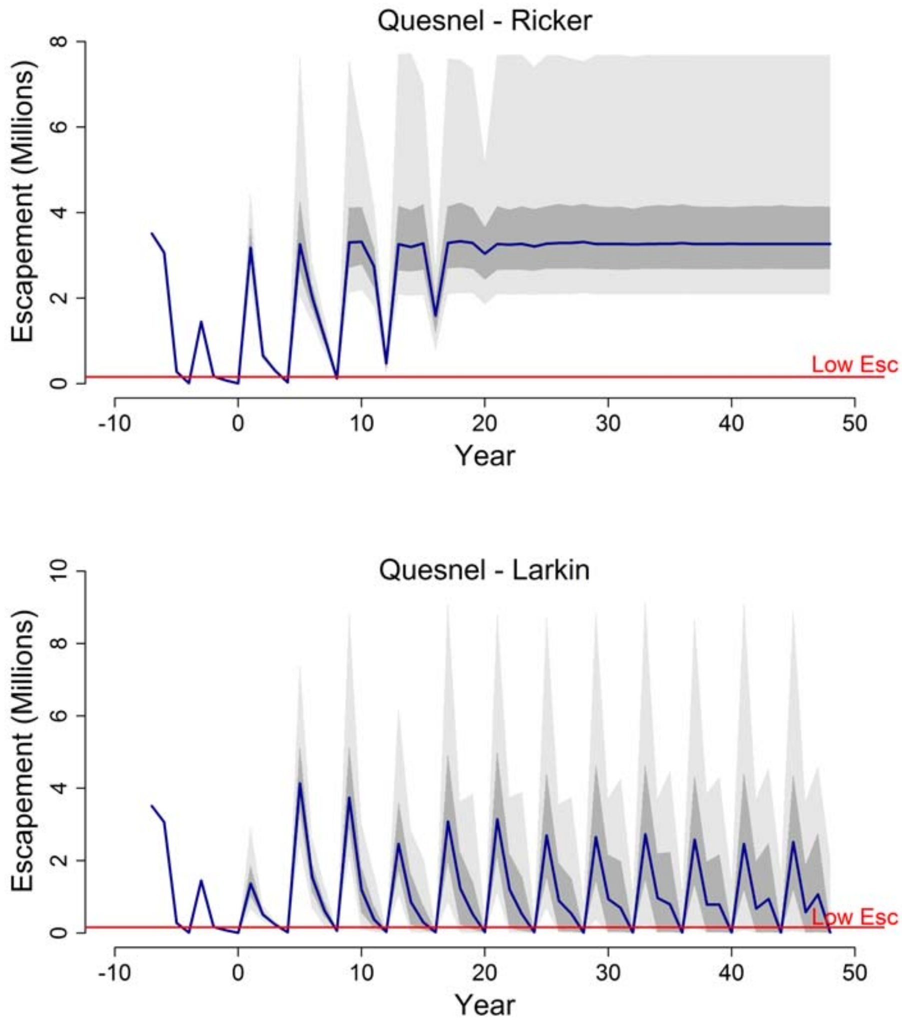


Figure 42: Spawner trajectory illustration for Quesnel - Ricker vs. Larkin with 30% fixed ER
Summary of the sparklines in Figure 40 and Figure 41 (no random variation).

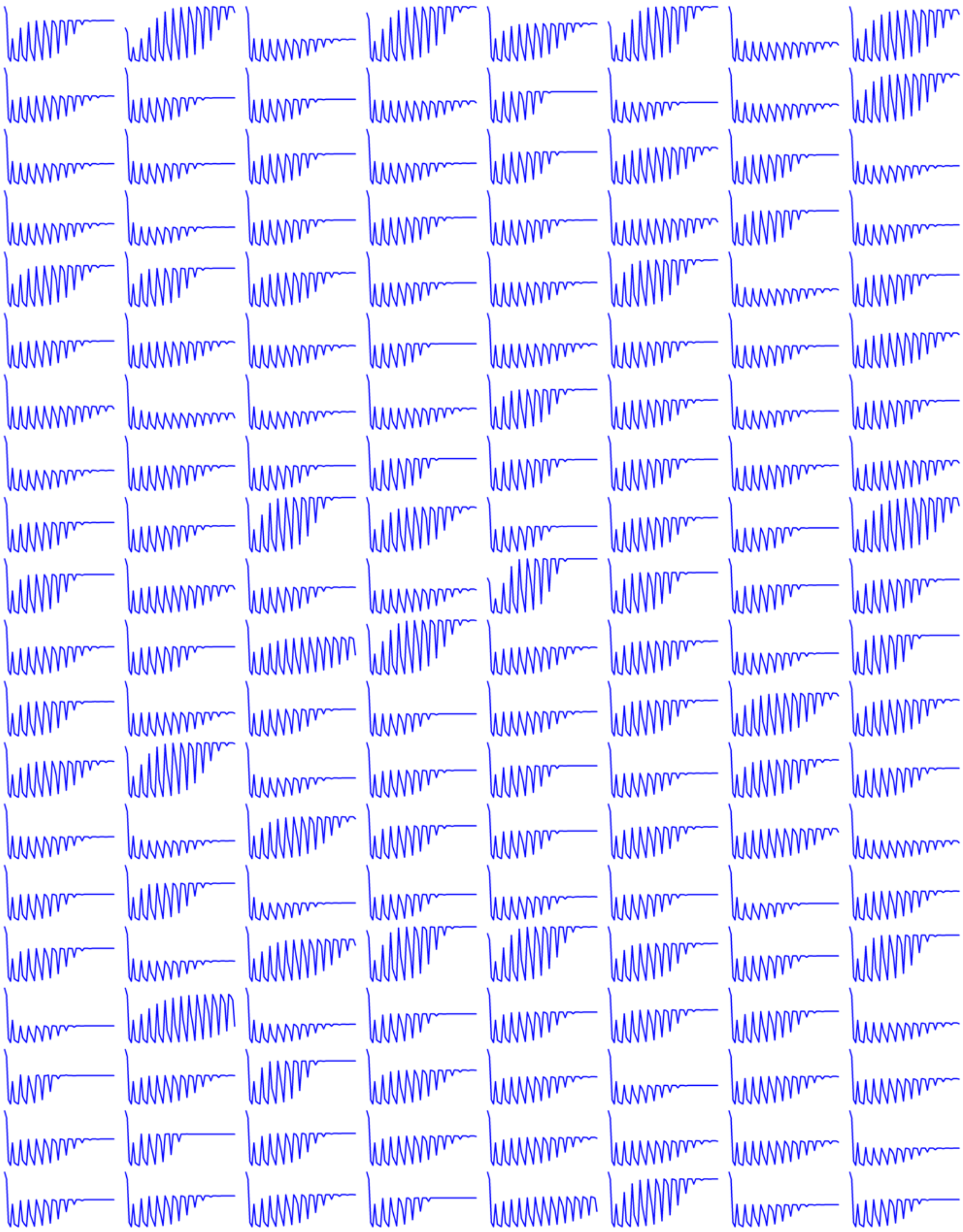


Figure 43: Ricker illustration 2 – Quesnel spawner trajectories with 60% fixed ER and median ERM
The sparklines show 160 sample trajectories, each one for a different set of par estimates. (60% fixed ER plus median en-route mortality, no random variation)

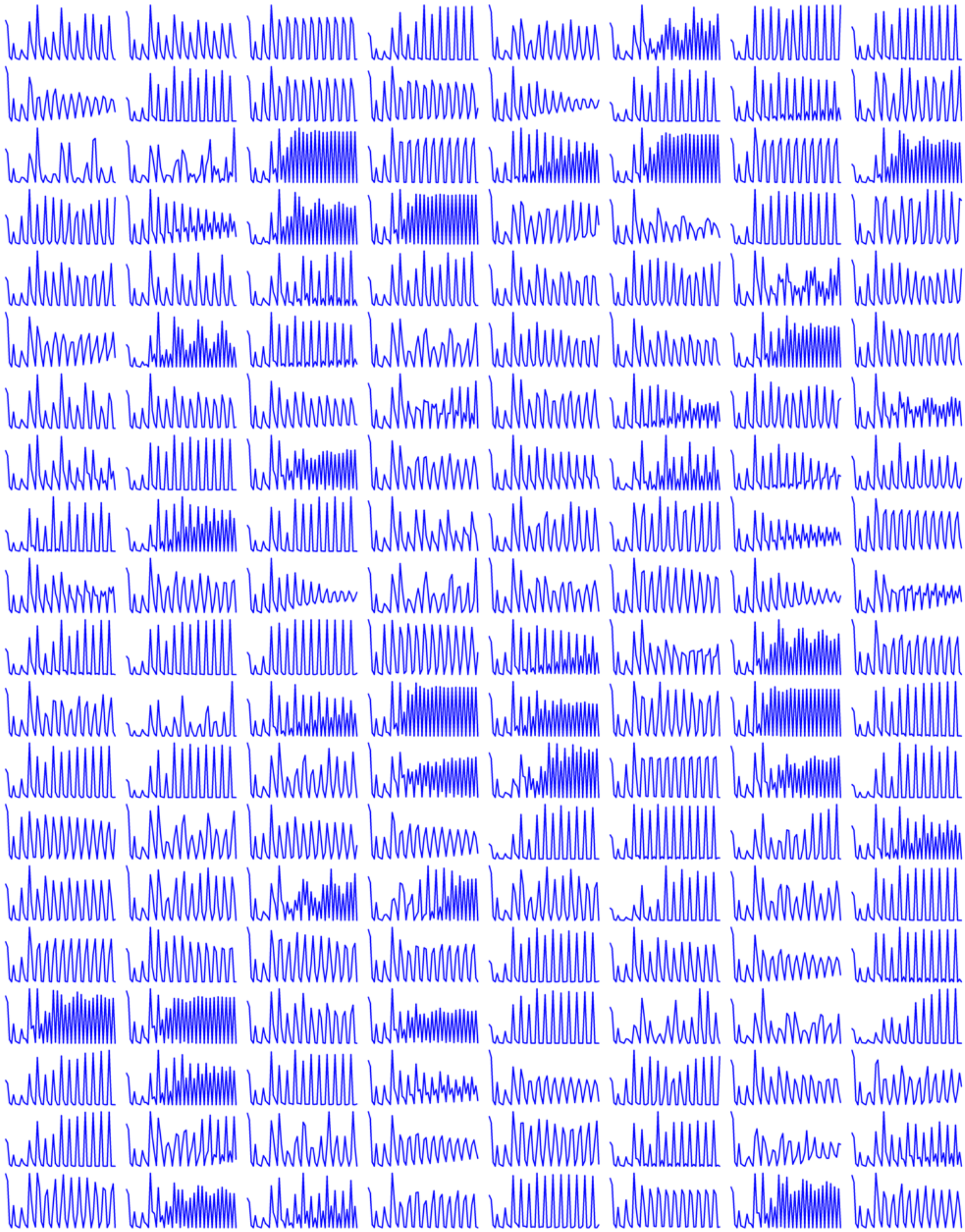


Figure 44: Larkin illustration 2 – Quesnel spawner trajectories with 60% fixed ER, median ERM, and random variation.

The sparklines show 160 sample trajectories, each one for a different set of par estimates. (60% fixed ER plus median en-route mortality, random variation in recruitment)

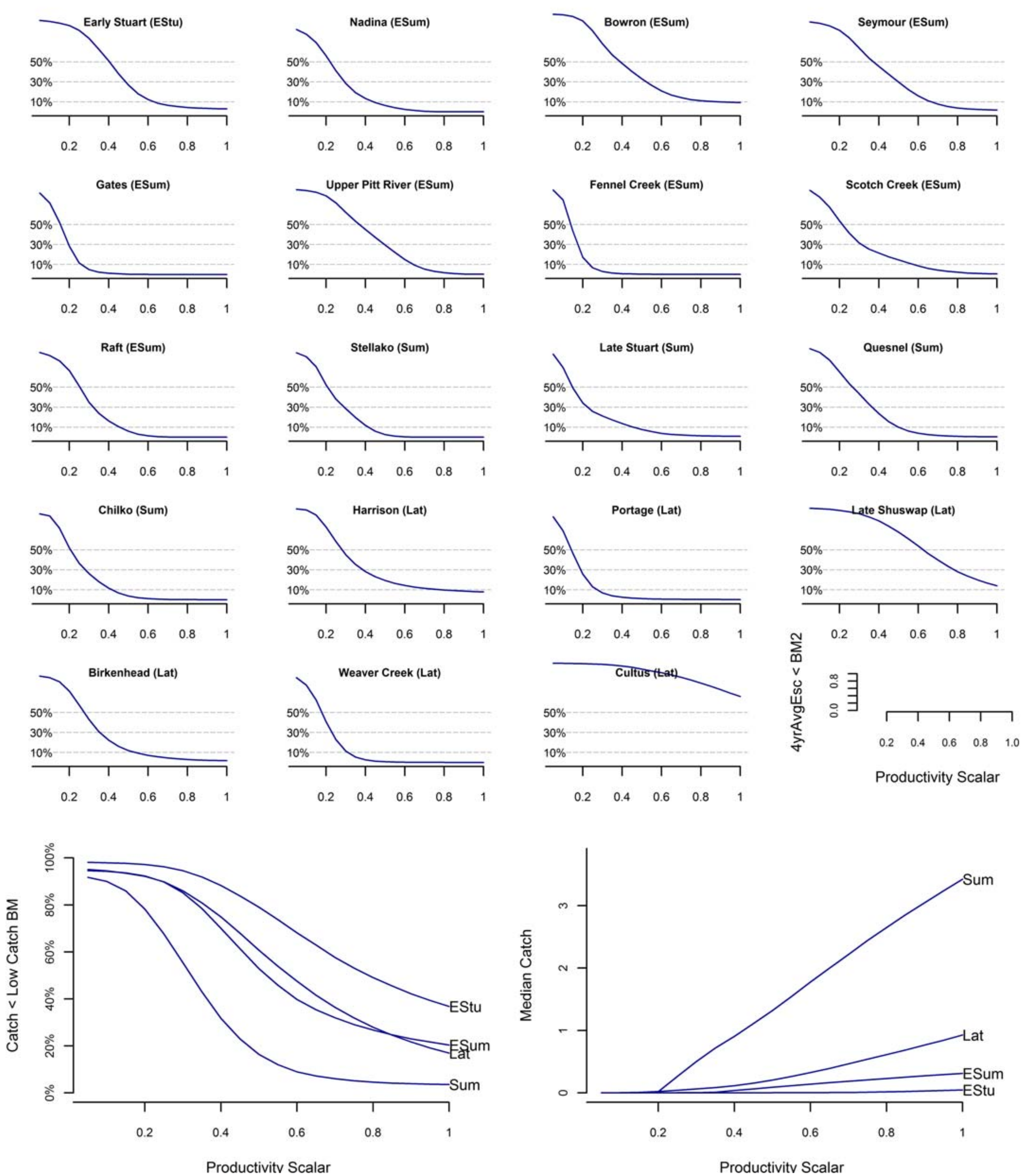


Figure 45: Reduced productivity scenarios – 2009 TAM rules, Ricker
The four top panels show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with BM listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1). Productivity ranges from "like the past" (scalar=1) to severe loss (scalar = 0.05, only 5% of modeled recruits actually return).This figure differs from Figure 37 only in the SR model form.

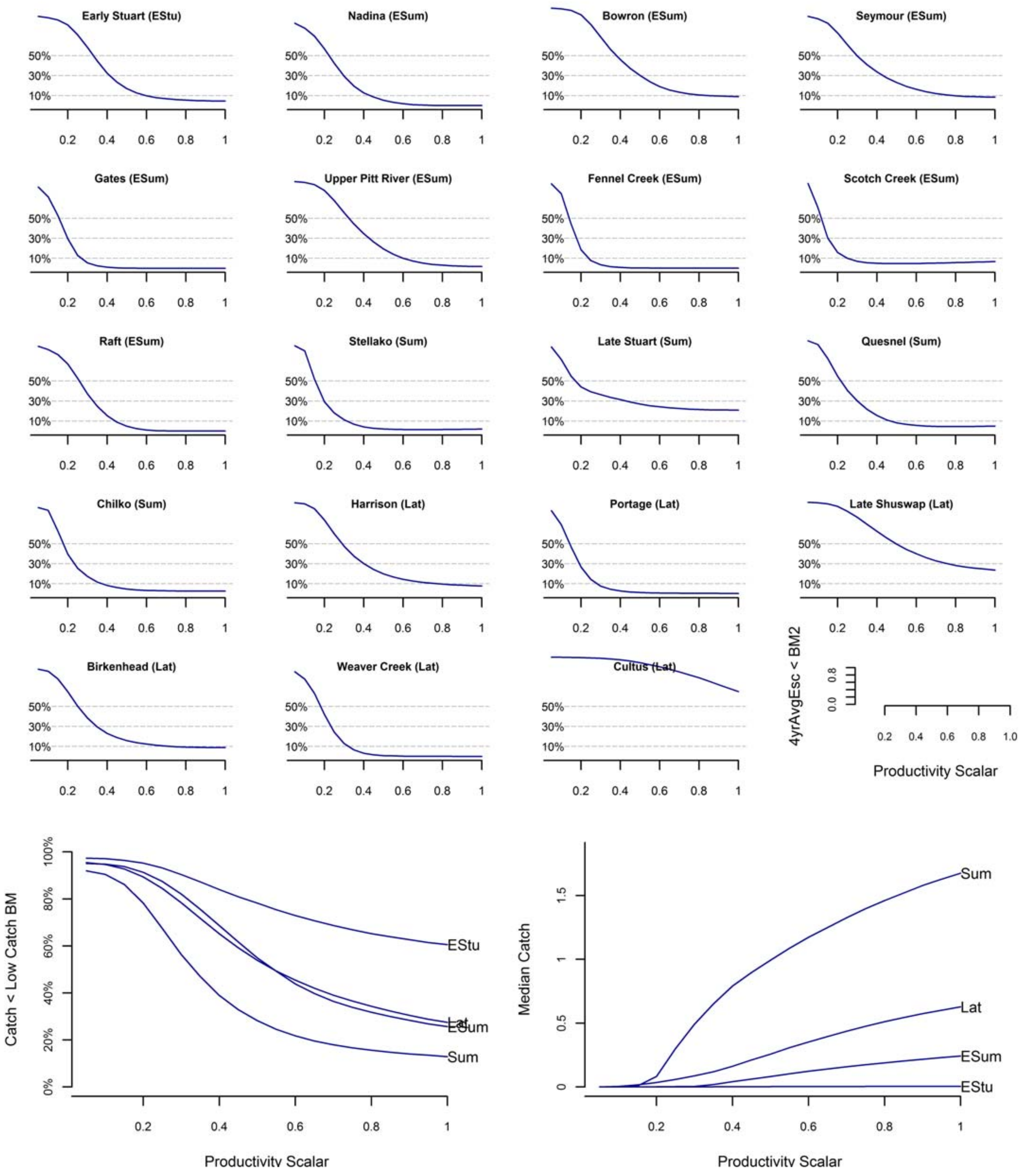


Figure 46: Reduced productivity scenarios – 2009 TAM rules, Mixed SR model forms

The four top panels show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with BM listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1). Productivity ranges from "like the past" (scalar=1) to severe loss (scalar = 0.05, only 5% of modeled recruits actually return). This figure differs from Figure 37 only in the SR model form. Mixed models as marked in Table 4.

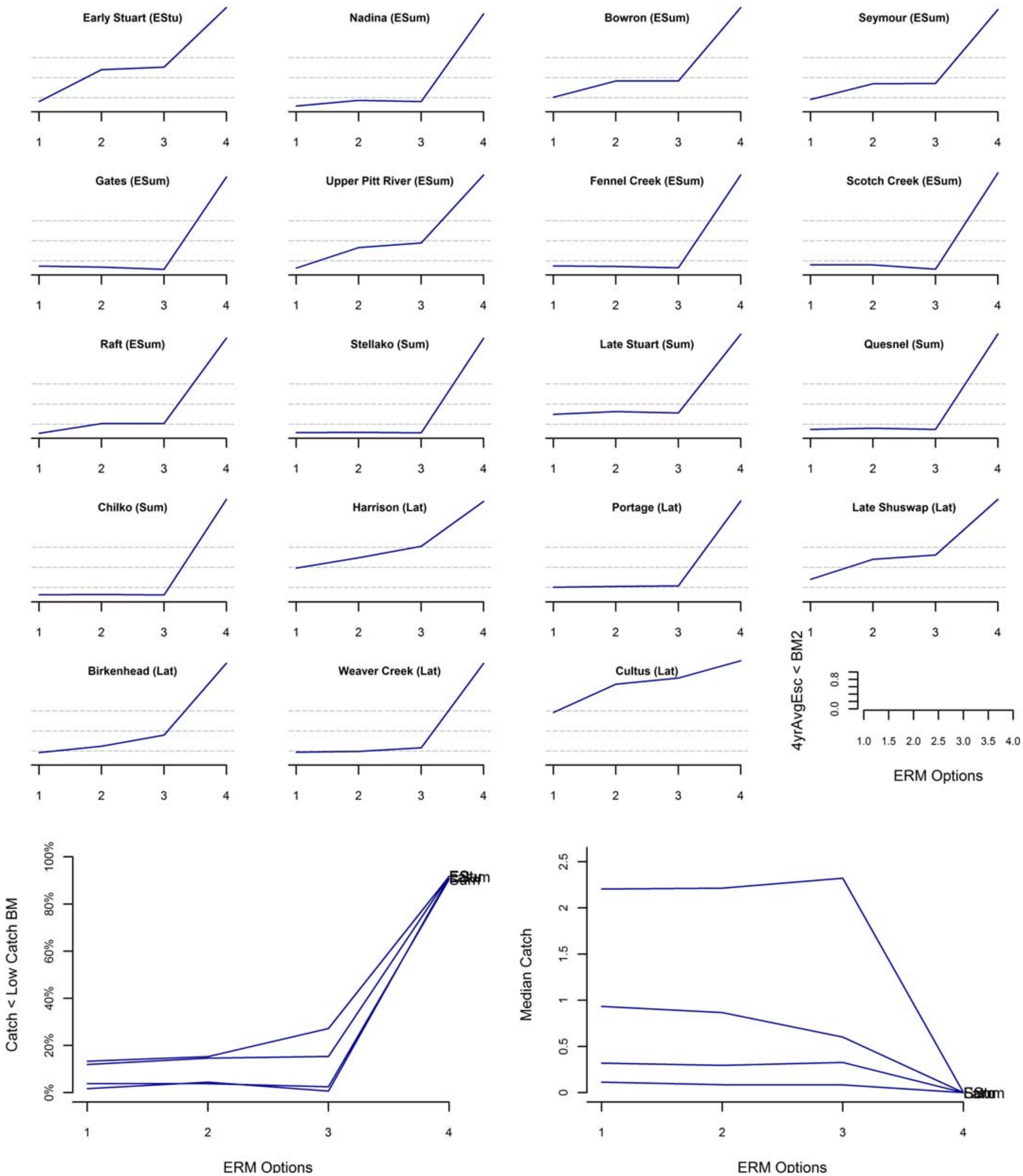


Figure 47: Effect of en-route mortality assumptions under 60% fixed ER.
ERM settings are 1="none", 2="obs", 3="abd_log", 4="abd_lin"; as in Figure 16. TAM rules are as in 2009 management plan. The five top rows show Prob(4yr Avg Esc < BM2) for each stock. Bottom left panel shows Prob(Catch < Low catch BM) for each management group, with BM listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1).

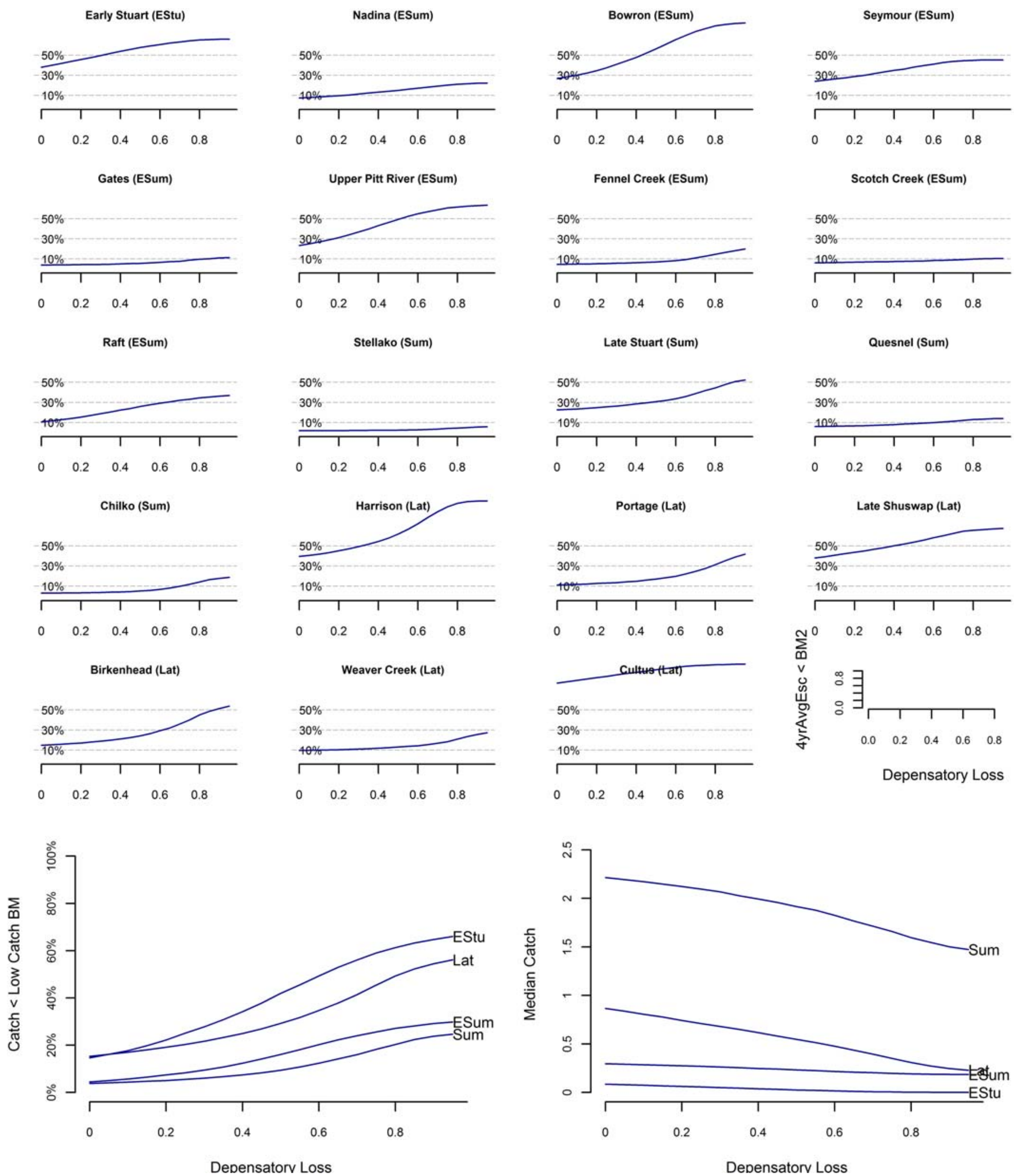


Figure 48: Effect of depensatory mortality assumptions on sensitivity to changing ER.
The five top rows show Prob(4yr Avg Esc < BM2) for each stock, with BM 2 listed in Table 1. Bottom left panel show Prob(Catch < Low catch BM) for each management group, with low catch benchmarks listed in Section 2.4.3. Bottom right shows median catch. All other settings as in Base Case 1 (Section 3.3.1).

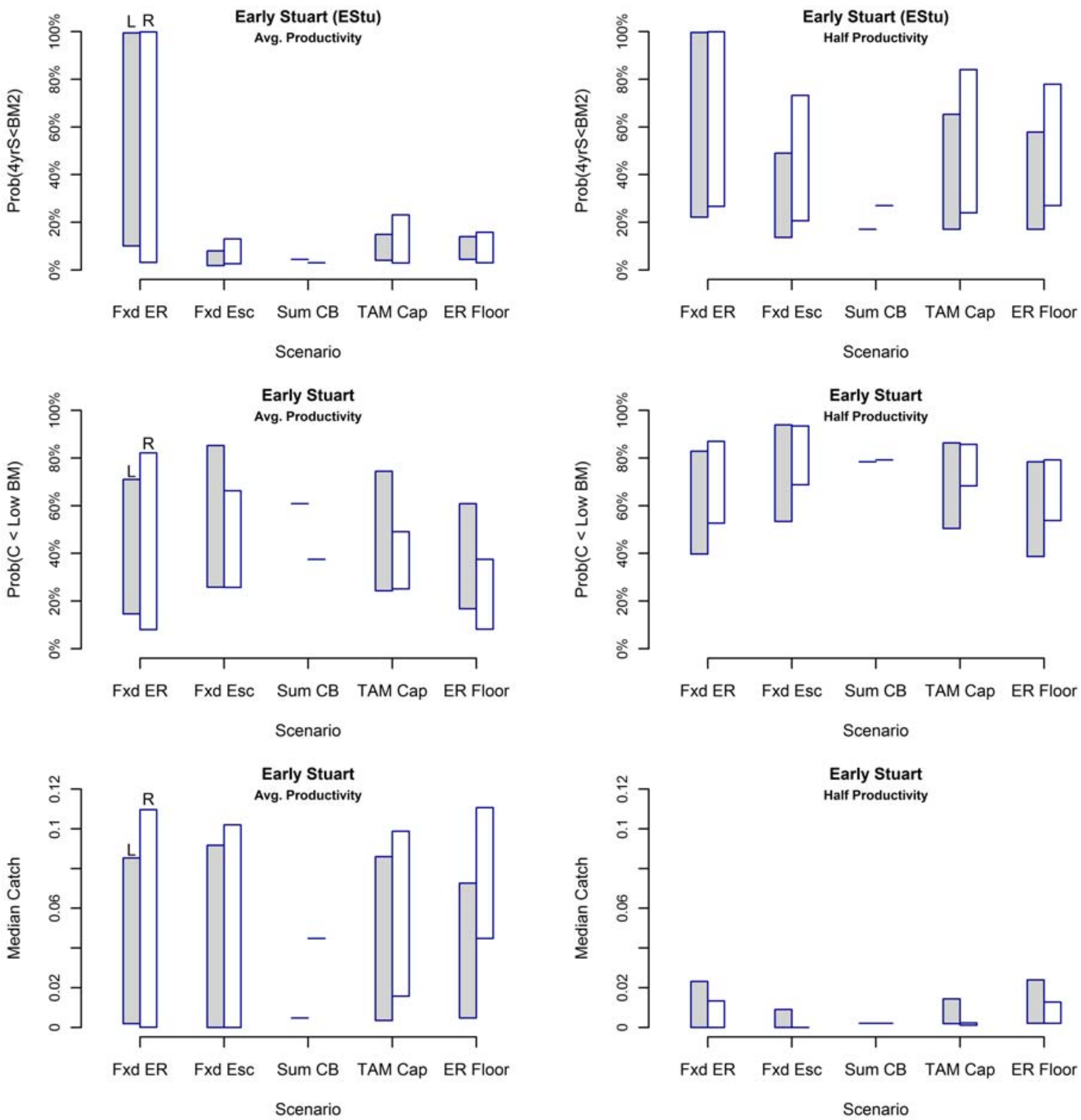


Figure 49: Scenario comparisons – Early Stuart spawner abundance and catch
Each bar shows the range of a performance measure. Each panel has 5 sets of bars, each set corresponding to one scenario that varies an aspect of a harvest strategy (Figure 30 to Figure 35). Each set of bars compares the range of results for Larkin (L) and Ricker (R) SR fits. Each row of plots compares two productivity assumptions side-by-side.

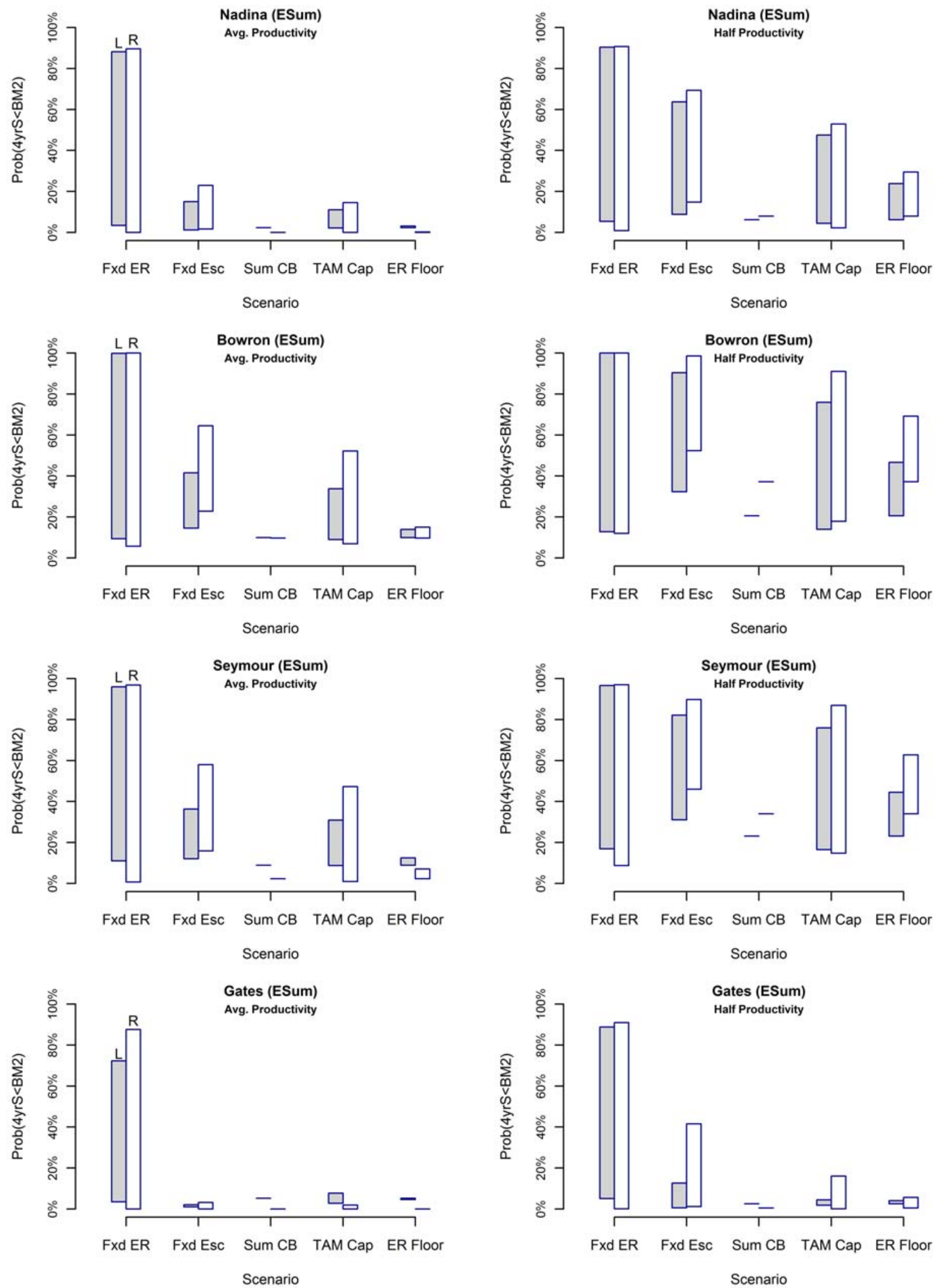


Figure 50: Scenario comparisons – Early Summer spawner abundance 1
Each bar shows the range of a performance measure. Each panel has 5 sets of bars, each set corresponding to one scenario that varies an aspect of a harvest strategy (Figure 30 to Figure 35). Each set of bars compares the range of results for Larkin (L) and Ricker (R) SR fits. Each row of plots compares two productivity assumptions side-by-side.

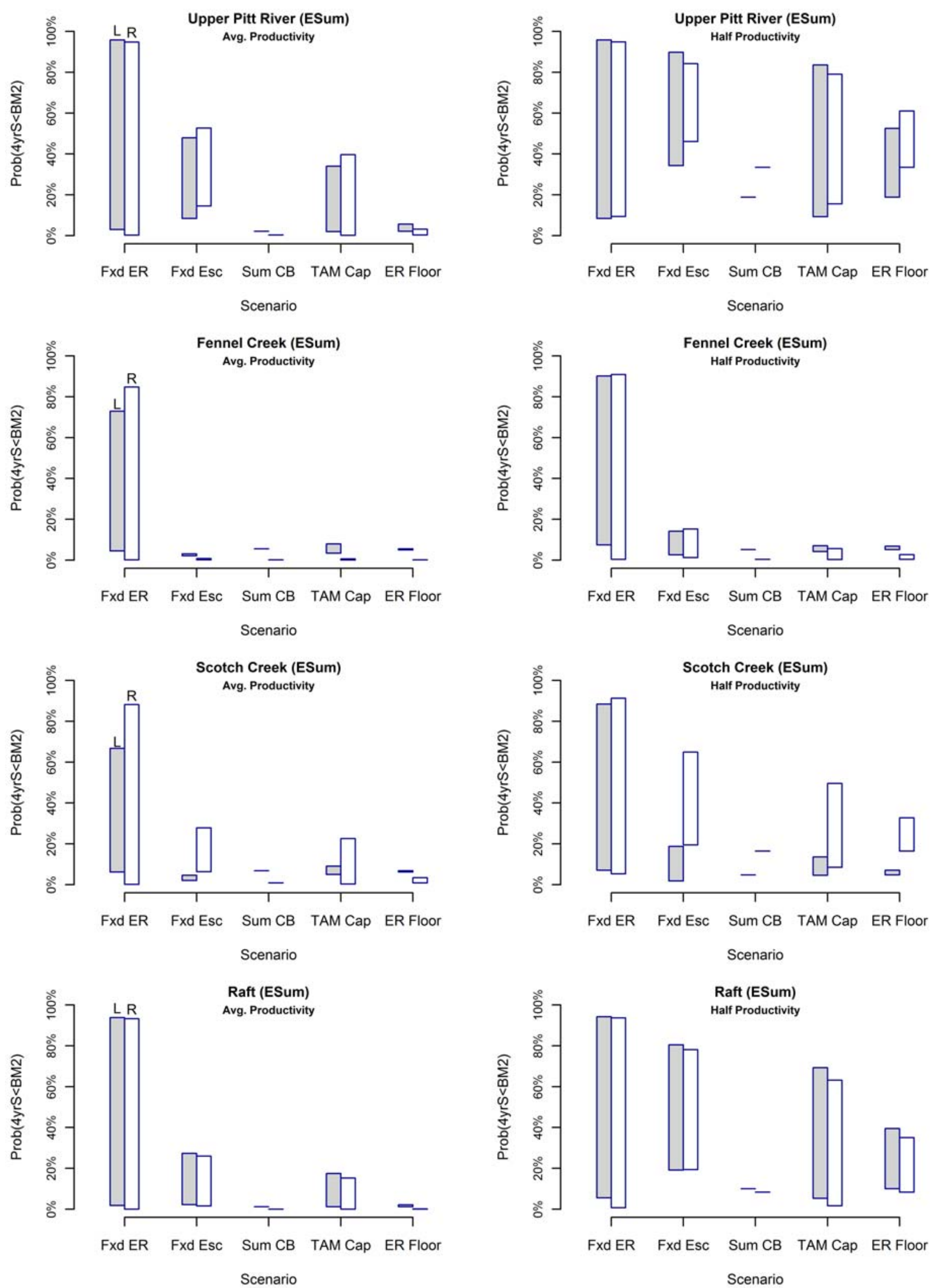


Figure 51: Scenario comparisons – Early Summer spawner abundance 2
Each bar shows the range of a performance measure. Each panel has 5 sets of bars, each set corresponding to one scenario that varies an aspect of a harvest strategy (Figure 30 to Figure 35). Each set of bars compares the range of results for Larkin (L) and Ricker (R) SR fits. Each row of plots compares two productivity assumptions side-by-side.

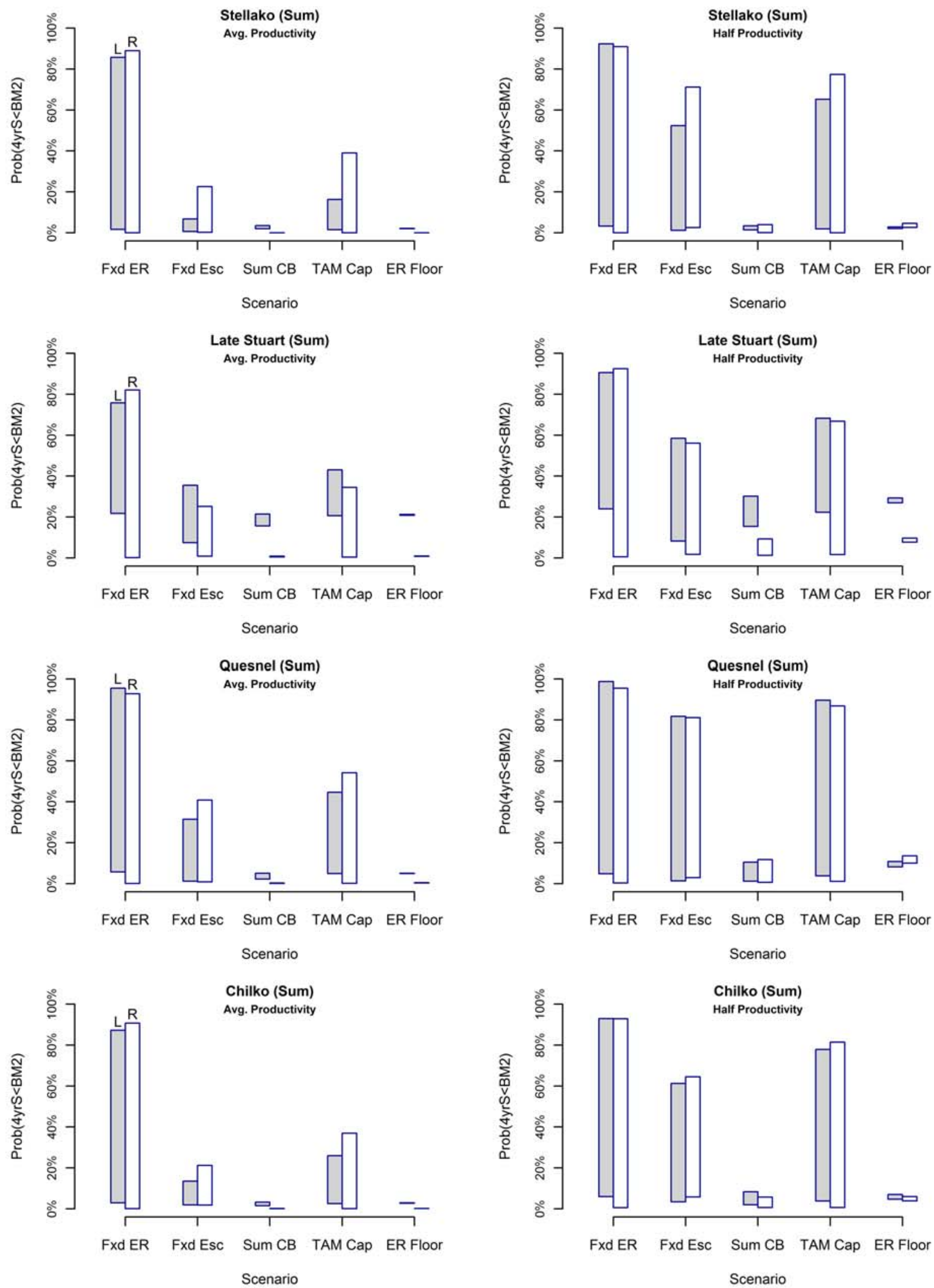


Figure 52: Scenario comparisons – Summer spawner abundance

Each bar shows the range of a performance measure. Each panel has 5 sets of bars, each set corresponding to one scenario that varies an aspect of a harvest strategy (Figure 30 to Figure 35). Each set of bars compares the range of results for Larkin (L) and Ricker (R) SR fits. Each row of plots compares two productivity assumptions side-by-side.

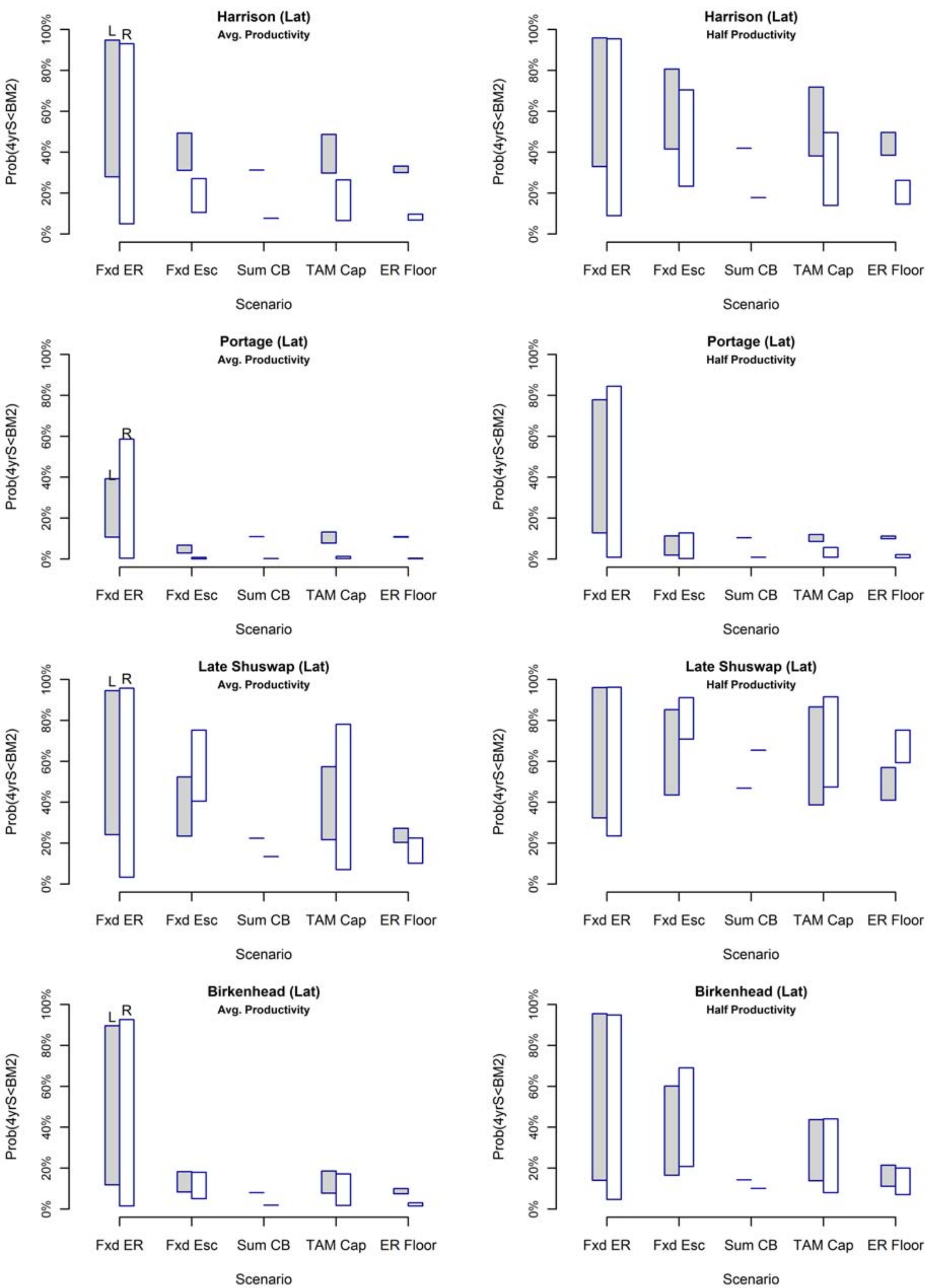


Figure 53: Scenario comparisons – Late spawner abundance 1

Each bar shows the range of a performance measure. Each panel has 5 sets of bars, each set corresponding to one scenario that varies an aspect of a harvest strategy (Figure 30 to Figure 35). Each set of bars compares the range of results for Larkin (L) and Ricker (R) SR fits. Each row of plots compares two productivity assumptions side-by-side.

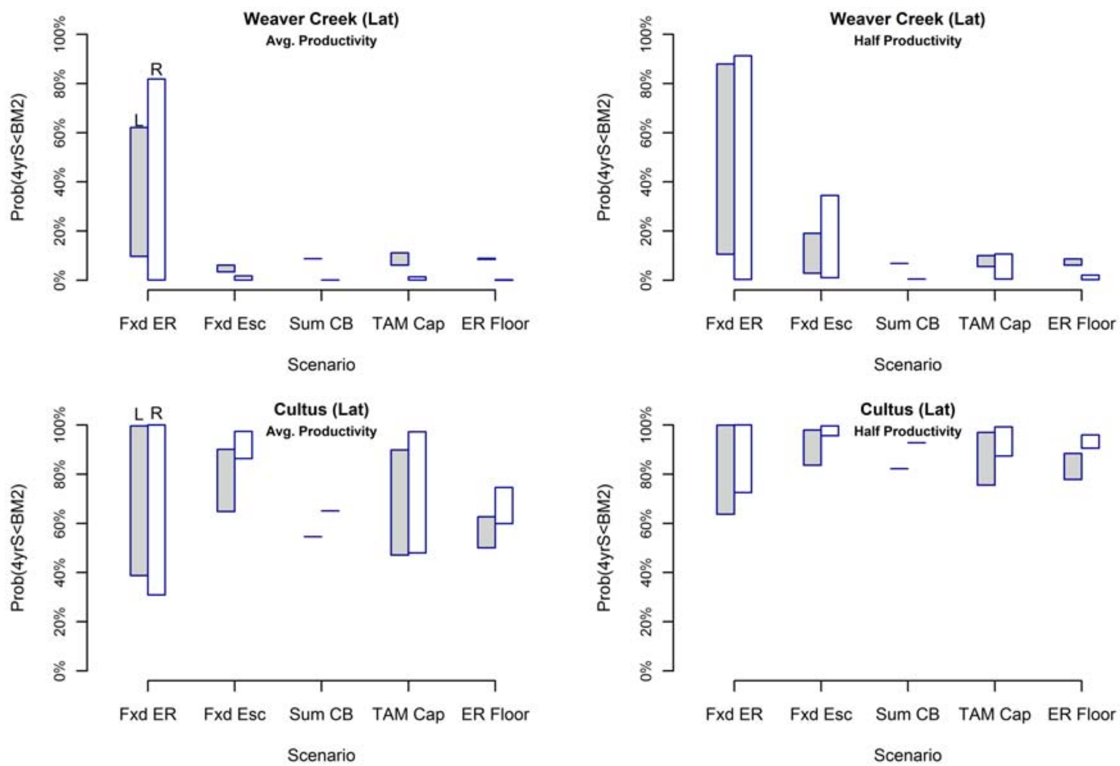


Figure 54: Scenario comparisons – Late spawner abundance 2

Each bar shows the range of a performance measure. Each panel has 5 sets of bars, each set corresponding to one scenario that varies an aspect of a harvest strategy (Figure 30 to Figure 35). Each set of bars compares the range of results for Larkin (L) and Ricker (R) SR fits. Each row of plots compares two productivity assumptions side-by-side.

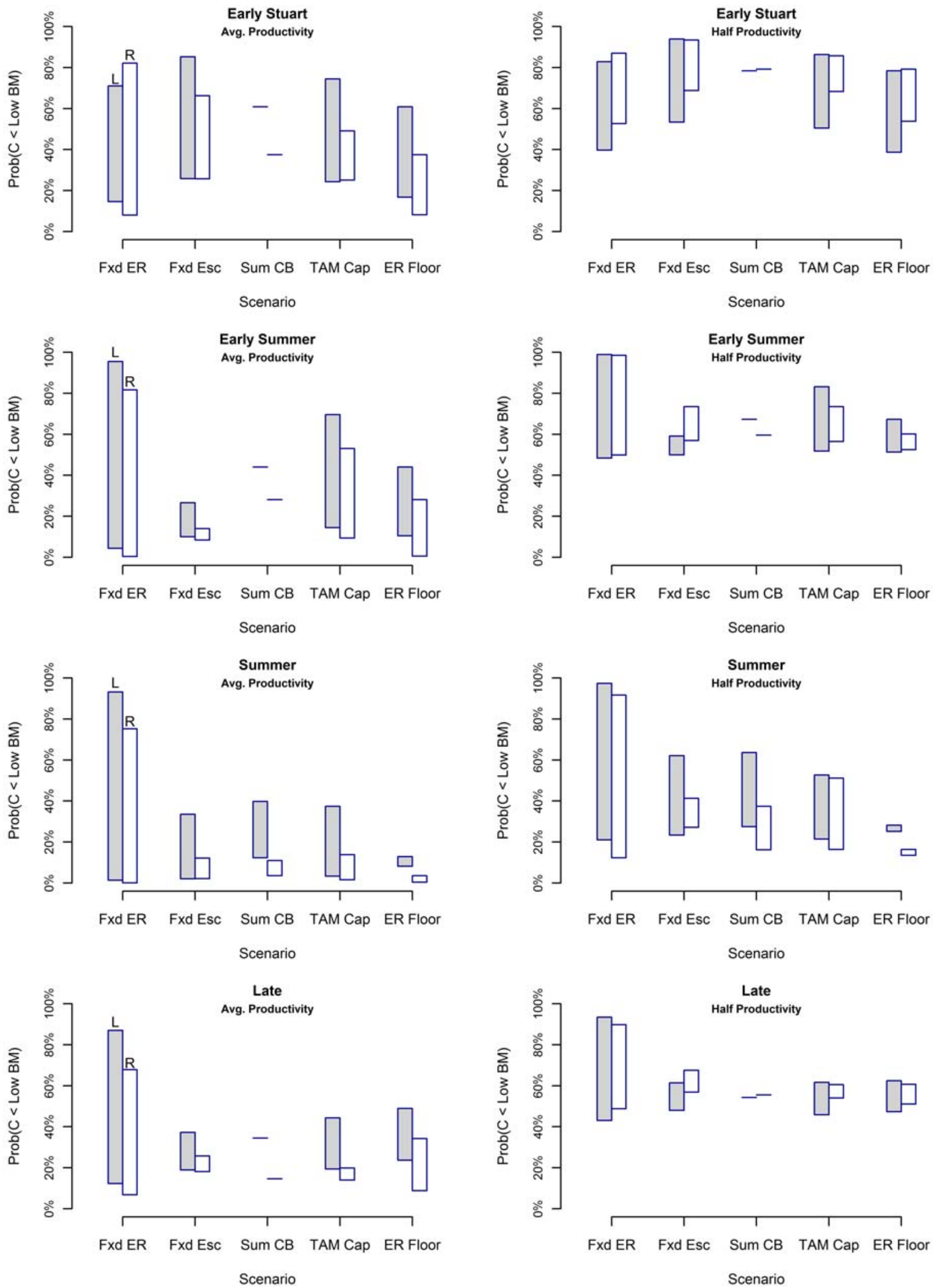


Figure 55: Scenario comparisons – 4 management groups, low catch
Each bar shows the range of a performance measure. Each panel has 5 sets of bars, each set corresponding to one scenario that varies an aspect of a harvest strategy (Figure 30 to Figure 35). Each set of bars compares the range of results for Larkin (L) and Ricker (R) SR fits. Each row of plots compares two productivity assumptions side-by-side.

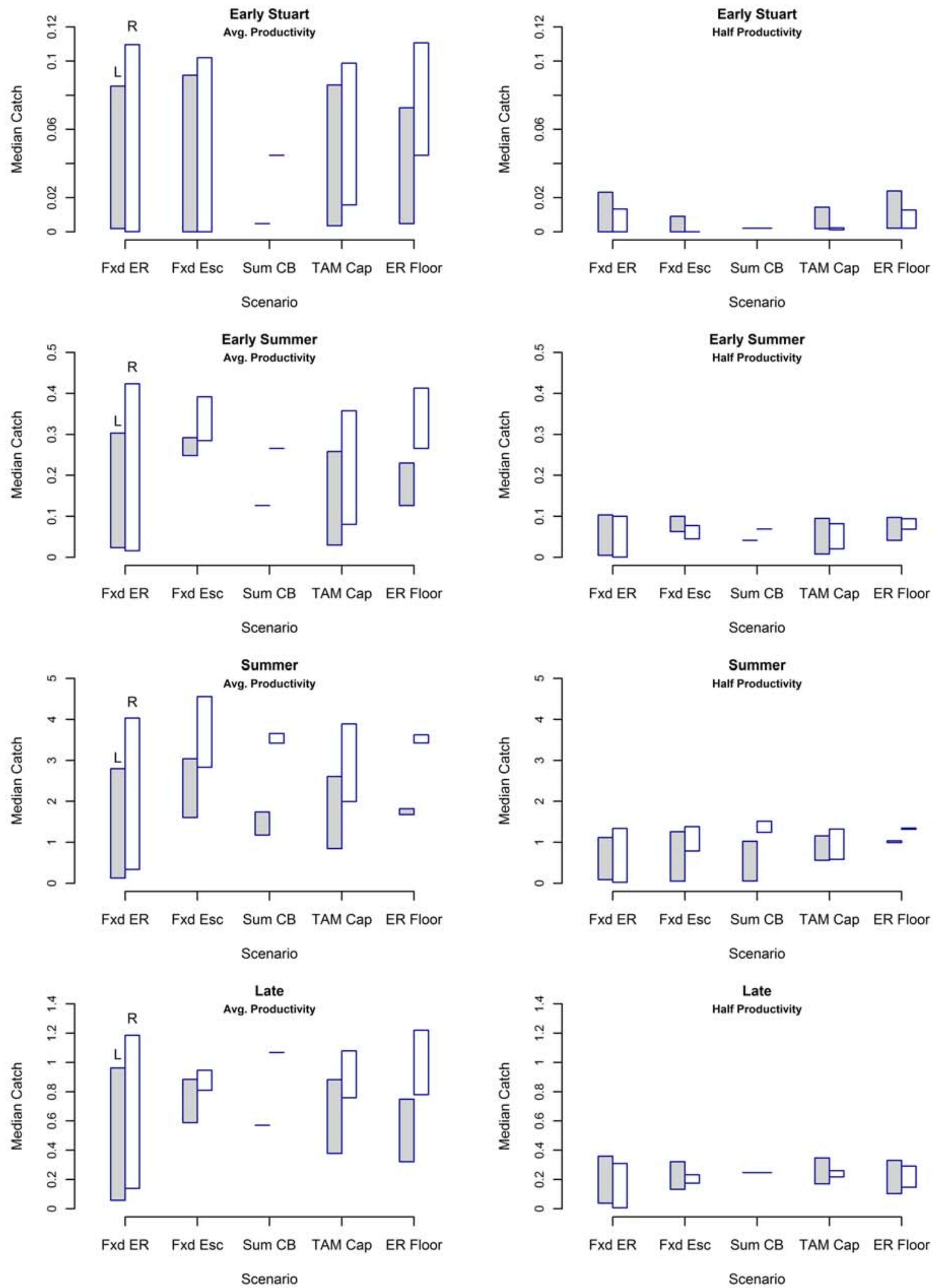


Figure 56: Scenario comparisons – 4 Management groups, median catch
Each bar shows the range of a performance measure. Each panel has 5 sets of bars, each set corresponding to one scenario that varies an aspect of a harvest strategy (Figure 30 to Figure 35). Each set of bars compares the range of results for Larkin (L) and Ricker (R) SR fits. Each row of plots compares two productivity assumptions side-by-side.

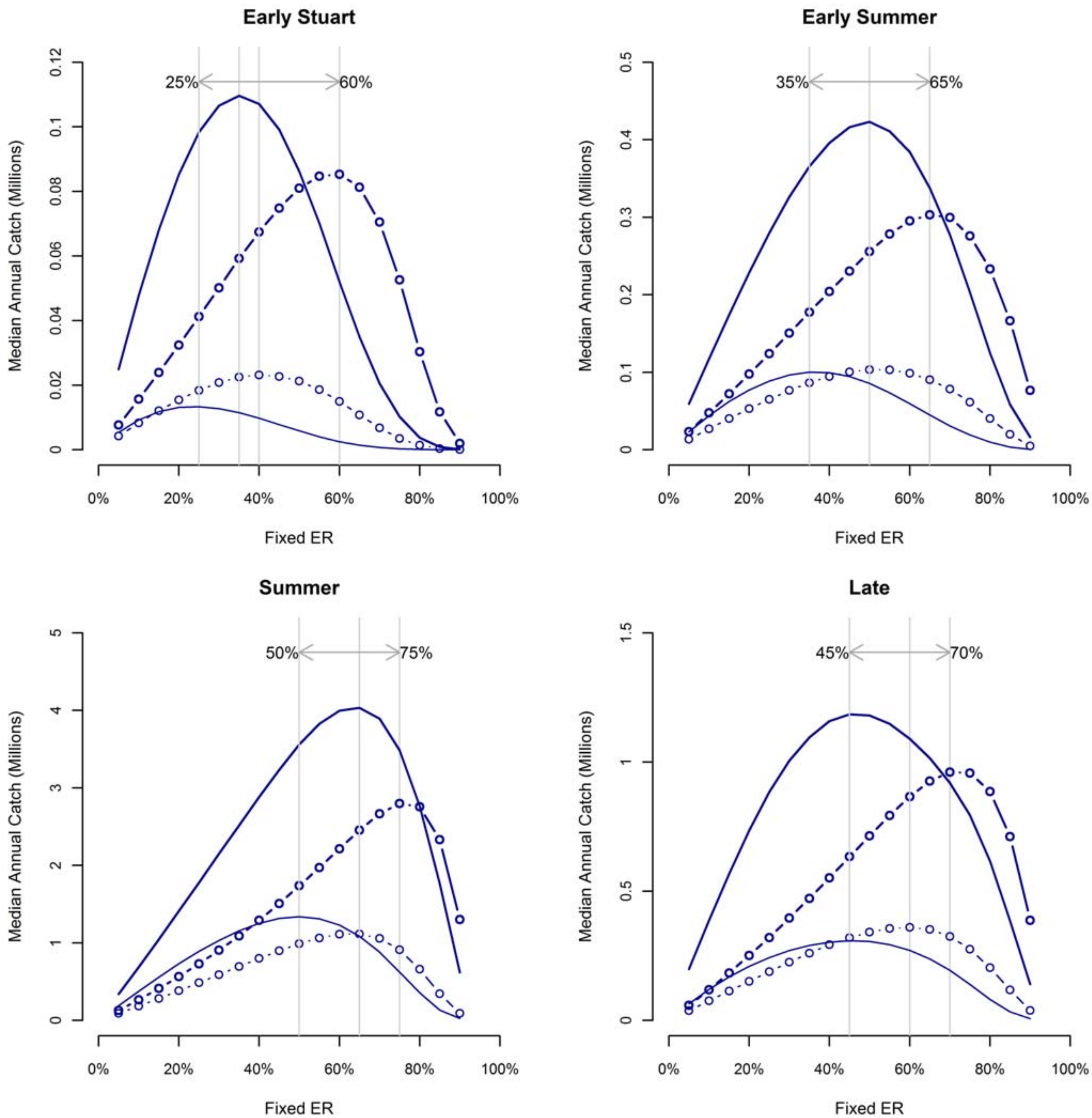


Figure 57: Median catch patterns – Changing fixed ER, 4 alternative assumptions
Each panel shows the effect of changing fixed ER from 5% to 90% under 4 alternative assumptions: Ricker (line) or Larkin (circles) SR models with average (thick line) or half (thin line) productivity. A vertical line marks the peak in median catch for each alternative, and the horizontal arrow shows the range of fixed ER that maximizes median annual catch across the 4 alternatives.

APPENDIX 1 : WINBUGS CODE FOR ESTIMATING LARKIN PARAMETERS

```
#Larkin Model

model{
   for( i in 4 : N) {
         R_Obs[i] ~ dlnorm(R[i],tau_R)          #  likelihood function
         R[i] <- RS_log[i] + log(S[i])          #  prediction model

         # Larkin model
         RS_log[i] <-alpha - beta0 * S[i] -beta1*S[i-1] -beta2*S[i-2]-beta3*S[i-3]

         #  model checking section (residuals, replicated data, p-values)
         resid[i] <- log(R_Obs[i]) - R[i]
         Rep[i] ~ dlnorm(R[i],tau_R)
         Pvalue[i] <- step(Rep[i]-log(R_Obs[i]) )
   }

# Larkin model priors
   alpha ~ dnorm(0,0.001)              # prior for Larkin α

   beta0 <- 1/Smax                      # relationship between capacity parameter and the
                                        number of spawners at maximum recruitment
   Smax~ dlnorm(log_Shi,1)I(,sShi)         # prior for Larkin β0 with upper constraint sShi
   sShi <- 3*Shi                        # upper constraint – 3 times highest number of
                                        spawners in dataset
   log_Shi<- log(Shi)                   # mean for lognormal prior for β0

   beta1 ~ dunif(0,100)                 # prior for Larkin β1
   beta2 ~ dunif(0,100)                 # prior for Larkin β2
   beta3 ~ dunif(0,100)                 # prior for Larkin β3

   tau_R ~ dgamma(0.001,0.001)          # prior for precision parameter
   sigma <- 1 / sqrt(tau_R)             # transform precision to standard deviation
}
```

WinBUGS notation	Description
data based inputs	
R_Obs[i]	observed recruits from broodyear i
S[i]	spawners on the grounds in year i
Shi	highest number of spawners in dataset

APPENDIX 2: DETAILED BAYES DIC RESULTS.

Eight alternative model forms were fitted under 2 different assumptions about random errors (Section 2.2.10). Model forms differ in the number of lag terms to capture delayed-density dependence. The Ricker model has no lag terms, the full Larkin model has 3 lag terms, and the Larkin model variations have one or two lag-terms, as labeled. The default assumption for random error is a lognormal distribution (L), but a normal error (N) distribution was also tested. Model comparisons are based on the difference in the Deviance Information Criterion (DIC). Models within 5 of the lowest DIC are considered plausible candidate models (Section 3.2.1), and are highlighted in the table.

deltaDIC Cut-off
5

	Ricker		**Larkin**		**Larkin 1**		**Larkin 1,2**		**Larkin 1,2,3**		**Larkin 2**		**Larkin 2,3**		**Larkin 1,3**		
	L	N	L	N	L	N	L	N	L	N	L	N	L	N	L	N	min DIC
E. Stuart	-80.9	-4.21	**-86**	-8.65	**-85.4**	-6	-81.3	-5.88	-79.8	-3.63	**-86.8**	-9.31	-80.3	-6.49	**-84.7**	-7.25	-86.833
L. Stuart	**-34.7**	130.8	**-33.3**	104.6	**-35**	101.4	**-32.9**	116.3	**-31.4**	123	**-34.9**	102.7	**-31.3**	118	**-33.3**	103.6	-34.961
Stellako	25.48	38.34	**6.076**	23.41	25.14	35.85	26.94	38.21	**3.478**	23.36	26.69	36.27	**5.035**	24.11	**4.023**	22.95	3.478
Bowron	**-283**	-225	-268	-207	-271	-211	-271	-209	-270	-209	-269	-209	-269	-207	-268	-209	-283.048
Raft	**-308**	-275	-295	-262	-295	-259	-297	-265	-296	-263	-295	-263	-296	-264	-294	-260	-307.987
Quesnel	**-161**	235.4	**-165**	118.8	-142	212.2	-154	180.5	-152	210.1	-154	137	**-162**	182.4	-160	129.7	-165.255
Chilko	124.9	165.1	**121.9**	160.5	**119.4**	157.9	**123.7**	160.2	125.2	161.2	**120.4**	159.2	125.1	161.8	**121.2**	159.3	119.362
Seymour	**-168**	-78.3	**-167**	-76.4	-163	-79.1	**-164**	-70	-159	-70.2	**-166**	-77.3	-163	-68.4	**-167**	-78.1	-168.41
L. Shuswap	-33.6	243.4	**-39.7**	218.8	-33.1	218.3	-33.5	229.5	-29.9	228.6	**-37.8**	220.5	-32.4	230.2	-32.5	216	-39.711
Birkenhead	**1.176**	37.83	**2.113**	39.01	**0.291**	36.98	**3.987**	38.57	**4.205**	37.85	**1.254**	38.33	**4.795**	39.51	**1.549**	37.55	0.291
Cultus	**-283**	-185	-267	-170	-270	-169	-270	-174	-269	-170	-268	-171	-268	-172	-268	-168	-283.272
Portage	**-245**	-175	-223	-159	-225	-162	-221	-161	-220	-160	-224	-161	-219	-158	-224	-160	-245.048
Weaver	**1.183**	10.37	8.1	15.89	7.892	13.91	8.824	14.46	**4.929**	12.66	9.79	16.11	6.999	14.41	**6.103**	14.09	1.183
Fennell	**-222**	-197	-202	-180	-200	-179	-202	-181	-200	-180	-202	-181	-202	-180	-201	-180	-221.943
Scotch	**-125**	-65.3	**-126**	-82.2	-114	-69.6	-110	-56.5	-112	-59.7	-115	-69	-112	-59	-121	-84.1	-126.451
Gates	**-171**	-118	-155	-105	-145	-105	-151	-109	-149	-104	-150	-107	-155	-107	-149	-103	-170.546
Nadina	**-128**	-64.3	-115	-55.7	-116	-54.5	-117	-58	-117	-54	-115	-57.1	-117	-56.5	-116	-52.3	-128.388
Upper Pitt	**-185**	-180	**-185**	-169	-177	-169	**-185**	-171	-178	-170	**-185**	-170	**-186**	-171	-179	-169	-186.169
Harrison	**-208**	-139	-192	-132	-195	-132	-196	-133	-195	-130	-194	-134	-194	-132	-193	-134	-207.986

APPENDIX 3: SPAWNER-RECRUIT DATA

Stock ID	Stock Name
1	Early Stuart
2	Late Stuart
3	Stellako
4	Bowron
5	Raft
6	Quesnel
7	Chilko
8	Seymour
9	Late Shuswap
10	Birkenhead
11	Cultus
12	Portage
13	Weaver Creek
14	Fennel Creek
15	Scotch Creek
16	Gates
17	Nadina
18	Upper Pitt River
19	Harrison

1 **Early Stuart** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	1,671,741	688,013	386,816	1,814,783
Avg	315,809	93,389	44,030	313,620
Min	12,731	1,522	793	10,031

Year	Run	Spawners	Effective Females	Recruits
1948	NA	19,979	10,859	198,153
1949	NA	582,228	168,471	1,036,926
1950	NA	59,104	25,658	241,666
1951	NA	60,423	29,787	173,654
1952	NA	29,925	15,483	88,600
1953	1,048,757	154,036	78,332	540,891
1954	241,825	35,050	18,010	155,823
1955	158,998	2,159	1,397	27,467
1956	93,523	25,020	16,662	110,394
1957	548,612	234,850	119,278	1,222,913
1958	157,678	38,807	22,196	103,107
1959	26,525	2,670	1,297	20,835
1960	103,397	14,447	7,401	74,149
1961	1,225,877	198,921	87,809	255,842
1962	108,532	26,716	14,075	75,785
1963	14,944	4,607	2,590	92,554
1964	76,708	2,390	1,300	42,887
1965	256,325	23,045	11,242	417,211
1966	71,082	10,830	5,959	84,786
1967	99,548	21,044	11,167	339,693
1968	28,197	1,522	793	10,423
1969	432,919	109,655	48,687	1,375,518
1970	84,989	32,578	15,806	182,136
1971	326,153	95,940	45,612	431,210
1972	24,188	4,657	2,253	32,232
1973	1,367,393	299,892	153,870	1,352,015
1974	187,232	39,518	21,603	145,244
1975	426,227	65,752	26,248	223,085
1976	44,187	11,761	6,792	31,877
1977	1,343,698	117,445	53,381	761,694
1978	146,425	50,004	20,005	72,852
1979	222,745	92,746	36,172	107,936
1980	32,300	16,939	7,361	63,501
1981	755,703	129,457	67,227	350,141
1982	80,159	4,557	2,158	27,816
1983	90,997	23,867	13,121	188,892
1984	56,091	45,201	21,868	242,028
1985	356,844	234,219	116,610	1,208,877
1986	46,024	28,584	15,219	145,942
1987	178,007	148,194	75,970	525,920
1988	223,990	179,807	88,069	379,269
1989	1,211,856	384,799	211,039	1,138,789
1990	154,872	97,035	47,063	166,086
1991	512,486	141,119	85,454	144,459
1992	350,827	66,098	36,564	100,376
1993	1,151,645	688,013	386,816	1,814,783
1994	204,097	29,125	14,498	29,030
1995	138,323	122,856	57,322	189,600
1996	96,397	87,570	41,063	464,146
1997	1,671,741	266,941	73,417	147,572
1998	189,780	32,570	9,375	28,692
1999	171,629	24,552	8,189	30,566
2000	378,192	89,858	35,334	135,874
2001	214,191	170,981	82,849	252,006
2002	62,663	24,637	12,939	24,566
2003	30,276	13,166	6,932	10,031
2004	137,101	9,281	5,253	37,815
2005	219,696	98,537	51,183	NA
2006	55,988	35,816	15,914	NA
2007	12,731	5,347	2,376	NA
2008	34,036	29,867	14,446	NA

2 **Late Stuart** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	5,163,174	1,363,826	744,565	5,327,124
Avg	567,905	132,071	67,026	558,360
Min	2,147	35	16	327

Year	Run	Spawners	Effective Females	Recruits
1948	NA	NA	NA	327
1949	NA	107,752	39,085	1,530,202
1950	NA	5,843	1,834	39,681
1951	NA	4,364	1,247	63,810
1952	NA	35	16	3,973
1953	1,527,145	368,634	78,689	1,552,239
1954	36,886	5,470	2,687	137,965
1955	58,590	7,582	3,274	51,345
1956	12,413	913	466	46,102
1957	1,548,251	531,108	300,029	1,329,884
1958	138,477	23,619	13,152	54,677
1959	52,900	8,225	4,090	7,392
1960	15,466	2,396	1,307	9,617
1961	1,360,396	410,887	194,469	778,478
1962	55,027	18,643	9,073	45,069
1963	7,080	3,222	1,092	12,049
1964	8,034	1,816	824	3,101
1965	773,362	214,943	122,789	1,124,519
1966	51,082	9,027	4,164	74,079
1967	13,888	1,629	897	16,556
1968	2,147	389	179	31,299
1969	1,103,957	207,014	114,306	1,625,590
1970	94,021	14,978	8,027	70,838
1971	8,145	1,535	725	66,770
1972	40,187	7,341	3,411	18,766
1973	1,607,170	214,230	116,706	666,098
1974	91,651	14,190	7,371	50,716
1975	65,527	14,229	5,679	215,116
1976	16,470	2,898	1,674	3,339
1977	661,599	146,459	75,890	1,357,741
1978	56,784	12,738	7,115	79,447
1979	215,365	31,918	16,711	6,854
1980	3,921	946	286	21,440
1981	1,314,560	249,494	120,124	2,033,901
1982	113,596	16,758	8,681	60,989
1983	15,782	2,246	1,451	17,944
1984	21,440	1,228	672	14,744
1985	1,978,203	274,621	159,101	3,507,629
1986	107,988	28,715	15,044	816,561
1987	23,116	6,472	2,393	380,071
1988	26,026	7,117	3,638	208,786
1989	3,367,350	575,697	327,096	5,327,124
1990	858,898	189,079	111,747	389,823
1991	376,655	76,860	40,200	109,581
1992	322,645	19,513	12,422	135,399
1993	5,163,174	1,363,826	744,565	3,764,256
1994	517,217	76,462	40,717	115,440
1995	108,095	34,362	17,181	133,454
1996	150,838	62,991	27,297	1,023,000
1997	3,255,574	907,652	415,149	430,895
1998	620,406	138,397	67,836	277,262
1999	100,749	61,574	33,801	133,622
2000	849,458	454,397	226,267	913,822
2001	564,418	351,569	179,540	505,343
2002	343,512	34,498	17,820	125,952
2003	131,907	36,647	19,212	21,783
2004	884,765	83,418	51,370	284,071
2005	458,862	293,124	164,657	NA
2006	211,304	27,504	14,283	NA
2007	20,631	8,487	4,144	NA
2008	269,580	146,569	57,879	NA

3 **Stellako** ||| = 1/10 of max for each variable

Max	1,852,392	371,604	200,541	1,904,124
Avg	469,977	105,909	52,692	465,579
Min	59,073	15,763	9,242	49,132

Year	Run	Spawners	Effective Females	Recruits
1948	NA	15,763	9,242	207,177
1949	NA	104,720	40,228	179,876
1950	NA	145,021	77,415	939,117
1951	NA	96,076	51,413	455,367
1952	NA	40,384	19,920	110,701
1953	200,034	42,134	20,388	174,245
1954	910,135	141,859	72,273	1,211,299
1955	384,791	51,739	29,937	629,796
1956	195,306	38,438	22,276	246,735
1957	176,197	38,522	18,044	151,843
1958	1,158,256	112,251	61,581	340,460
1959	670,552	79,305	41,872	541,420
1960	247,499	38,880	22,718	164,514
1961	171,234	46,863	18,136	147,402
1962	331,106	124,485	44,532	589,505
1963	531,152	138,794	41,535	727,926
1964	170,113	30,890	16,182	177,837
1965	158,301	39,385	20,479	243,651
1966	583,074	101,529	51,509	359,906
1967	731,057	91,480	32,467	550,524
1968	184,315	30,368	13,680	129,822
1969	238,902	49,211	25,629	253,245
1970	348,976	45,797	26,727	234,108
1971	554,728	39,691	20,147	509,267
1972	144,381	36,700	20,386	756,214
1973	240,736	30,404	15,424	85,901
1974	246,689	41,275	23,718	303,122
1975	513,105	175,941	68,451	1,904,124
1976	711,237	150,734	65,299	244,357
1977	122,420	23,047	10,894	265,700
1978	295,694	58,898	32,528	437,405
1979	1,852,392	290,042	152,583	623,924
1980	284,339	72,050	28,477	755,406
1981	237,504	21,826	12,030	285,898
1982	445,024	69,420	34,888	357,773
1983	526,984	121,692	61,357	1,257,480
1984	681,128	60,957	32,672	1,011,189
1985	455,291	42,099	21,968	128,742
1986	362,232	77,177	44,611	561,845
1987	1,144,418	211,085	98,179	435,676
1988	903,283	367,702	200,541	991,499
1989	364,112	43,179	15,926	222,287
1990	476,408	93,920	56,536	951,836
1991	470,053	94,884	54,400	336,569
1992	648,446	97,979	55,190	868,461
1993	553,471	91,071	42,858	309,844
1994	956,333	136,709	63,628	682,889
1995	388,978	122,676	41,176	183,959
1996	771,677	332,207	167,671	811,994
1997	202,078	55,357	23,264	125,173
1998	835,157	185,641	97,011	637,997
1999	216,713	138,137	66,125	174,462
2000	692,039	371,604	195,418	717,671
2001	245,067	151,409	61,635	287,128
2002	561,079	322,711	177,668	248,375
2003	277,491	78,093	43,879	49,132
2004	678,056	86,688	53,805	248,252
2005	273,546	175,299	102,347	NA
2006	307,985	147,189	79,884	NA
2007	59,073	41,328	19,649	NA
2008	228,384	159,737	73,837	NA

4 **Bowron** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	207,472	35,000	16,178	214,316
Avg	39,575	9,577	4,559	40,345
Min	3,098	836	275	3,822

Year	Run	Spawners	Effective Females	Recruits
1948	NA	25,205	12,826	80,266
1949	NA	22,283	10,721	62,791
1950	NA	16,146	7,298	75,548
1951	NA	21,731	10,039	103,821
1952	NA	18,645	8,568	43,304
1953	63,296	13,277	5,734	75,579
1954	65,743	10,515	4,566	66,916
1955	113,084	9,350	4,471	96,955
1956	36,995	6,994	3,639	38,484
1957	77,555	12,011	6,416	41,966
1958	67,991	14,843	8,297	18,155
1959	95,916	29,247	14,614	61,865
1960	31,875	7,620	3,506	17,733
1961	51,949	7,449	3,675	28,148
1962	18,914	6,286	3,219	21,327
1963	56,625	25,141	11,468	214,316
1964	22,678	1,500	690	27,507
1965	27,292	2,659	1,170	17,849
1966	20,163	2,470	1,151	22,249
1967	207,472	31,695	13,991	206,494
1968	34,781	3,611	1,710	44,642
1969	18,861	3,872	1,936	17,211
1970	22,349	1,305	497	16,197
1971	194,910	25,497	10,761	124,507
1972	49,906	4,138	1,969	16,971
1973	23,623	4,558	2,012	10,662
1974	17,034	1,850	1,046	17,431
1975	124,161	29,700	14,735	122,780
1976	17,206	2,250	1,069	7,112
1977	10,649	2,500	1,214	15,396
1978	15,948	3,141	1,678	40,627
1979	123,471	35,000	16,178	29,984
1980	8,028	2,894	1,376	45,170
1981	5,875	1,170	562	16,532
1982	49,424	1,647	990	5,277
1983	16,438	6,451	3,484	38,556
1984	53,651	10,461	4,909	50,603
1985	20,513	6,395	3,030	19,177
1986	4,891	3,118	1,396	21,198
1987	38,820	11,071	5,660	22,592
1988	46,654	12,780	7,405	13,050
1989	22,328	2,534	1,367	12,842
1990	23,422	7,860	5,065	31,130
1991	18,807	4,920	2,460	48,807
1992	15,958	2,560	1,117	12,883
1993	6,326	1,184	592	20,467
1994	26,858	4,380	1,845	10,849
1995	59,839	34,417	13,487	27,391
1996	11,707	8,176	4,054	26,776
1997	19,274	4,811	2,119	5,024
1998	10,289	4,751	2,830	17,001
1999	29,198	8,238	3,295	19,734
2000	22,954	13,440	6,720	25,283
2001	7,416	5,842	2,752	6,825
2002	14,961	8,770	4,505	7,674
2003	25,463	6,752	3,038	3,822
2004	23,887	836	418	6,225
2005	5,829	1,649	825	NA
2006	9,671	1,501	614	NA
2007	4,157	2,069	1,023	NA
2008	3,098	1,005	275	NA

5 **Raft** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	142,932	66,292	27,668	115,396
Avg	31,958	8,849	4,127	32,933
Min	1,510	464	198	1,461

Year	Run	Spawners	Effective Females	Recruits
1948	NA	10,359	5,524	63,337
1949	NA	6,113	2,109	39,626
1950	NA	6,404	1,917	45,556
1951	NA	8,544	3,365	47,653
1952	NA	15,617	5,116	51,182
1953	37,449	7,904	3,600	32,124
1954	42,435	9,988	5,352	50,488
1955	40,631	5,079	2,905	60,522
1956	59,176	9,037	5,180	27,140
1957	35,526	6,860	3,314	21,015
1958	40,810	10,214	6,235	23,143
1959	63,790	10,210	5,232	23,614
1960	25,425	5,513	2,690	16,948
1961	28,760	7,293	3,014	24,325
1962	24,602	7,613	4,197	40,549
1963	21,010	8,683	2,693	9,817
1964	17,944	5,177	2,666	48,724
1965	24,308	6,624	2,669	20,626
1966	39,740	6,244	2,666	23,539
1967	12,152	1,279	358	9,658
1968	41,065	8,089	3,455	106,397
1969	27,547	5,537	2,577	14,370
1970	22,206	4,462	1,205	8,860
1971	11,060	801	223	12,361
1972	102,664	11,048	4,507	57,821
1973	15,727	2,714	1,345	9,361
1974	12,043	2,383	1,479	12,223
1975	10,180	2,609	1,391	6,716
1976	59,753	8,665	3,976	19,926
1977	2,583	617	198	5,917
1978	19,271	2,493	1,343	18,748
1979	6,164	1,758	693	3,039
1980	19,616	5,418	2,056	51,723
1981	4,312	815	312	8,639
1982	15,077	2,992	1,533	3,770
1983	7,902	2,780	1,821	5,601
1984	49,712	19,086	6,701	47,055
1985	11,150	3,637	1,922	4,533
1986	3,791	2,095	1,080	3,013
1987	4,441	1,436	723	3,820
1988	35,407	19,851	9,207	50,175
1989	16,868	1,647	925	11,299
1990	4,598	630	412	2,544
1991	1,510	464	264	1,461
1992	44,211	8,236	4,112	67,359
1993	15,749	5,047	2,934	33,202
1994	5,545	1,712	800	28,472
1995	1,848	1,040	682	27,270
1996	65,906	46,592	21,381	112,592
1997	24,410	6,093	2,367	51,264
1998	15,571	7,198	3,585	16,238
1999	47,072	6,979	3,499	61,149
2000	93,799	66,292	27,668	115,396
2001	48,675	32,498	16,025	96,695
2002	30,278	18,369	8,402	42,833
2003	37,804	10,040	4,890	8,475
2004	142,932	5,611	3,244	67,284
2005	87,357	26,456	16,967	NA
2006	37,794	6,073	3,442	NA
2007	25,240	14,353	8,064	NA
2008	47,043	10,406	3,562	NA

6 **Quesnel** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	12,161,405	3,510,789	1,740,472	12,544,246
Avg	1,380,161	365,248	177,480	1,356,472
Min	194	49	9	165

Year	Run	Spawners	Effective Females	Recruits
1948	NA	100	48	618
1949	NA	30,664	19,209	486,378
1950	NA	398	264	2,048
1951	NA	49	9	413
1952	NA	184	51	562
1953	463,443	110,917	47,564	610,245
1954	2,014	299	146	10,692
1955	413	63	30	180
1956	6,464	80	38	1,133
1957	604,123	223,667	134,562	999,533
1958	10,912	1,863	1,269	3,412
1959	198	65	29	165
1960	10,894	292	123	1,475
1961	989,607	302,565	69,990	1,240,890
1962	3,536	1,078	566	7,287
1963	194	83	40	956
1964	45,950	254	77	2,812
1965	1,195,837	364,706	105,401	1,667,172
1966	7,859	1,753	1,040	7,462
1967	956	119	24	1,761
1968	16,973	699	333	428
1969	1,652,135	278,961	78,639	1,640,832
1970	7,953	1,368	388	20,339
1971	2,146	171	16	747
1972	6,910	111	46	865
1973	1,626,582	278,311	112,538	2,336,434
1974	28,107	4,459	2,587	31,024
1975	756	193	105	1,865
1976	6,497	305	209	1,233
1977	2,326,885	516,199	160,712	3,878,522
1978	33,233	8,614	4,349	196,724
1979	3,564	511	238	6,011
1980	9,679	308	98	2,446
1981	3,810,928	748,621	332,306	9,786,652
1982	245,363	39,841	20,053	555,386
1983	12,612	2,155	1,098	40,412
1984	25,962	914	551	6,953
1985	9,553,856	1,349,263	694,708	12,544,246
1986	712,295	181,467	94,844	2,532,784
1987	87,912	20,546	11,238	176,592
1988	46,737	6,832	4,185	26,342
1989	12,161,405	1,870,820	940,610	10,641,495
1990	2,716,516	488,259	259,597	3,283,634
1991	287,552	46,259	24,862	151,175
1992	96,025	5,862	3,046	29,214
1993	10,340,080	2,620,454	1,507,416	6,851,040
1994	3,236,300	659,499	356,244	2,477,091
1995	436,433	216,109	116,916	167,306
1996	82,090	41,187	21,719	90,690
1997	6,446,284	1,858,652	904,886	4,692,773
1998	2,666,551	1,179,252	534,587	4,739,875
1999	332,450	189,360	106,950	810,586
2000	117,802	63,703	37,162	53,810
2001	4,381,602	3,510,789	1,740,472	3,701,006
2002	4,800,147	3,062,151	1,312,599	640,265
2003	853,991	279,170	148,465	143,876
2004	271,722	10,222	6,628	13,042
2005	3,592,160	1,447,381	777,707	NA
2006	723,165	169,768	90,415	NA
2007	119,068	75,100	33,777	NA
2008	68,161	7,091	2,471	NA

8 **Seymour** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	823,255	272,041	108,279	824,169
Avg	134,308	32,080	15,051	132,489
Min	7,831	1,323	311	1,944

Year	Run	Spawners	Effective Females	Recruits
1948	NA	3,889	1,280	29,658
1949	NA	10,772	3,476	34,705
1950	NA	11,049	4,697	162,026
1951	NA	24,320	11,505	68,943
1952	NA	5,963	2,780	11,249
1953	26,526	5,692	2,907	45,268
1954	169,597	24,774	12,852	461,522
1955	68,057	8,971	5,178	310,002
1956	12,160	2,490	1,102	12,763
1957	69,000	10,870	7,416	24,583
1958	429,330	78,371	44,285	195,518
1959	317,483	52,310	25,773	175,980
1960	12,088	2,901	1,862	8,837
1961	20,357	3,622	1,957	32,923
1962	201,147	57,836	28,664	176,546
1963	175,764	71,654	26,742	114,086
1964	9,120	2,745	1,321	18,498
1965	28,815	6,089	2,550	34,890
1966	177,006	28,698	12,943	141,828
1967	116,094	13,361	7,264	220,851
1968	19,851	3,838	2,064	22,108
1969	35,869	7,176	3,276	14,875
1970	139,811	11,971	3,603	226,369
1971	218,158	19,028	9,463	135,310
1972	26,273	2,802	1,418	56,785
1973	15,232	2,704	1,150	24,800
1974	225,046	44,588	25,868	248,730
1975	134,549	36,828	16,844	180,684
1976	58,818	8,306	4,898	18,422
1977	25,734	5,709	2,883	70,046
1978	249,042	62,808	30,757	261,925
1979	175,050	49,306	24,866	135,614
1980	22,335	8,309	4,616	52,848
1981	54,756	11,359	5,354	30,875
1982	272,372	63,271	27,219	508,455
1983	97,986	29,831	14,014	272,460
1984	87,664	17,172	9,148	36,017
1985	36,716	5,620	2,684	43,576
1986	499,854	126,166	57,069	824,169
1987	274,809	84,315	41,081	442,220
1988	44,371	16,781	7,989	10,843
1989	33,250	5,507	2,864	18,877
1990	823,255	272,041	108,279	278,827
1991	427,423	128,253	60,845	95,565
1992	34,900	5,742	3,586	17,906
1993	20,761	10,119	4,950	8,716
1994	272,278	64,038	19,151	172,547
1995	90,723	48,746	23,928	66,040
1996	26,383	21,654	9,590	39,470
1997	9,029	2,254	836	1,944
1998	172,367	34,048	14,548	214,404
1999	66,985	18,895	10,072	133,931
2000	34,691	25,465	11,860	59,563
2001	8,605	6,892	3,743	19,042
2002	210,570	113,408	55,465	507,957
2003	109,587	31,345	18,483	12,366
2004	86,533	1,323	762	6,904
2005	16,798	3,590	2,326	NA
2006	501,926	107,941	57,783	NA
2007	20,507	9,979	5,905	NA
2008	7,831	1,350	311	NA

9 **Late Shuswap** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	15,110,393	5,532,263	2,845,464	15,869,336
Avg	2,199,677	647,524	321,206	2,161,609
Min	2,659	164	83	1,388

Year	Run	Spawners	Effective Females	Recruits
1948	NA	10,356	8,502	28,330
1949	NA	3,606	2,011	40,793
1950	NA	1,271,381	583,045	9,944,058
1951	NA	143,498	82,097	529,582
1952	NA	7,317	4,211	17,932
1953	623,812	3,472	1,623	31,027
1954	9,325,573	2,026,693	1,067,603	15,869,336
1955	564,055	63,859	44,632	865,520
1956	18,289	3,321	2,103	7,974
1957	746,422	2,809	1,651	3,163
1958	15,110,393	3,297,045	1,644,152	2,213,808
1959	909,161	134,826	89,270	382,302
1960	8,114	1,907	1,322	2,549
1961	127,110	1,150	854	8,147
1962	2,086,042	1,144,115	651,863	2,925,312
1963	386,642	158,468	80,244	3,131,346
1964	2,659	604	345	19,626
1965	97,559	2,087	1,332	24,808
1966	2,820,125	1,280,308	660,849	4,051,932
1967	3,144,289	844,896	402,412	3,184,223
1968	22,588	3,686	2,713	21,961
1969	125,541	5,985	3,166	29,860
1970	3,982,320	1,524,303	785,282	5,580,907
1971	3,143,039	289,908	158,976	702,125
1972	32,300	4,192	2,155	44,505
1973	202,978	3,808	2,467	67,868
1974	5,397,611	1,150,772	619,123	7,050,422
1975	715,459	167,381	85,544	1,026,264
1976	42,506	4,780	3,072	14,170
1977	211,326	12,510	6,027	93,645
1978	6,891,681	1,897,353	1,014,761	9,657,108
1979	1,039,295	299,547	162,142	1,499,666
1980	14,747	2,498	1,816	23,307
1981	212,923	10,314	5,959	9,470
1982	9,366,352	3,060,235	1,568,605	9,464,846
1983	1,655,793	211,365	100,256	1,980,917
1984	38,141	4,346	2,409	33,174
1985	89,787	1,468	806	13,723
1986	9,223,742	2,345,230	1,068,479	10,934,052
1987	2,125,988	617,343	319,734	3,903,932
1988	48,992	5,011	3,558	8,220
1989	72,317	563	380	13,135
1990	10,638,002	3,717,673	1,745,709	7,770,211
1991	4,086,523	1,255,852	616,033	866,189
1992	62,092	12,996	6,640	19,909
1993	36,347	1,395	765	15,366
1994	7,603,407	1,409,211	686,190	2,610,200
1995	991,547	428,875	210,969	771,591
1996	31,054	12,466	5,492	61,532
1997	24,420	1,072	597	34,711
1998	2,590,229	1,389,271	680,650	7,248,023
1999	770,717	343,540	138,247	698,913
2000	51,951	855	164	1,388
2001	149,532	4,861	2,141	8,890
2002	7,142,670	5,532,263	2,845,464	7,509,787
2003	697,945	381,278	189,793	138,420
2004	22,768	2,994	2,234	1,558
2005	75,289	21,113	11,792	NA
2006	7,394,430	2,897,709	1,170,725	NA
2007	175,092	61,043	32,296	NA
2008	12,198	164	83	NA

10 **Birkenhead** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	1,645,000	335,630	197,896	1,815,929
Avg	384,265	80,757	43,804	382,014
Min	54,042	11,905	5,510	13,338

Year	Run	Spawners	Effective Females	Recruits
1948	NA	83,787	54,755	207,185
1949	NA	70,504	43,328	306,824
1950	NA	64,440	41,370	241,164
1951	NA	21,296	13,590	215,197
1952	NA	47,041	24,744	243,943
1953	277,921	42,491	16,287	155,190
1954	241,810	18,213	8,635	174,476
1955	163,996	14,553	8,185	274,765
1956	267,364	49,754	27,156	277,412
1957	163,859	14,536	7,068	73,969
1958	209,572	15,166	5,510	128,540
1959	273,459	26,159	11,388	267,850
1960	229,571	36,838	19,198	168,764
1961	110,107	31,681	10,550	128,515
1962	131,644	26,369	14,311	102,483
1963	255,230	48,893	20,769	455,767
1964	188,770	48,908	27,978	365,682
1965	109,135	16,230	9,769	163,688
1966	200,785	20,116	13,462	316,227
1967	337,100	39,876	17,580	491,588
1968	332,046	57,947	31,042	285,105
1969	267,383	37,382	14,324	791,608
1970	238,082	30,656	19,252	736,053
1971	491,308	24,629	16,143	368,545
1972	359,172	54,516	26,202	519,125
1973	616,194	56,653	28,374	216,524
1974	880,175	119,637	85,495	722,909
1975	354,038	61,538	23,315	120,109
1976	528,870	77,305	50,023	616,213
1977	247,970	23,845	12,799	425,661
1978	466,395	94,782	48,158	664,732
1979	351,482	60,988	35,482	414,741
1980	524,681	78,613	32,786	163,172
1981	439,405	49,023	27,175	266,159
1982	627,225	119,738	72,353	1,815,929
1983	413,274	44,029	21,113	806,674
1984	246,496	40,245	23,227	467,656
1985	190,989	11,905	5,758	244,631
1986	1,645,000	335,630	197,896	1,211,967
1987	926,526	164,849	89,432	988,553
1988	525,069	166,591	75,535	923,851
1989	262,065	29,334	15,739	1,147,929
1990	983,804	166,773	97,112	238,613
1991	1,047,153	293,626	152,083	120,668
1992	522,057	185,908	93,443	98,306
1993	1,638,660	244,954	151,096	573,466
1994	375,783	39,234	22,315	67,413
1995	87,005	39,871	18,430	170,525
1996	121,470	56,112	27,848	78,931
1997	228,234	50,202	23,275	30,582
1998	406,934	295,669	173,045	618,373
1999	186,244	48,916	26,268	83,528
2000	63,091	13,842	8,333	101,965
2001	62,556	44,450	28,361	191,674
2002	225,740	189,445	107,481	633,756
2003	452,736	309,878	152,651	13,338
2004	99,983	37,617	17,516	76,602
2005	149,258	53,546	27,116	NA
2006	583,865	266,459	137,364	NA
2007	136,045	93,480	54,290	NA
2008	54,042	19,500	6,784	NA

11 **Cultus** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	277,696	47,779	29,903	277,284
Avg	39,679	10,675	5,916	40,360
Min	108	52	17	80

Year	Run	Spawners	Effective Females	Recruits
1948	NA	12,746	6,671	39,076
1949	NA	9,055	5,617	39,151
1950	NA	29,928	18,582	105,287
1951	NA	12,677	9,034	174,068
1952	NA	17,833	11,331	44,424
1953	42,368	11,543	4,939	63,669
1954	105,162	22,036	10,496	65,195
1955	166,202	25,922	16,743	277,284
1956	38,023	13,718	8,486	37,505
1957	75,214	20,375	12,260	28,083
1958	64,096	13,324	7,031	50,913
1959	277,696	47,779	29,903	52,194
1960	36,444	17,640	9,449	23,503
1961	31,338	13,396	6,567	6,148
1962	47,647	26,997	16,384	36,007
1963	52,211	20,303	10,524	138,448
1964	24,249	11,067	5,798	70,603
1965	6,892	2,455	1,515	20,986
1966	39,308	16,919	8,630	45,065
1967	132,823	33,198	17,209	110,501
1968	72,233	25,314	13,889	42,454
1969	25,707	5,942	2,970	6,477
1970	47,795	13,941	7,622	45,857
1971	97,142	9,128	4,638	50,701
1972	49,978	10,366	5,410	30,360
1973	5,941	641	302	713
1974	47,470	8,984	4,999	29,718
1975	48,202	11,349	6,856	115,787
1976	30,377	4,435	2,693	6,129
1977	1,119	82	38	1,571
1978	35,140	5,076	2,947	73,948
1979	109,671	32,031	18,950	109,906
1980	6,490	1,657	900	4,825
1981	6,294	256	134	1,544
1982	70,773	16,725	9,599	18,831
1983	106,803	19,944	11,490	96,326
1984	6,845	720	389	9,321
1985	1,848	424	195	2,431
1986	12,842	3,210	2,020	10,488
1987	100,936	32,162	16,220	65,855
1988	10,114	861	455	7,825
1989	2,222	418	220	10,745
1990	10,419	1,860	944	24,767
1991	65,018	20,157	9,850	17,363
1992	7,505	1,203	698	1,880
1993	11,107	1,063	571	160
1994	23,266	4,399	2,524	10,408
1995	19,089	10,316	4,279	15,414
1996	2,442	2,022	723	4,365
1997	156	88	35	716
1998	10,503	1,959	955	6,025
1999	13,840	12,427	4,800	2,852
2000	5,837	1,227	470	80
2001	698	515	180	212
2002	5,974	4,873	2,375	5,292
2003	2,885	1,939	662	728
2004	108	52	17	NA
2005	402	112	57	NA
2006	5,015	3,509	1,305	NA
2007	934	538	210	NA
2008	1,192	338	145	NA

12 **Portage**

||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	202,593	31,343	15,201	210,984
Avg	46,723	6,448	3,346	42,423
Min	742	9	5	47

Year	Run	Spawners	Effective Females	Recruits
1953	NA	50	24	394
1954	NA	3,369	1,729	38,700
1955	NA	41	20	4,392
1956	NA	NA	NA	NA
1957	NA	40	20	47
1958	35,962	4,791	2,749	25,645
1959	NA	572	286	5,565
1960	NA	NA	NA	NA
1961	NA	23	12	2,723
1962	24,872	11,935	6,326	72,180
1963	NA	2,011	1,116	58,437
1964	NA	9	5	624
1965	NA	981	589	3,463
1966	72,325	31,343	15,201	31,339
1967	56,440	4,025	1,983	4,286
1968	742	86	51	1,046
1969	3,651	963	491	34,582
1970	30,871	3,873	2,139	58,068
1971	4,308	281	155	18,043
1972	4,999	190	98	15,283
1973	32,060	3,963	1,688	91,287
1974	58,801	8,475	4,843	42,611
1975	17,939	3,175	1,631	15,753
1976	23,928	1,042	753	7,590
1977	82,341	7,610	3,923	39,989
1978	41,513	9,978	3,963	111,703
1979	15,089	3,575	2,023	52,692
1980	8,100	1,800	996	12,225
1981	39,750	5,855	2,951	20,069
1982	100,971	23,867	11,734	210,984
1983	63,045	7,747	4,909	37,358
1984	12,420	1,710	941	50,565
1985	17,289	1,765	960	25,840
1986	202,593	14,291	6,212	71,594
1987	49,008	6,820	3,766	63,044
1988	25,630	1,068	797	21,096
1989	49,583	7,900	5,067	199,353
1990	69,041	18,336	8,415	50,970
1991	65,213	12,053	7,292	15,891
1992	17,361	2,706	1,378	17,136
1993	190,877	19,760	9,829	174,902
1994	63,474	9,270	3,890	127,670
1995	17,588	7,875	4,319	40,314
1996	14,118	3,422	1,759	86,511
1997	171,626	9,766	5,056	41,499
1998	130,209	25,179	11,873	18,053
1999	40,228	6,264	2,079	9,078
2000	86,582	1,269	671	12,829
2001	43,064	3,150	1,851	18,610
2002	18,931	14,953	8,001	48,191
2003	8,824	4,940	3,179	5,210
2004	13,572	1,287	778	5,695
2005	18,593	12,082	8,261	NA
2006	48,183	18,882	10,971	NA
2007	4,835	1,699	849	NA
2008	6,002	97	63	NA

13 **Weaver Creek** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	1,338,092	294,083	115,031	1,505,995
Avg	371,305	49,062	23,197	364,686
Min	59,471	2,756	616	42,717

Year	Run	Spawners	Effective Females	Recruits
1966	NA	19,489	9,860	76,161
1967	NA	22,581	10,619	88,405
1968	NA	3,799	2,202	155,396
1969	NA	58,727	30,604	412,913
1970	NA	10,435	5,004	384,039
1971	82,203	4,990	2,656	155,284
1972	154,227	25,738	15,027	350,142
1973	389,606	48,541	24,885	274,667
1974	420,933	64,093	28,099	284,880
1975	151,690	29,736	16,033	169,860
1976	340,808	49,932	28,243	304,434
1977	274,831	52,627	28,510	235,763
1978	268,428	75,171	42,315	1,366,185
1979	200,964	45,026	25,702	141,028
1980	275,796	73,830	43,285	364,714
1981	250,979	42,002	22,627	270,292
1982	1,201,868	294,083	115,031	1,505,995
1983	302,470	39,341	27,380	239,991
1984	346,248	59,602	30,435	635,778
1985	245,733	37,019	22,773	69,300
1986	1,338,092	110,738	41,837	42,717
1987	448,634	59,968	30,106	220,718
1988	594,647	49,258	27,623	513,778
1989	101,711	17,167	10,620	765,938
1990	59,471	16,365	8,524	634,660
1991	198,747	38,121	18,710	65,545
1992	365,168	58,686	28,480	753,217
1993	873,383	84,456	34,019	500,654
1994	672,610	64,956	35,516	715,932
1995	77,637	33,125	10,905	266,443
1996	640,946	72,070	26,849	383,413
1997	509,510	25,504	10,724	215,997
1998	766,084	57,091	29,811	566,885
1999	239,693	34,634	13,106	246,929
2000	446,928	6,613	2,732	114,132
2001	225,093	19,915	8,035	196,083
2002	524,062	101,033	36,269	242,830
2003	248,940	49,488	24,681	188,799
2004	168,587	25,379	13,967	102,858
2005	155,708	48,516	23,597	NA
2006	277,878	39,781	13,618	NA
2007	149,581	37,300	15,825	NA
2008	119,683	2,756	616	NA

14 **Fennel Creek**

||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	69,236	32,279	15,223	78,650
Avg	26,125	7,098	3,895	25,888
Min	1,003	9	5	586

Year	Run	Spawners	Effective Females	Recruits
1967	NA	916	294	15,201
1968	NA	954	577	15,037
1969	NA	52	22	881
1970	NA	9	5	740
1971	NA	1,293	306	16,707
1972	14,846	1,931	1,030	29,007
1973	1,058	205	83	1,106
1974	1,003	140	70	586
1975	15,603	4,005	2,181	62,451
1976	29,190	4,090	2,373	22,761
1977	1,764	355	174	10,484
1978	1,105	107	46	2,390
1979	58,955	15,565	8,046	18,386
1980	23,293	8,437	4,413	36,205
1981	10,031	2,076	1,069	3,947
1982	5,296	1,132	656	11,140
1983	9,144	4,977	2,596	39,122
1984	43,562	11,021	6,291	49,442
1985	4,680	1,598	696	33,819
1986	10,433	6,024	3,324	35,411
1987	38,191	16,633	9,211	78,650
1988	45,929	26,927	13,098	50,650
1989	30,062	3,988	2,813	19,804
1990	43,296	11,862	6,702	22,803
1991	68,149	20,554	11,944	14,854
1992	56,756	9,139	5,959	50,629
1993	20,431	7,546	4,928	42,656
1994	20,406	5,919	3,507	13,865
1995	18,960	11,245	5,986	37,010
1996	46,989	32,279	15,223	13,827
1997	36,539	9,000	4,326	6,261
1998	18,848	8,741	4,966	13,140
1999	40,391	5,697	3,333	43,525
2000	15,045	10,155	4,623	60,597
2001	8,113	5,721	3,302	11,861
2002	11,829	7,198	4,847	76,212
2003	34,407	9,087	5,226	13,693
2004	69,236	2,718	1,568	8,898
2005	13,930	4,220	2,760	NA
2006	69,185	11,117	8,038	NA
2007	19,719	11,212	6,783	NA
2008	10,262	2,270	210	NA

15 **Scotch Creek** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	675,243	144,199	72,732	693,222
Avg	84,587	19,829	9,173	81,275
Min	3,141	107	62	1,532

Year	Run	Spawners	Effective Females	Recruits
1980	NA	107	62	1,532
1981	NA	18,952	6,887	25,367
1982	NA	4,709	2,544	109,597
1983	NA	239	133	2,632
1984	NA	409	265	2,625
1985	25,488	3,385	1,422	44,012
1986	103,900	26,624	11,299	257,059
1987	7,899	2,089	1,149	30,444
1988	4,334	1,060	723	3,320
1989	42,541	7,236	3,928	16,728
1990	250,960	83,388	34,459	316,280
1991	26,781	9,954	4,540	25,716
1992	13,660	2,156	1,385	2,454
1993	16,415	8,359	3,259	11,886
1994	311,164	73,180	26,711	184,451
1995	26,899	14,772	7,811	14,176
1996	5,832	4,609	2,230	4,148
1997	12,372	3,085	1,440	2,253
1998	181,999	35,981	17,024	193,690
1999	14,507	4,093	2,060	26,423
2000	5,333	3,765	1,754	41,212
2001	3,141	2,449	1,336	17,024
2002	191,273	101,269	50,374	693,222
2003	17,993	5,089	2,478	1,681
2004	51,213	783	432	3,933
2005	19,891	4,163	2,686	NA
2006	675,243	144,199	72,732	NA
2007	17,117	8,272	4,758	NA
2008	4,140	654	138	NA

16 **Gates** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	315,105	99,470	17,840	319,543
Avg	54,259	13,496	4,393	55,275
Min	4,217	70	14	412

Year	Run	Spawners	Effective Females	Recruits
1968	NA	10,113	3,835	82,665
1969	NA	777	359	4,766
1970	NA	78	14	412
1971	NA	426	115	12,647
1972	NA	8,323	3,128	132,613
1973	4,217	795	351	14,685
1974	5,248	70	37	2,972
1975	11,901	1,982	1,246	19,756
1976	129,455	17,133	8,820	73,230
1977	11,328	2,582	1,174	21,324
1978	9,148	258	129	1,647
1979	18,924	3,828	1,648	18,266
1980	68,525	25,088	11,032	79,631
1981	20,047	4,670	1,908	18,129
1982	6,288	930	439	9,701
1983	17,608	7,384	3,055	28,098
1984	77,380	28,899	9,072	137,919
1985	19,424	4,578	2,031	131,962
1986	10,321	3,572	1,879	27,349
1987	28,806	9,417	4,105	27,833
1988	121,761	44,913	17,840	319,543
1989	142,321	16,963	9,794	53,094
1990	32,839	5,374	3,304	15,949
1991	32,755	9,040	4,618	21,685
1992	315,105	41,747	9,224	195,433
1993	43,840	17,952	9,089	67,524
1994	23,281	3,360	1,706	34,364
1995	32,130	7,181	4,533	23,459
1996	177,767	99,470	14,150	198,058
1997	63,368	6,498	1,877	13,409
1998	35,566	7,248	2,442	4,812
1999	33,872	4,135	1,765	42,642
2000	190,293	88,647	16,571	92,002
2001	20,535	12,921	4,008	50,246
2002	7,523	2,173	1,144	13,001
2003	38,916	9,811	5,036	4,761
2004	89,834	9,606	5,484	49,579
2005	48,716	15,150	8,850	NA
2006	17,999	2,858	1,456	NA
2007	4,915	2,555	1,079	NA
2008	41,380	14,838	1,754	NA

17 **Nadina** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	451,557	194,381	65,444	546,597
Avg	81,361	21,858	9,044	81,525
Min	3,824	1,625	846	3,186

Year	Run	Spawners	Effective Females	Recruits
1973	NA	16,720	9,638	73,354
1974	NA	3,730	2,074	20,212
1975	NA	15,309	8,359	158,876
1976	NA	1,625	846	7,274
1977	NA	16,858	9,260	132,049
1978	26,098	2,584	1,527	31,247
1979	152,834	55,681	20,415	101,373
1980	13,148	3,017	1,518	21,372
1981	125,386	18,912	10,924	76,800
1982	34,976	2,349	1,423	6,775
1983	86,683	26,876	15,419	149,731
1984	33,498	7,070	3,501	24,917
1985	78,545	13,807	7,722	46,853
1986	8,977	3,545	2,048	20,838
1987	139,891	37,624	15,150	191,036
1988	31,813	8,744	4,304	57,739
1989	45,734	4,940	2,653	20,016
1990	21,538	6,033	3,404	15,734
1991	175,659	61,074	33,360	56,339
1992	68,657	7,728	2,355	104,713
1993	24,667	9,595	4,797	56,702
1994	19,657	2,008	1,076	18,358
1995	47,970	23,998	8,403	65,517
1996	63,955	38,654	18,093	546,597
1997	101,188	9,499	2,681	3,186
1998	15,180	3,705	1,983	4,879
1999	73,967	10,338	5,026	11,388
2000	451,557	194,381	65,444	259,537
2001	97,489	54,824	17,875	96,125
2002	4,655	1,925	1,031	6,180
2003	12,345	3,163	1,678	3,705
2004	233,547	22,603	13,773	219,368
2005	74,010	21,834	12,140	NA
2006	53,863	8,655	4,487	NA
2007	3,824	1,741	1,006	NA
2008	200,870	65,754	10,174	NA

18 **Upper Pitt River** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	203,986	131,481	72,407	217,474
Avg	73,150	28,249	13,772	72,902
Min	8,622	3,560	2,088	9,117

Year	Run	Spawners	Effective Females	Recruits
1948	NA	55,380	20,340	122,720
1949	NA	9,290	4,449	20,778
1950	NA	40,061	13,312	146,337
1951	NA	37,837	17,922	120,302
1952	NA	48,899	21,904	71,842
1953	102,064	18,673	9,303	25,807
1954	105,924	17,624	8,332	51,094
1955	96,805	17,950	11,221	164,991
1956	118,493	32,094	11,107	68,770
1957	44,620	12,335	5,130	29,207
1958	51,050	10,381	6,658	16,147
1959	91,535	15,731	6,096	61,976
1960	114,761	24,510	12,493	33,277
1961	44,072	11,158	6,525	102,366
1962	38,721	16,580	8,460	57,275
1963	24,957	12,680	5,749	142,935
1964	46,082	13,756	6,313	191,918
1965	53,763	6,966	3,368	38,984
1966	100,163	20,842	10,723	77,701
1967	121,828	10,282	5,236	67,780
1968	102,267	16,988	8,189	105,539
1969	158,842	25,073	11,710	61,083
1970	48,638	6,642	3,098	55,281
1971	77,235	15,452	6,663	217,474
1972	81,841	13,412	6,569	122,915
1973	76,625	11,895	4,744	29,176
1974	74,089	20,581	8,854	135,238
1975	124,762	39,920	21,369	85,230
1976	203,986	36,525	19,467	105,338
1977	56,665	13,852	7,791	34,586
1978	70,731	24,786	14,109	34,854
1979	145,893	37,542	20,307	38,236
1980	34,838	17,101	9,169	16,913
1981	106,816	25,327	13,224	34,272
1982	29,956	8,708	5,086	18,265
1983	27,896	16,852	10,074	62,053
1984	45,180	15,797	8,755	75,696
1985	8,622	3,560	2,088	23,208
1986	36,196	29,177	12,283	40,001
1987	25,747	13,637	5,503	21,968
1988	68,939	37,747	17,876	61,300
1989	63,157	16,037	5,583	16,609
1990	23,421	12,202	5,701	9,117
1991	40,959	22,500	10,867	33,888
1992	17,185	9,129	4,335	100,553
1993	63,675	22,835	9,040	102,923
1994	13,220	9,500	4,365	34,714
1995	9,248	5,500	2,352	52,971
1996	62,069	50,077	19,451	150,961
1997	87,030	35,798	14,996	96,262
1998	91,252	76,888	47,612	133,321
1999	38,855	35,961	19,390	142,614
2000	65,492	42,638	18,584	111,288
2001	141,955	131,481	72,407	54,820
2002	118,367	90,280	39,416	69,160
2003	123,415	78,229	39,927	13,786
2004	159,989	60,942	33,796	41,620
2005	76,754	62,047	33,243	NA
2006	72,421	38,816	21,346	NA
2007	44,547	41,829	19,926	NA
2008	22,809	16,921	6,186	NA

19 **Harrison** ||| = 1/10 of max for each variable

	Run	Spawners	Effective Females	Recruits
Max	421,280	388,605	211,552	386,967
Avg	55,674	22,947	12,077	55,596
Min	2,312	313	172	1,963

Year	Run	Spawners	Effective Females	Recruits
1948	NA	26,162	14,577	43,283
1949	NA	8,000	4,372	37,073
1950	NA	33,044	18,216	78,099
1951	NA	17,145	13,181	122,022
1952	NA	25,794	17,215	23,054
1953	73,919	21,030	7,641	9,784
1954	132,871	28,800	16,869	14,797
1955	36,499	5,595	3,405	141,038
1956	6,865	2,586	1,266	96,858
1957	13,698	3,793	1,820	60,554
1958	68,766	14,701	6,404	59,892
1959	168,094	27,868	17,692	41,545
1960	34,971	17,210	7,076	29,451
1961	90,445	42,773	21,725	13,225
1962	14,932	8,162	4,197	50,812
1963	57,173	22,258	9,803	87,825
1964	4,991	2,202	1,101	51,177
1965	42,684	15,034	7,779	20,432
1966	69,955	32,646	9,295	55,444
1967	81,431	20,548	12,672	50,935
1968	15,484	5,379	2,854	17,838
1969	54,978	14,959	7,559	7,302
1970	34,391	12,666	6,471	39,763
1971	42,468	3,790	1,970	84,459
1972	6,370	1,346	794	1,963
1973	23,962	3,060	1,571	37,681
1974	82,138	16,920	8,709	40,338
1975	24,329	5,987	3,381	128,650
1976	33,066	5,130	2,933	44,728
1977	11,558	2,246	1,374	24,058
1978	57,214	19,717	10,488	41,193
1979	149,185	45,615	20,234	10,895
1980	17,260	5,092	2,262	14,393
1981	14,998	3,193	1,788	17,869
1982	34,647	9,189	4,686	28,956
1983	23,841	4,239	2,132	17,919
1984	13,443	1,267	689	5,265
1985	9,678	5,097	1,825	14,476
1986	32,605	7,265	4,145	9,610
1987	13,622	5,228	2,686	46,184
1988	5,263	1,544	947	4,013
1989	16,393	2,934	1,998	13,564
1990	7,412	4,515	1,888	129,502
1991	44,707	15,000	7,958	38,111
1992	2,312	313	172	3,736
1993	74,831	3,258	2,271	19,096
1994	72,172	9,515	6,087	20,682
1995	34,202	16,618	6,758	49,813
1996	17,864	15,379	8,255	7,560
1997	4,737	1,418	1,084	82,240
1998	21,933	4,496	3,013	64,475
1999	51,334	8,577	5,592	91,504
2000	14,859	4,343	1,745	12,173
2001	90,043	15,309	8,335	386,967
2002	63,163	41,542	24,384	276,837
2003	82,956	8,259	6,043	104,854
2004	57,833	2,106	986	143,000
2005	421,280	388,605	211,552	NA
2006	209,463	168,259	90,943	NA
2007	191,321	128,295	57,444	NA
2008	41,115	6,717	4,411	NA

APPENDIX 4: SPAWNER-RECRUIT SUMMARY FIGURES

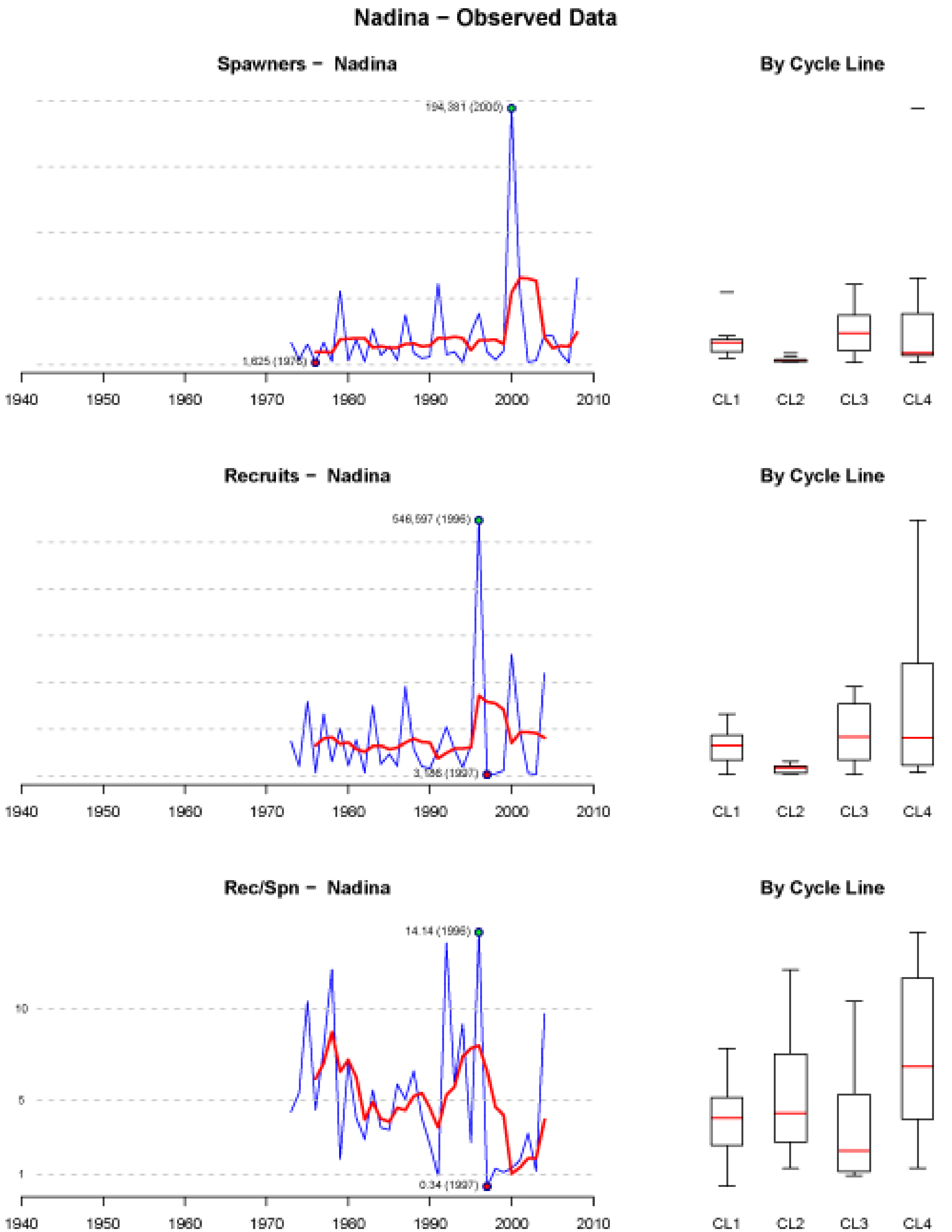


Figure A.1a: Observed Data – Nadina

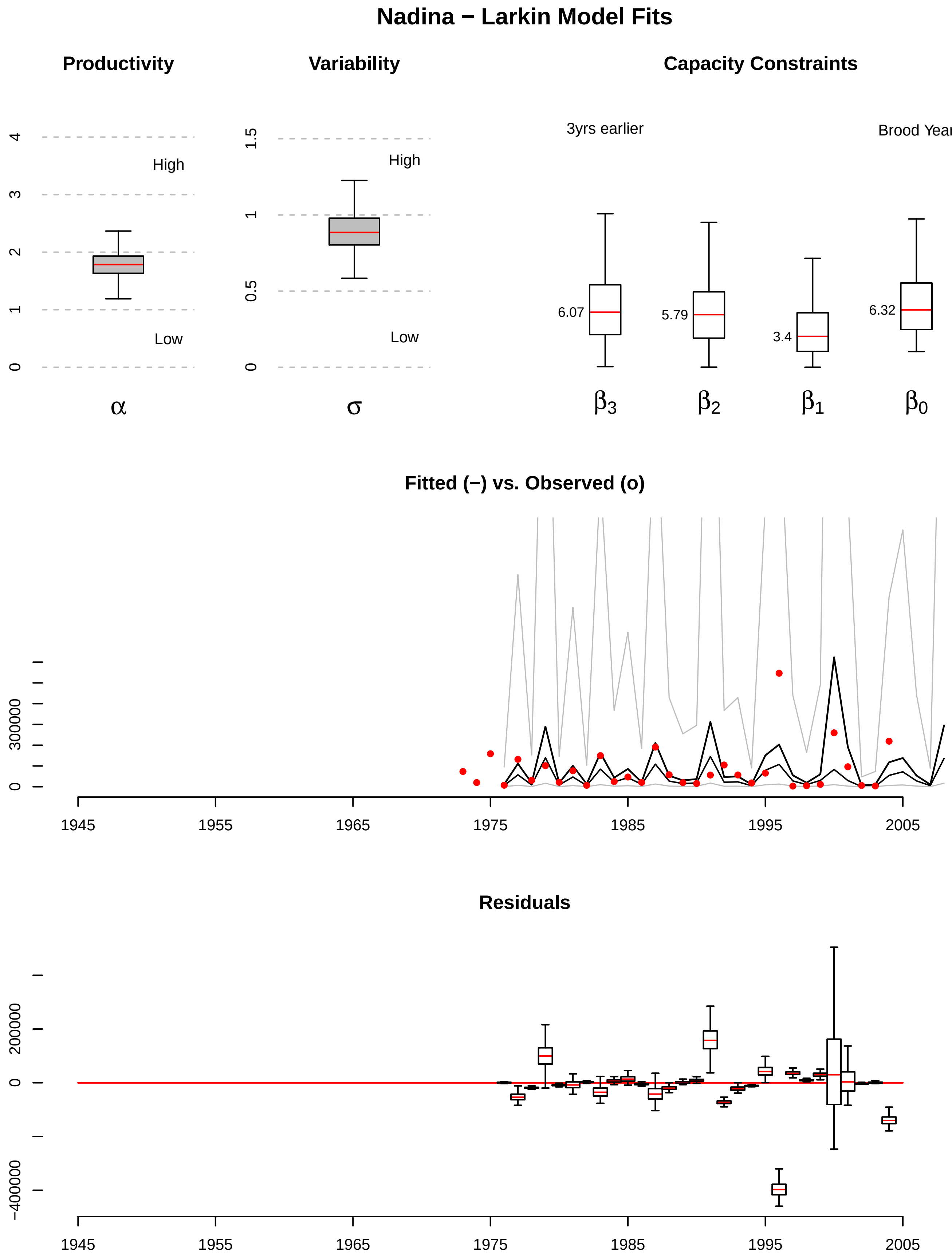


Figure A.1b: Larkin Model Fits − Nadina

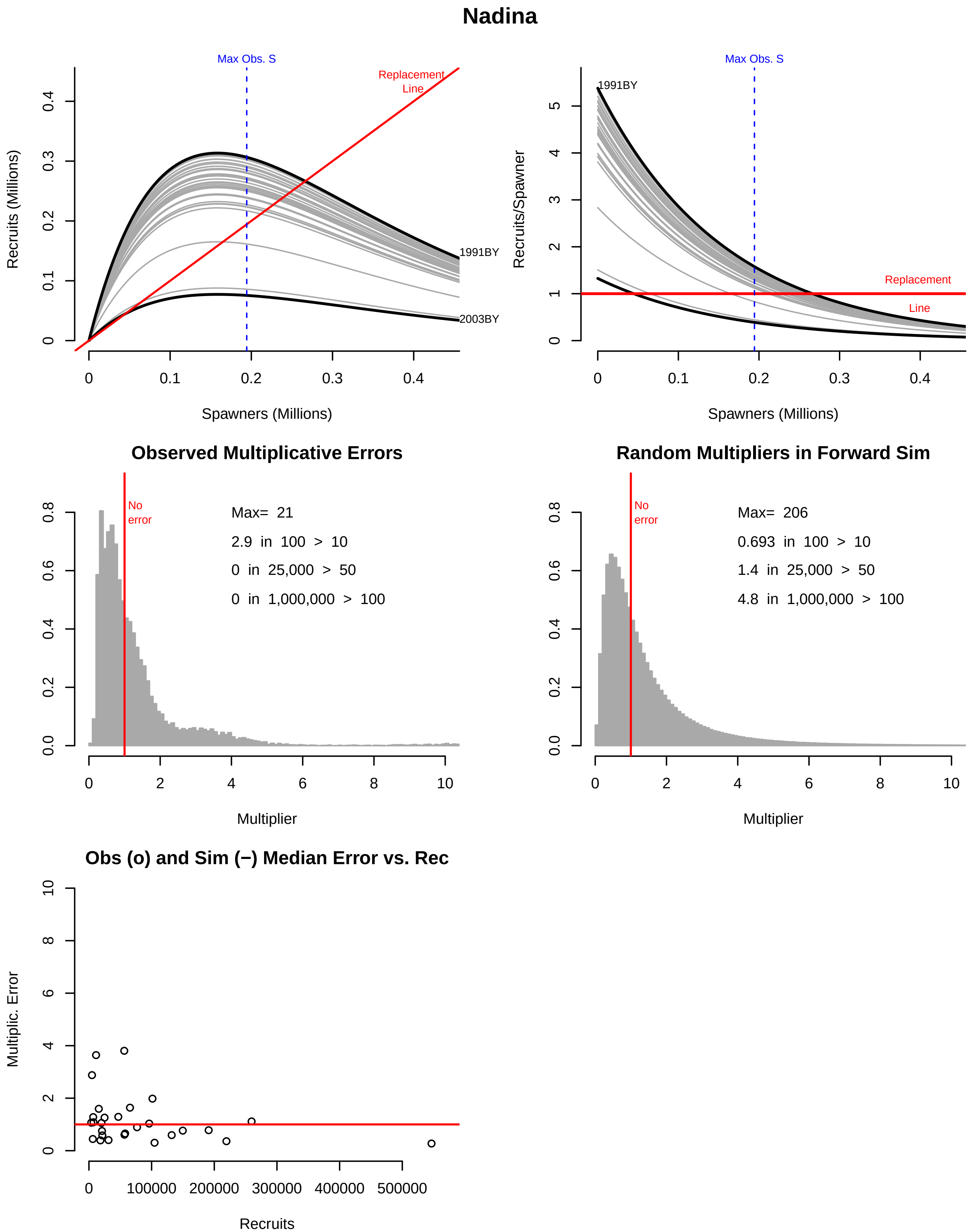


Figure A.1c: Delayed−density effects and error structure − Nadina

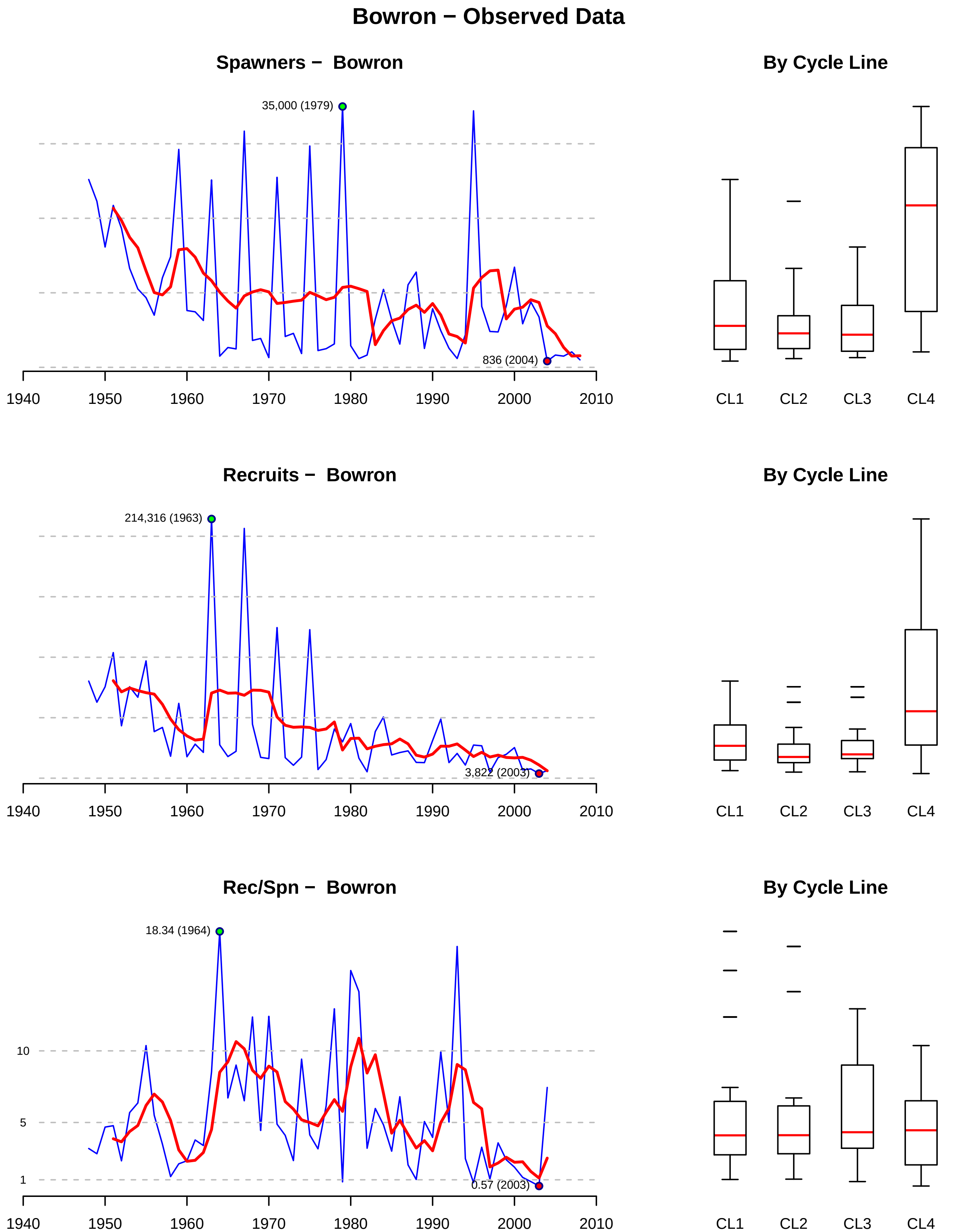


Figure A.2a: Observed Data − Bowron

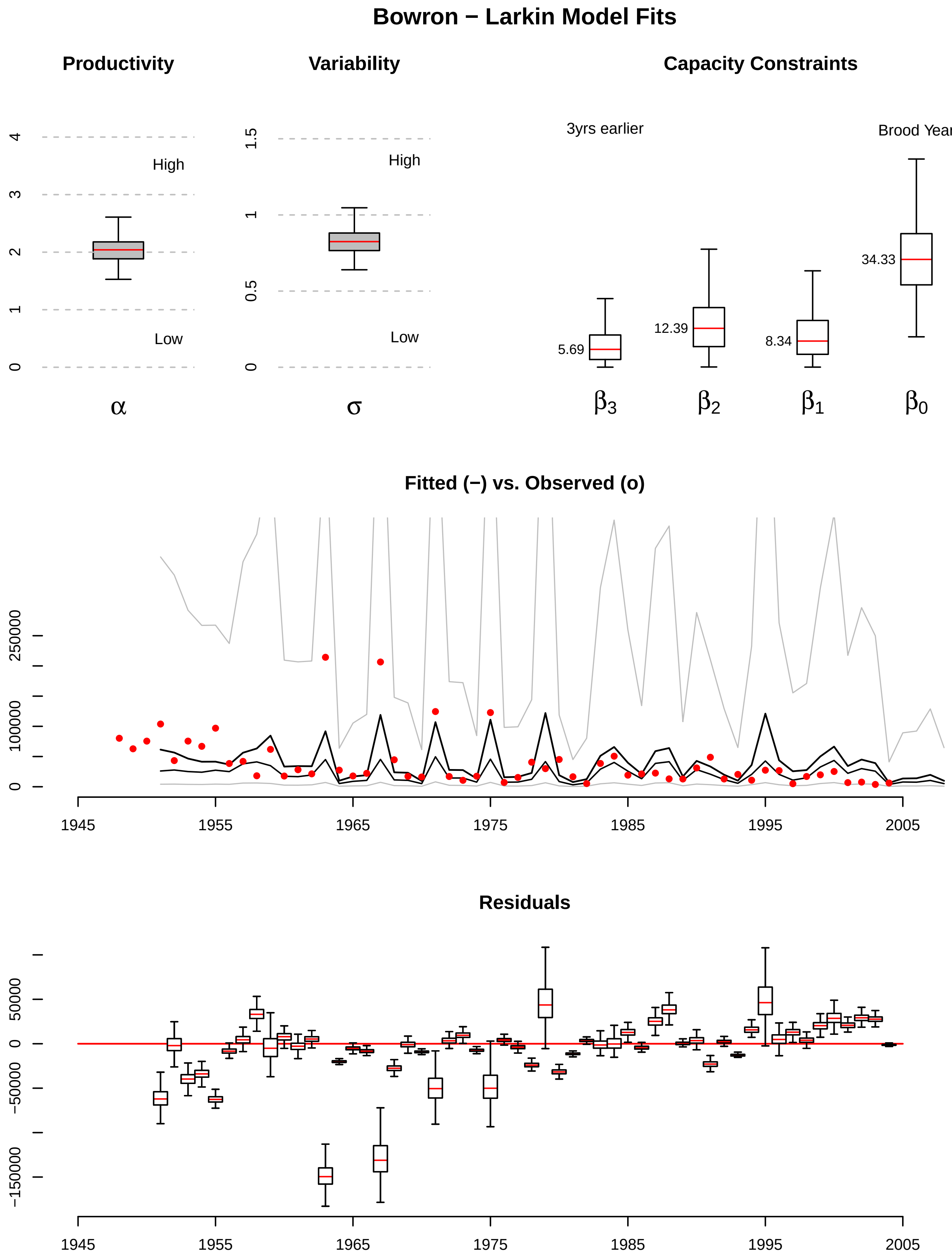


Figure A.2b: Larkin Model Fits − Bowron

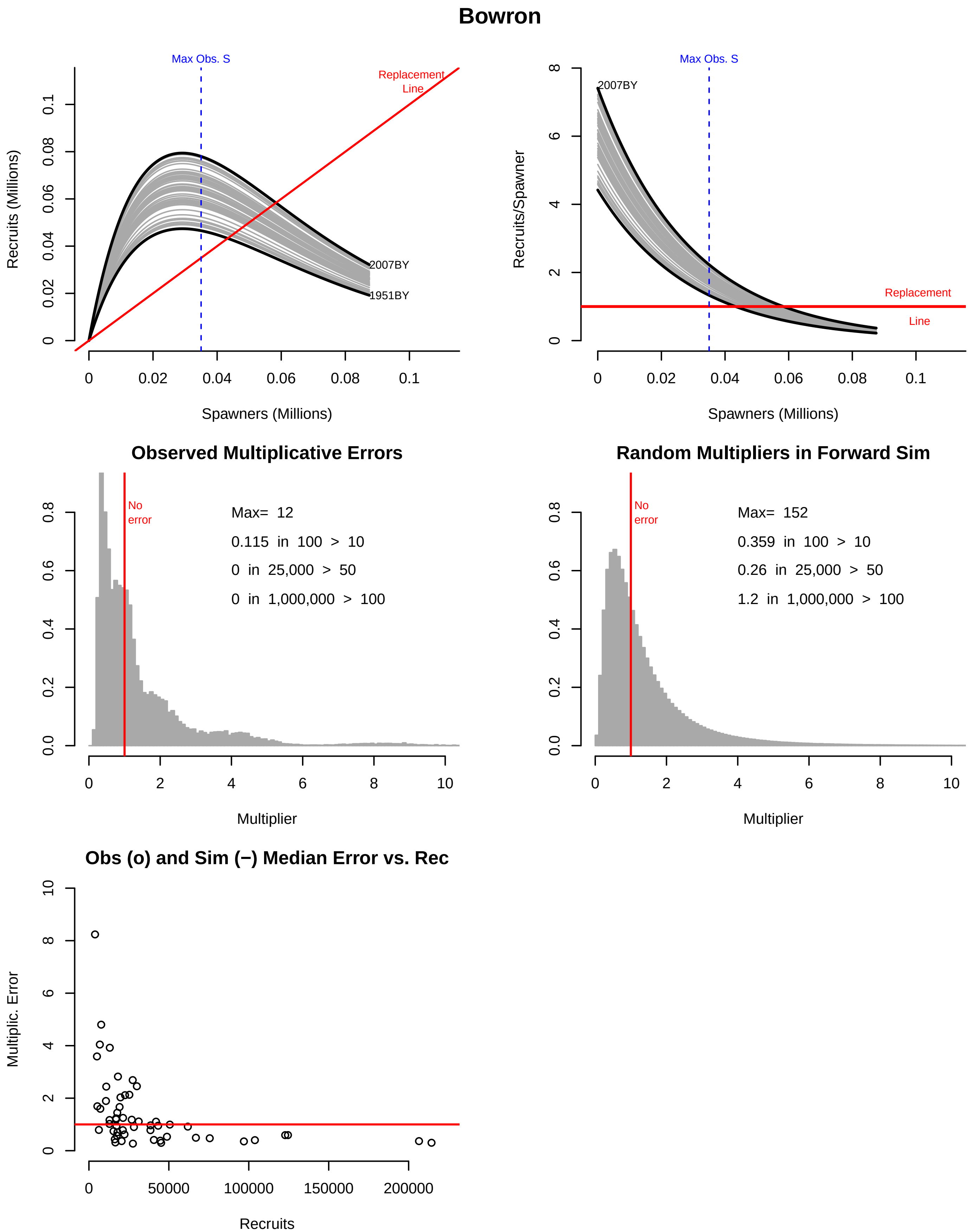


Figure A.2c: Delayed−density effects and error structure − Bowron

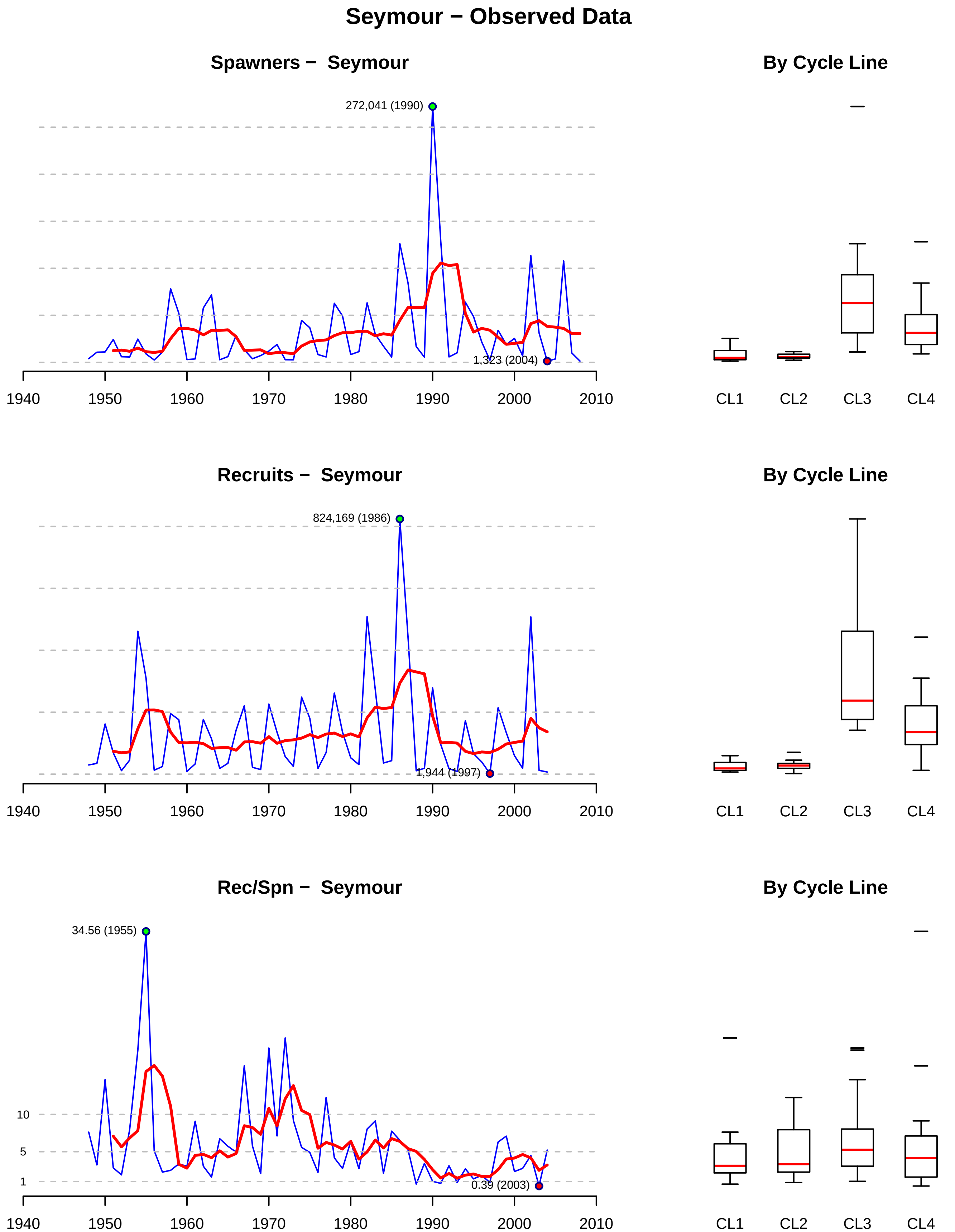


Figure A.3a: Observed Data − Seymour

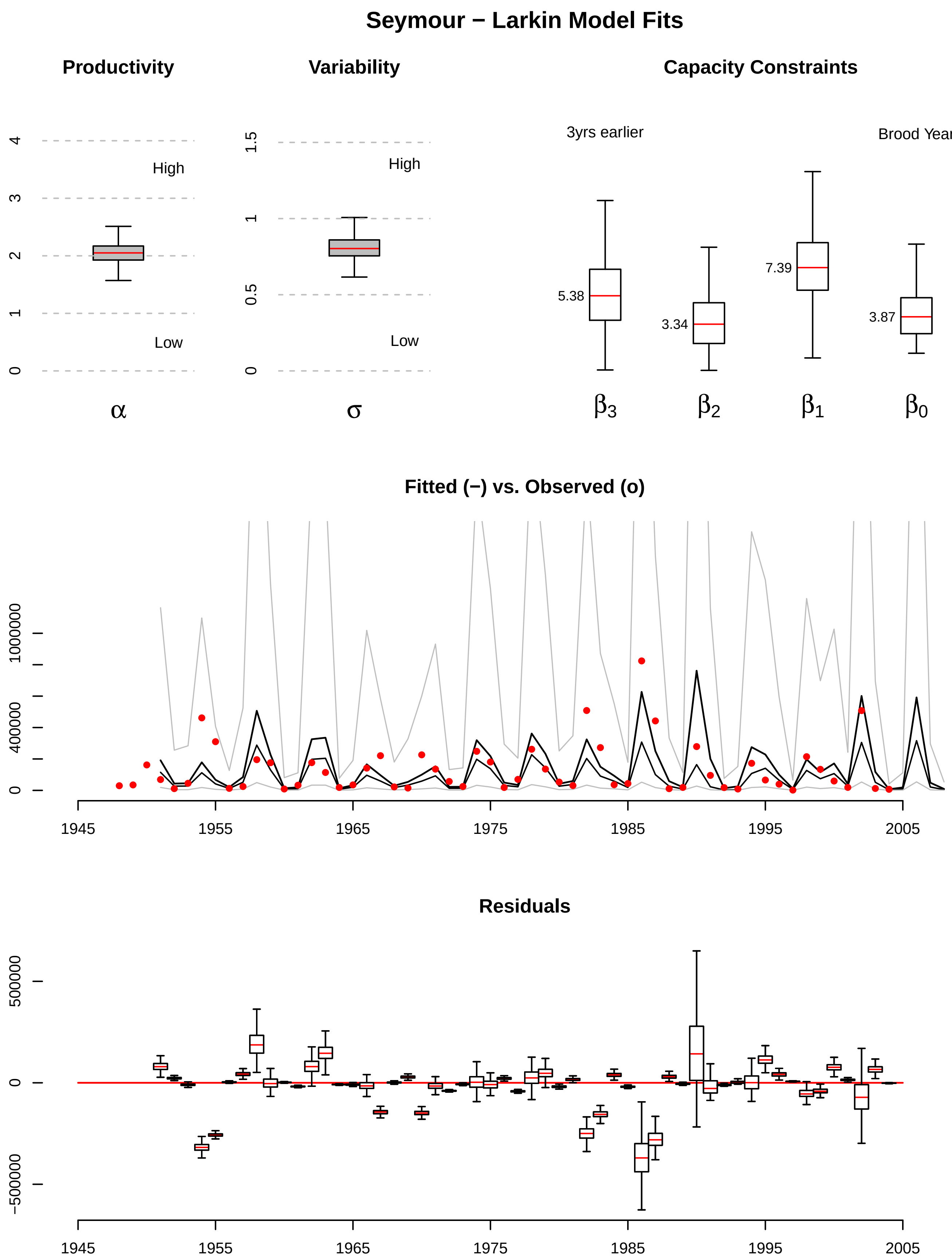


Figure A.3b: Larkin Model Fits − Seymour

Seymour

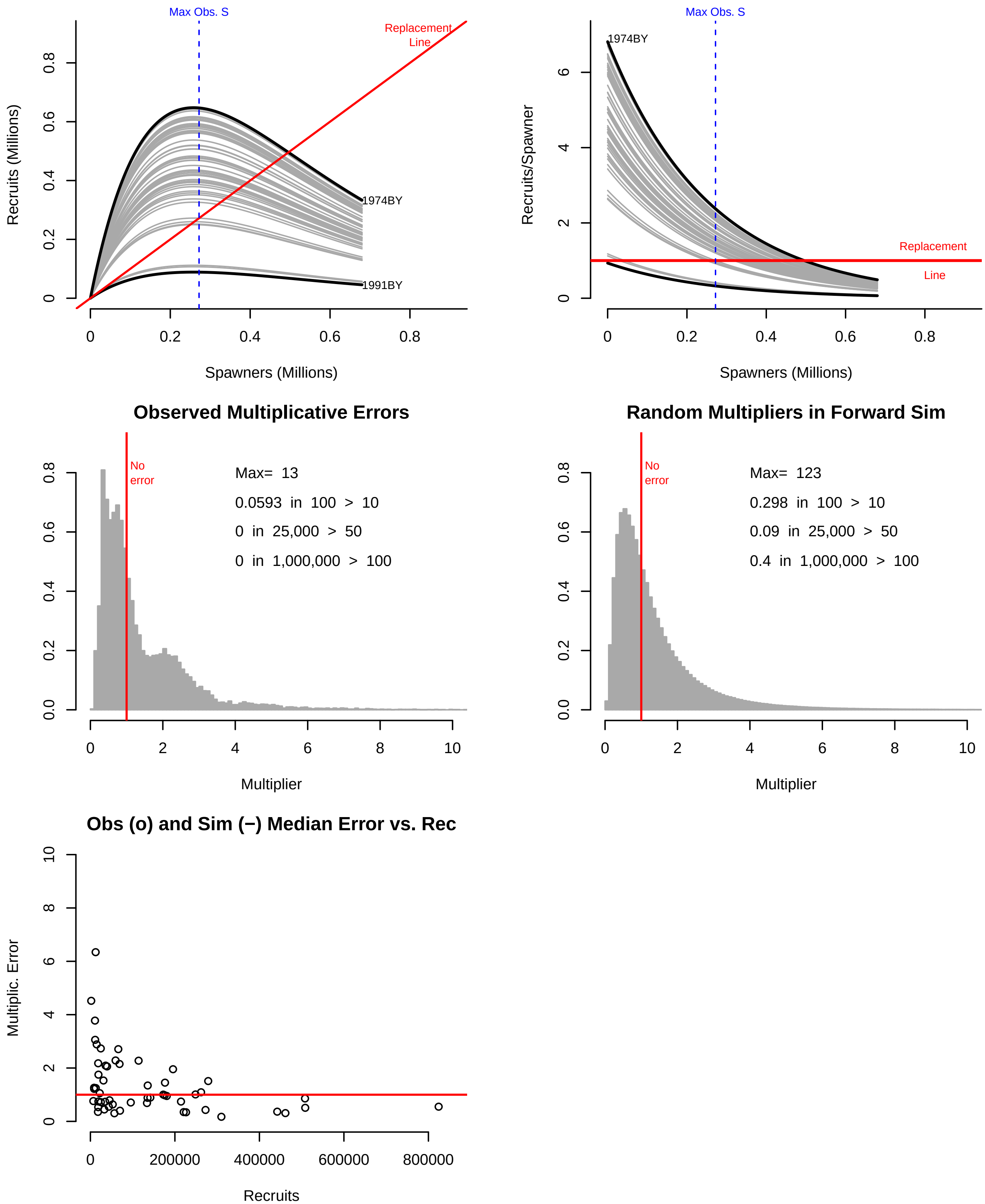


Figure A.3c: Delayed−density effects and error structure − Seymour

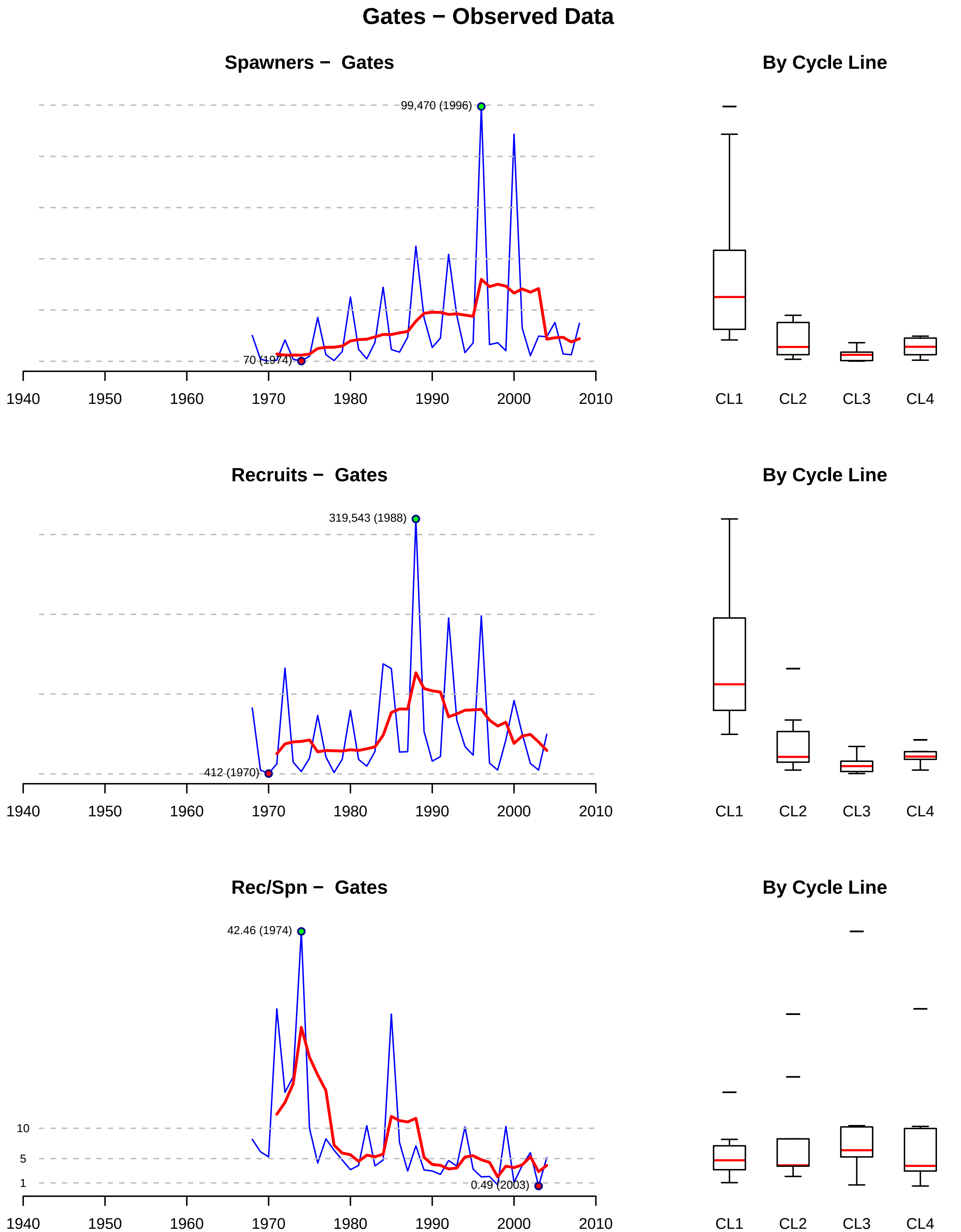


Figure A.4a: Observed Data − Gates

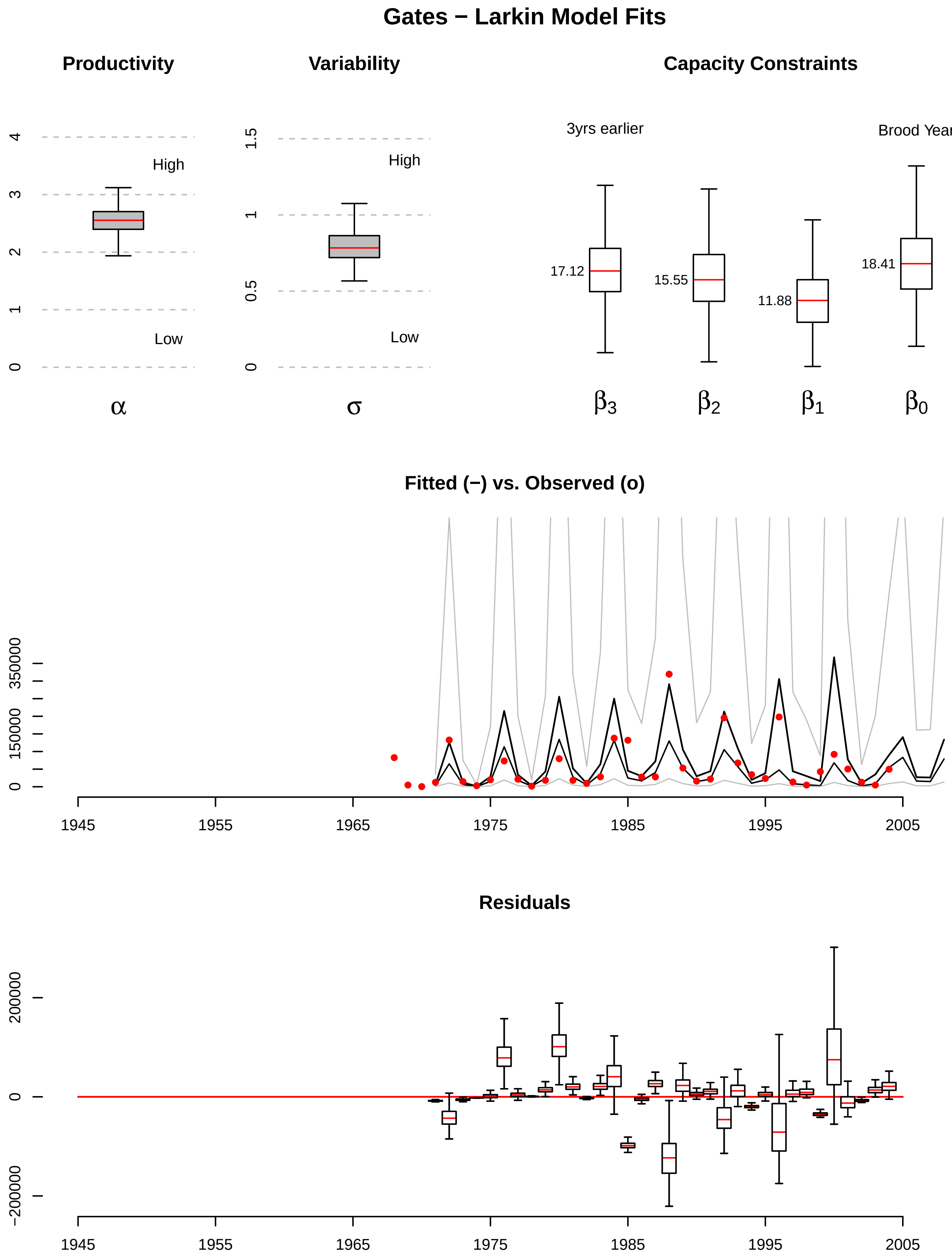


Figure A.4b: Larkin Model Fits − Gates

Gates

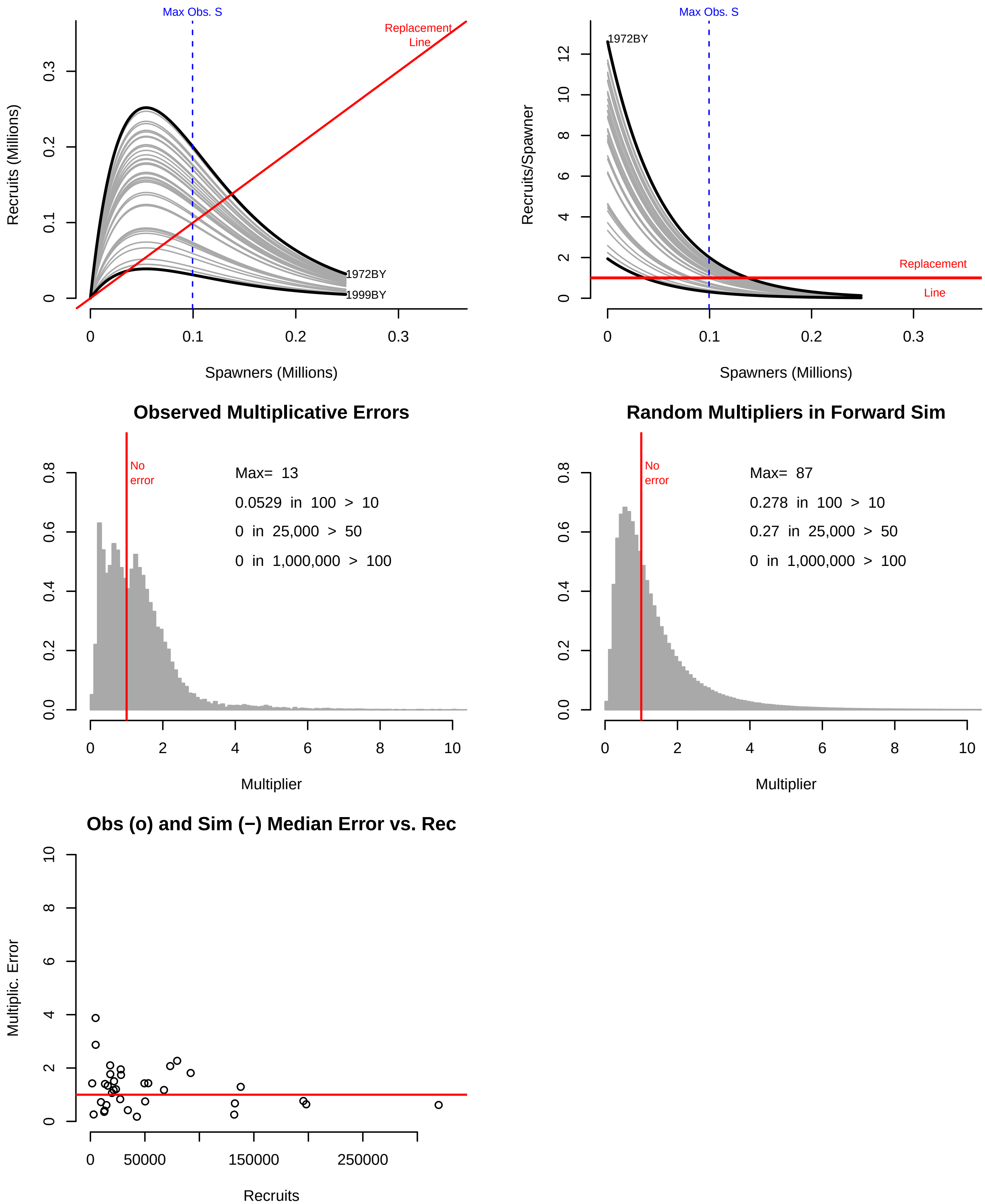


Figure A.4c: Delayed−density effects and error structure − Gates

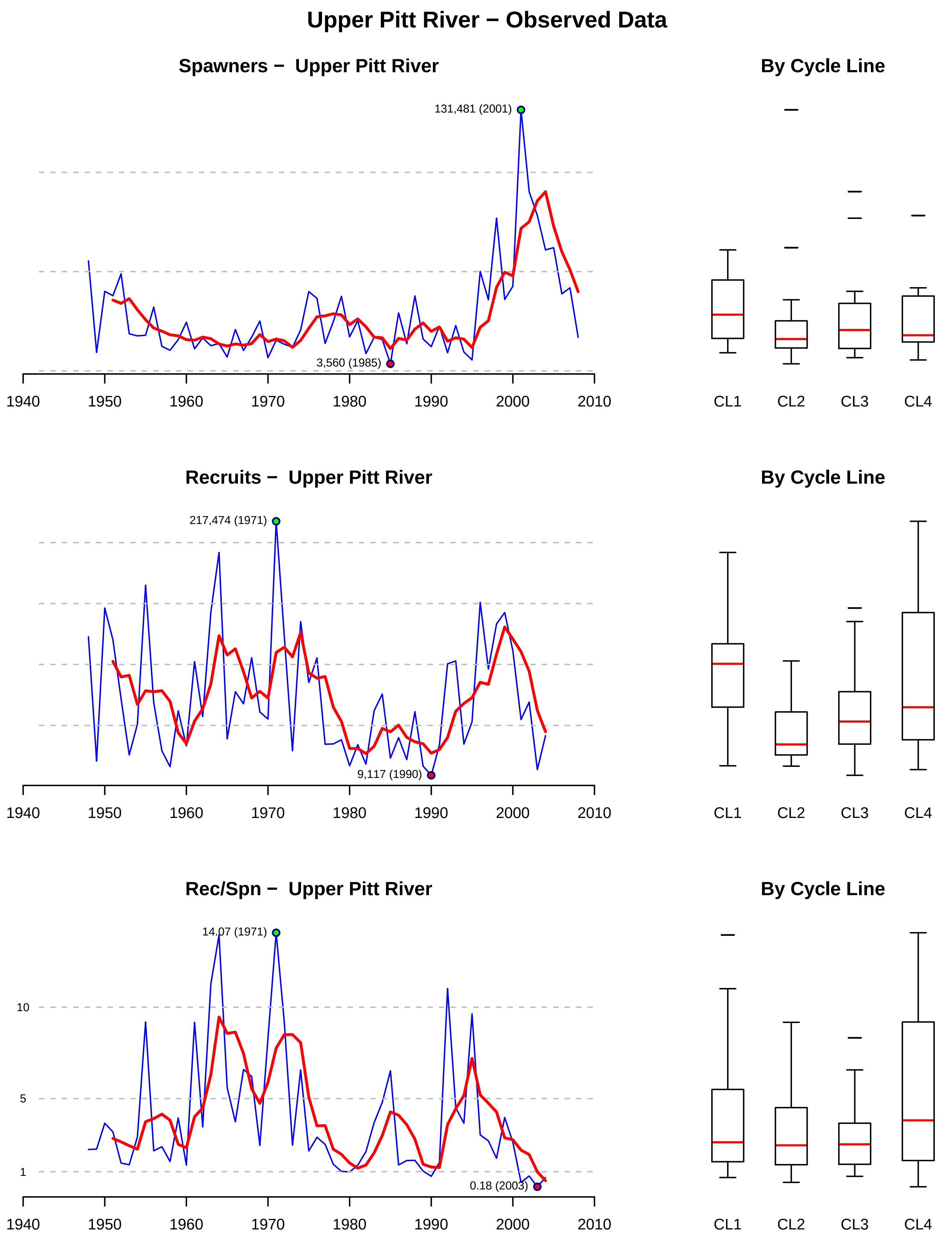


Figure A.5a: Observed Data − Upper Pitt River

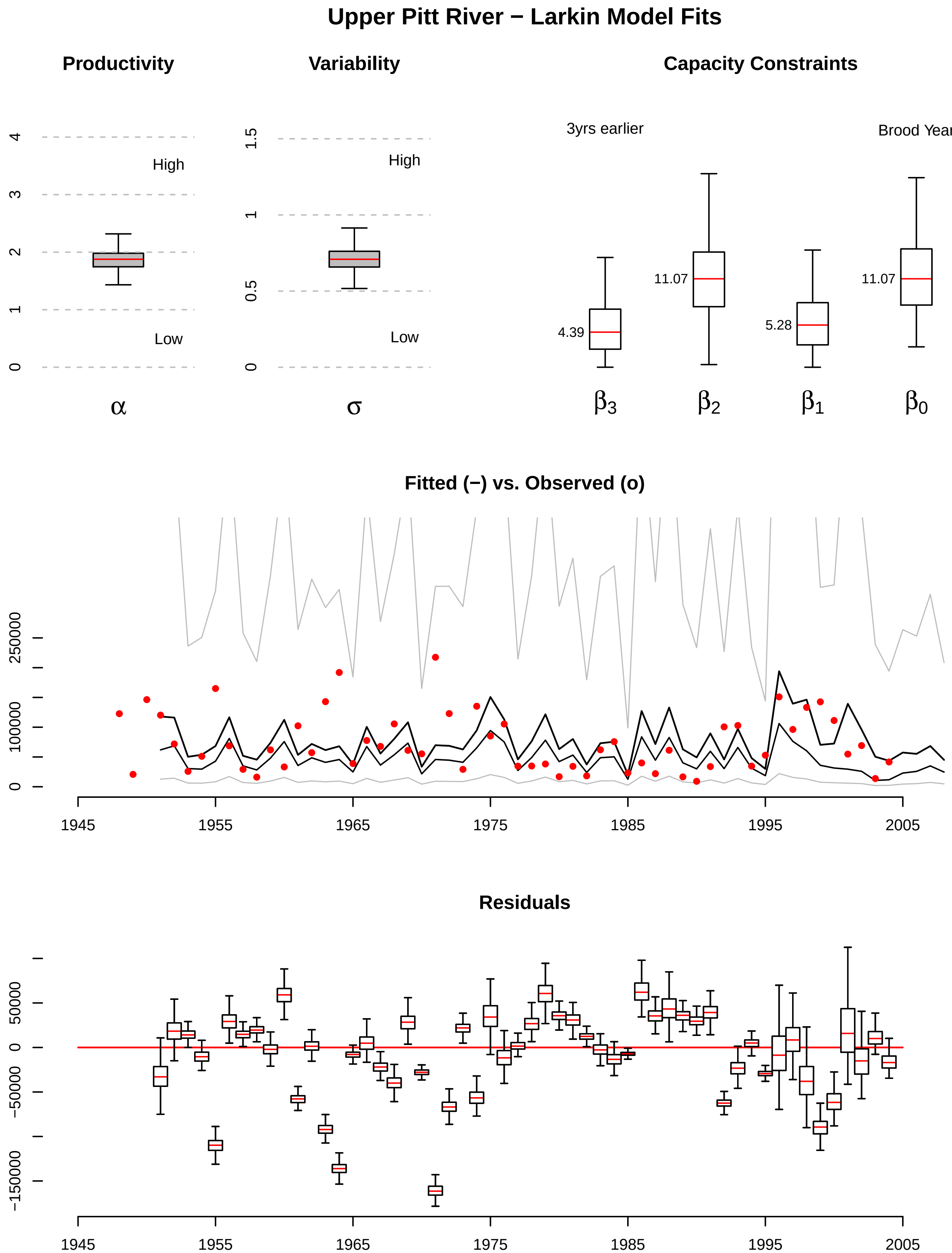


Figure A.5b: Larkin Model Fits – Upper Pitt River

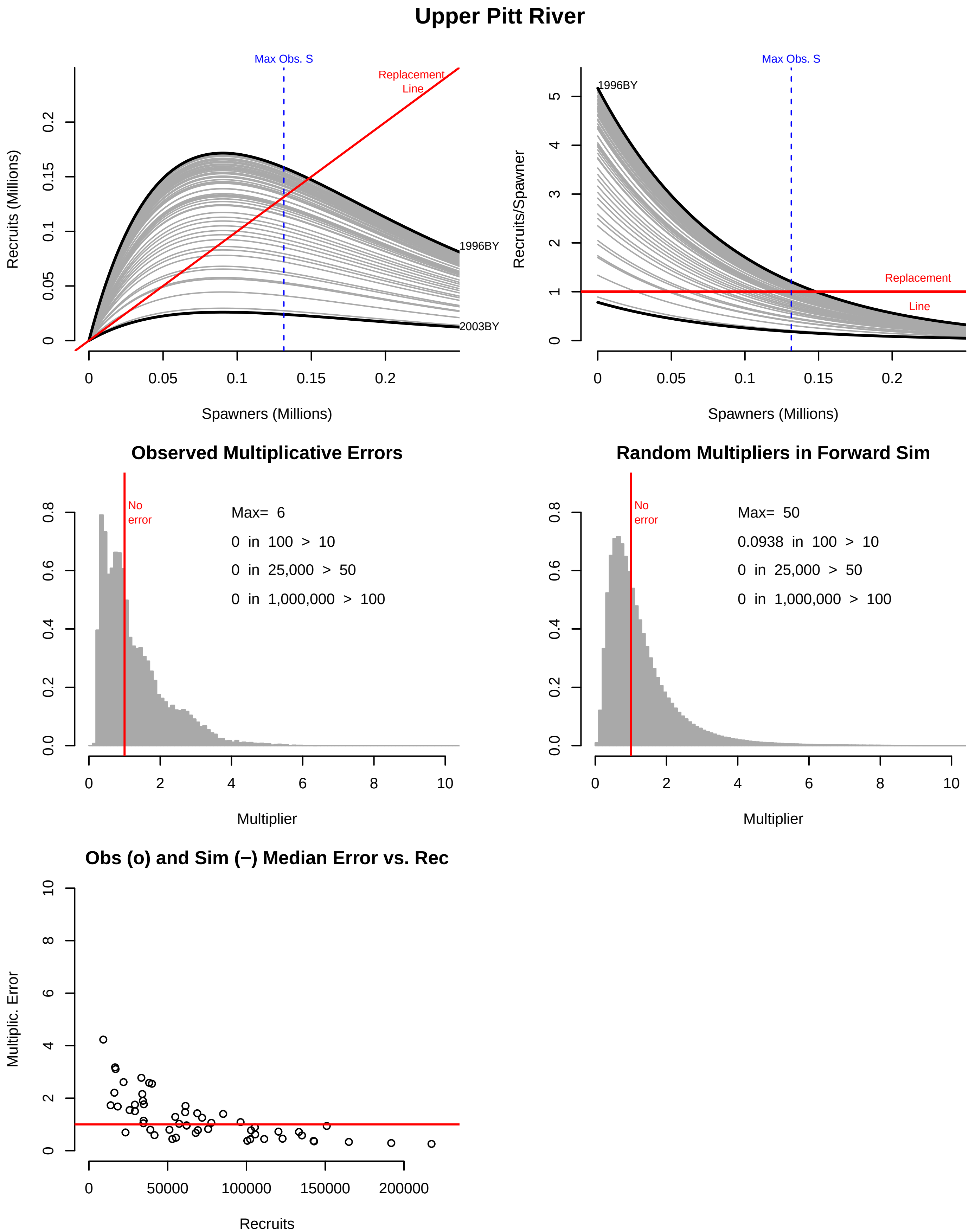


Figure A.5c: Delayed−density effects and error structure − Upper Pitt River

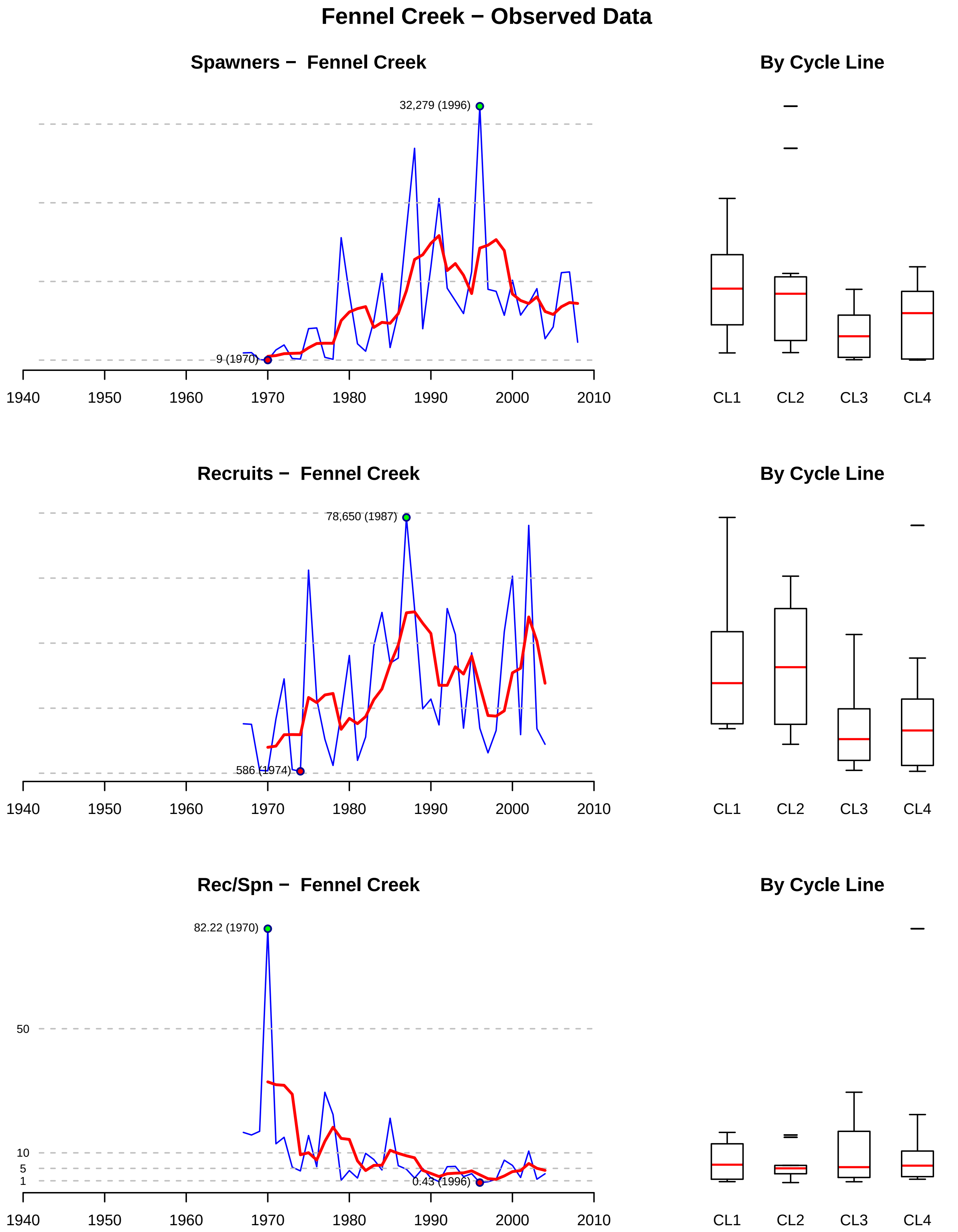


Figure A.6a: Observed Data − Fennel Creek

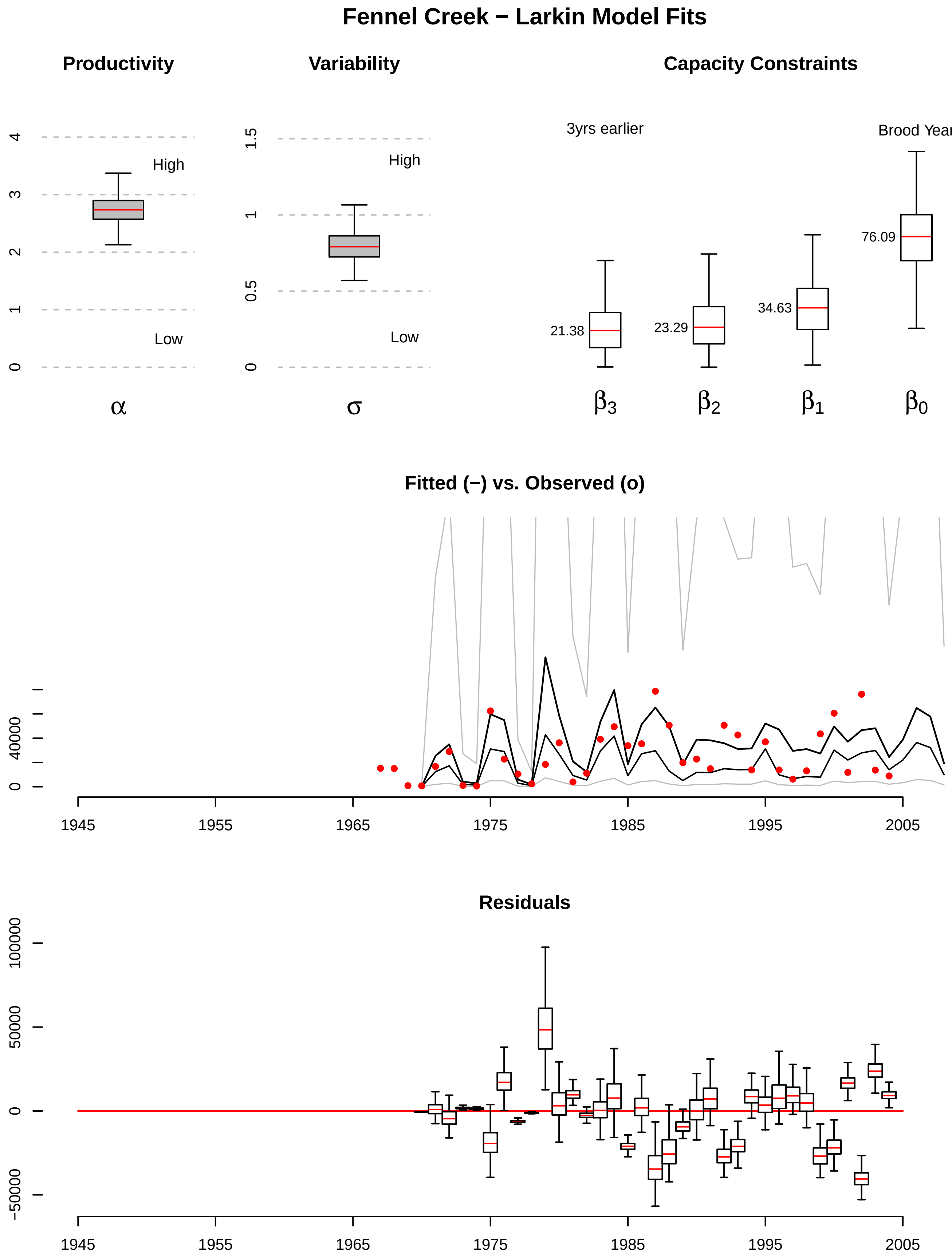


Figure A.6b: Larkin Model Fits − Fennel Creek

Fennel Creek

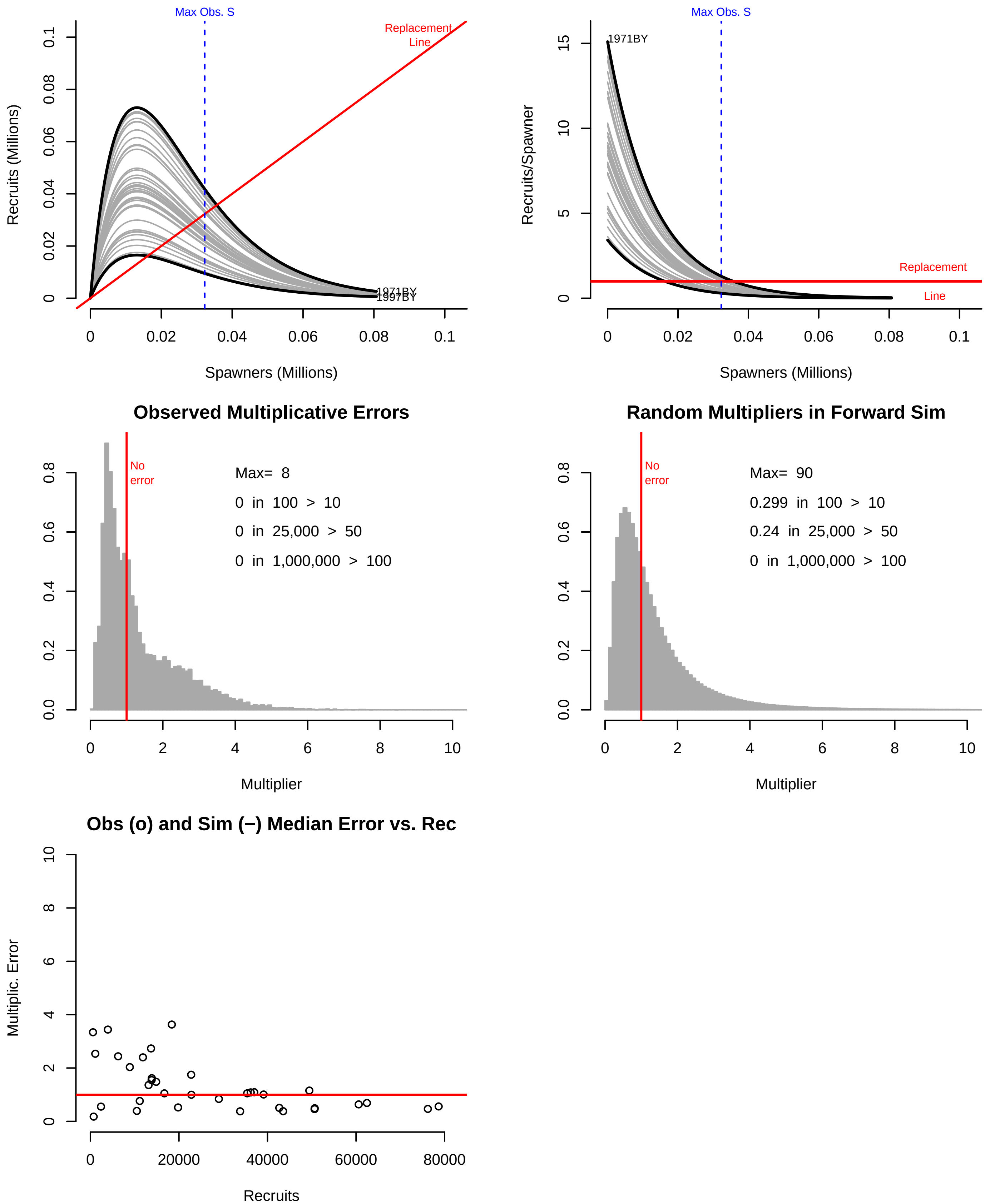


Figure A.6c: Delayed−density effects and error structure − Fennel Creek

Scotch Creek − Observed Data

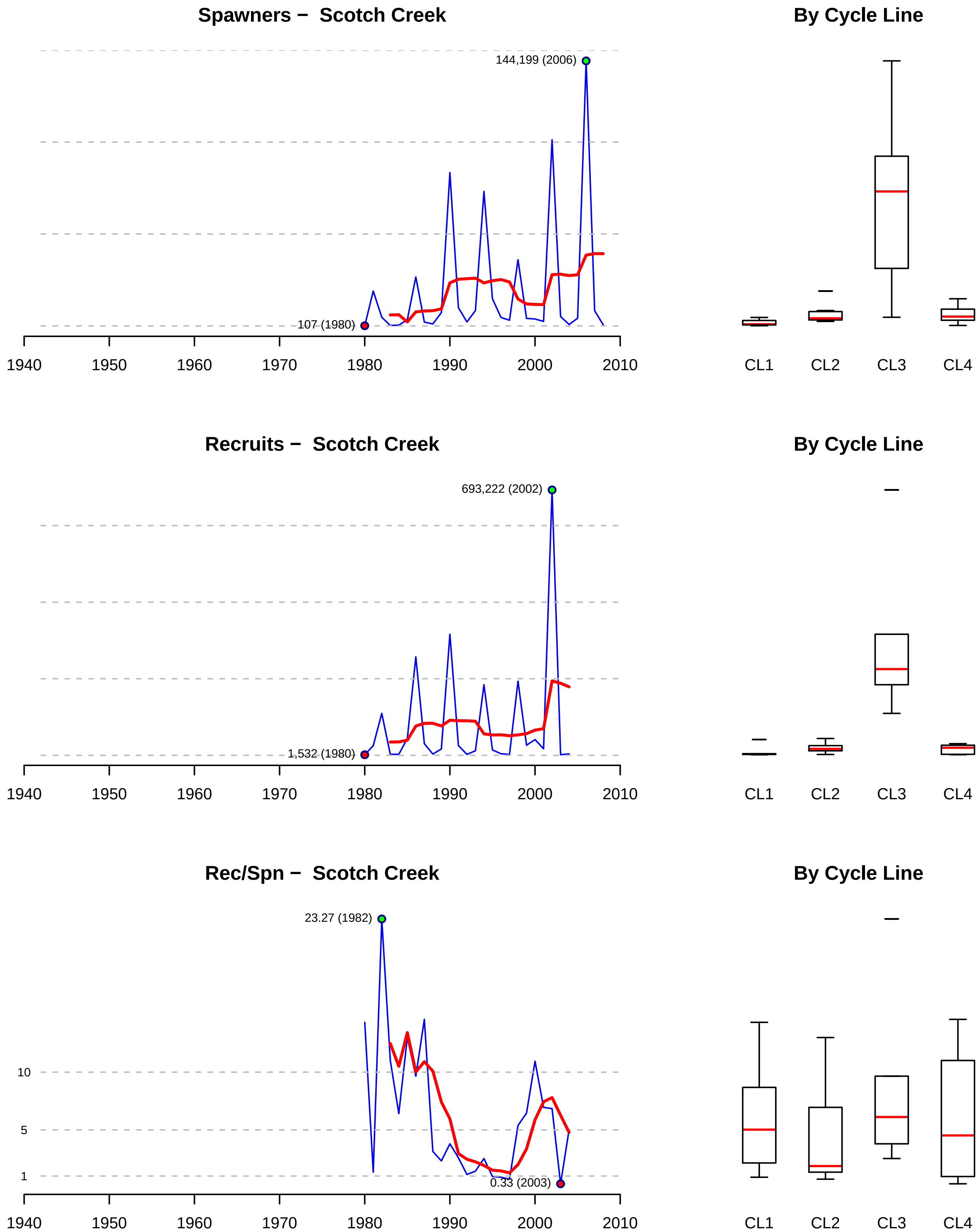


Figure A.7a: Observed Data − Scotch Creek

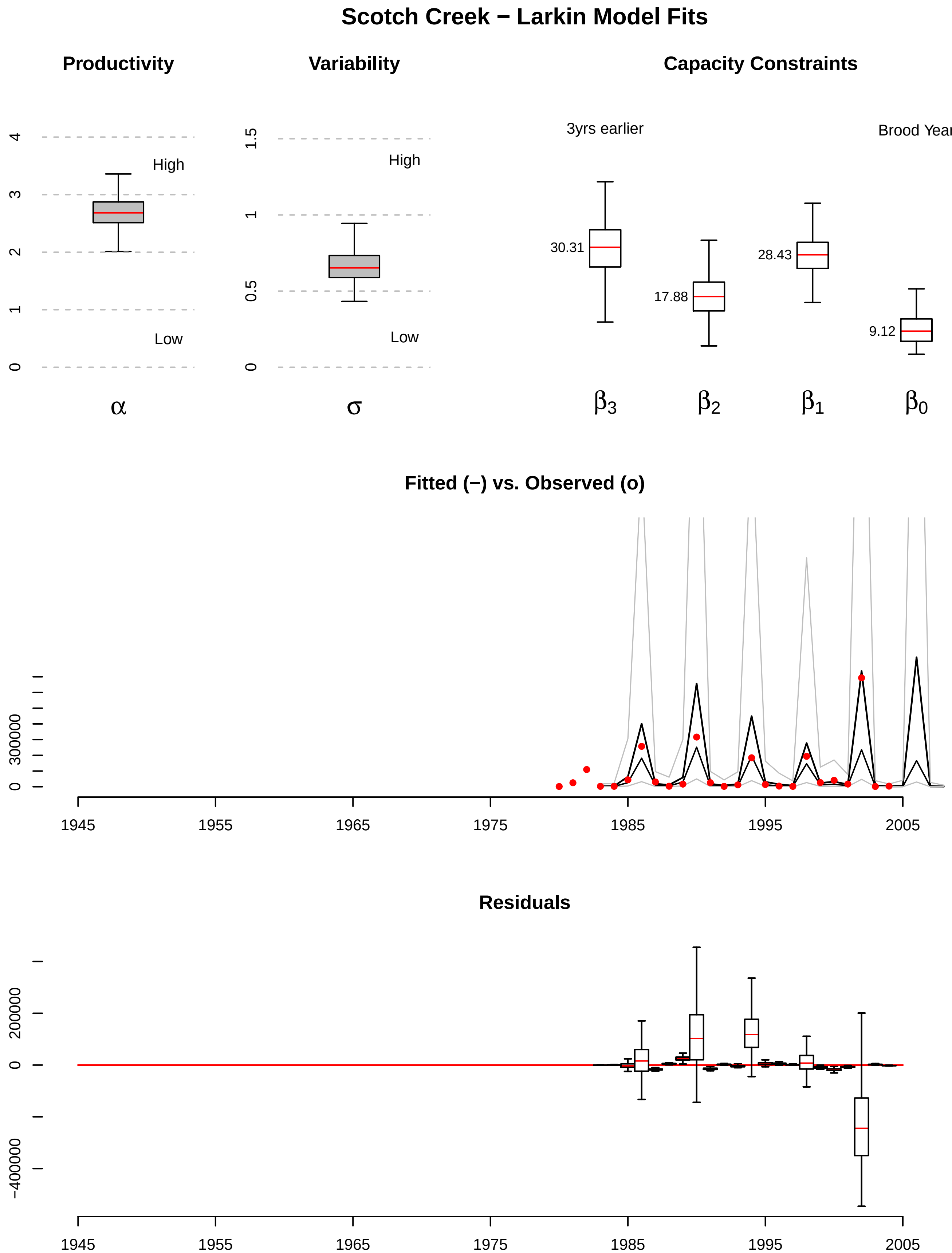


Figure A.7b: Larkin Model Fits − Scotch Creek

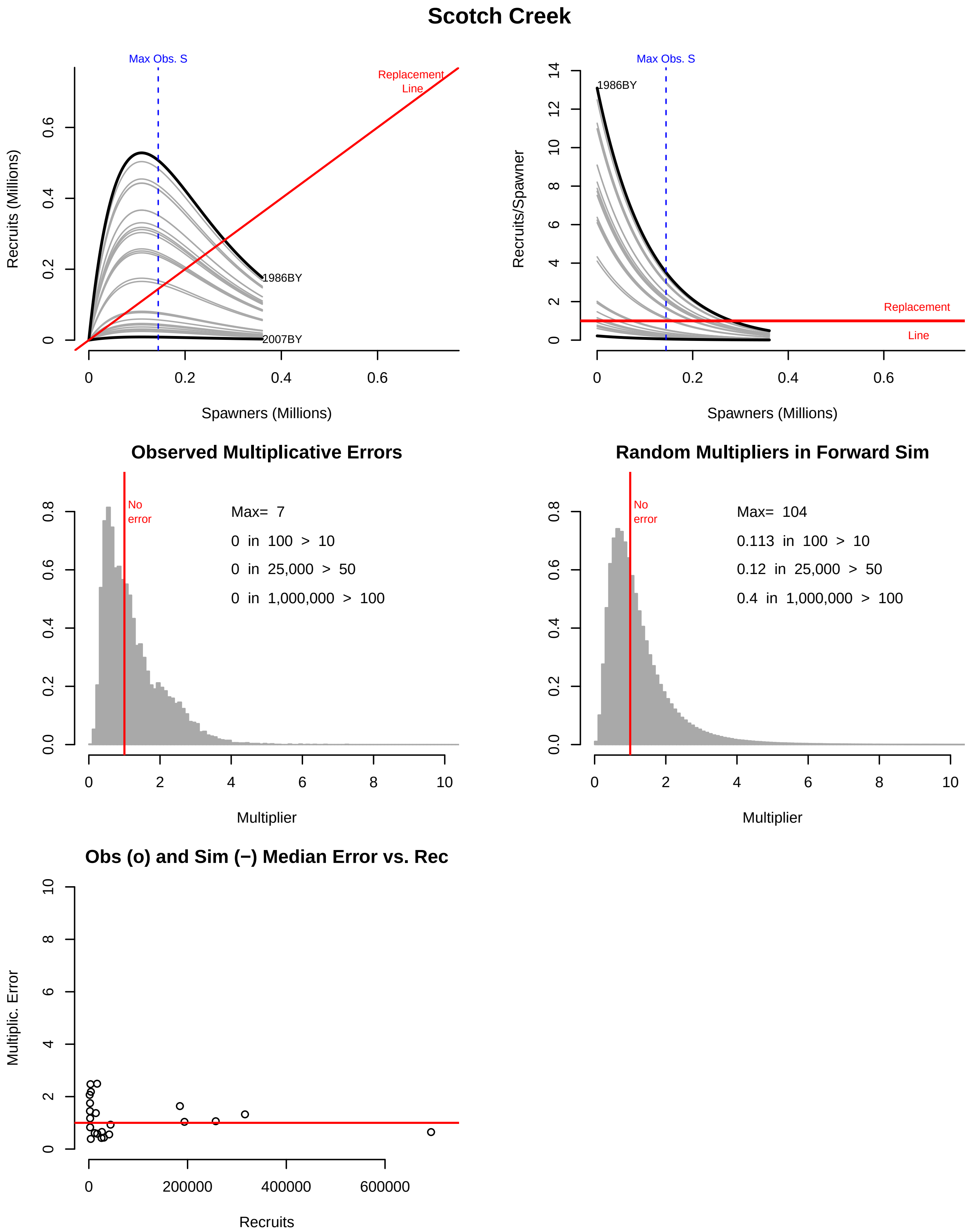


Figure A.7c: Delayed−density effects and error structure − Scotch Creek

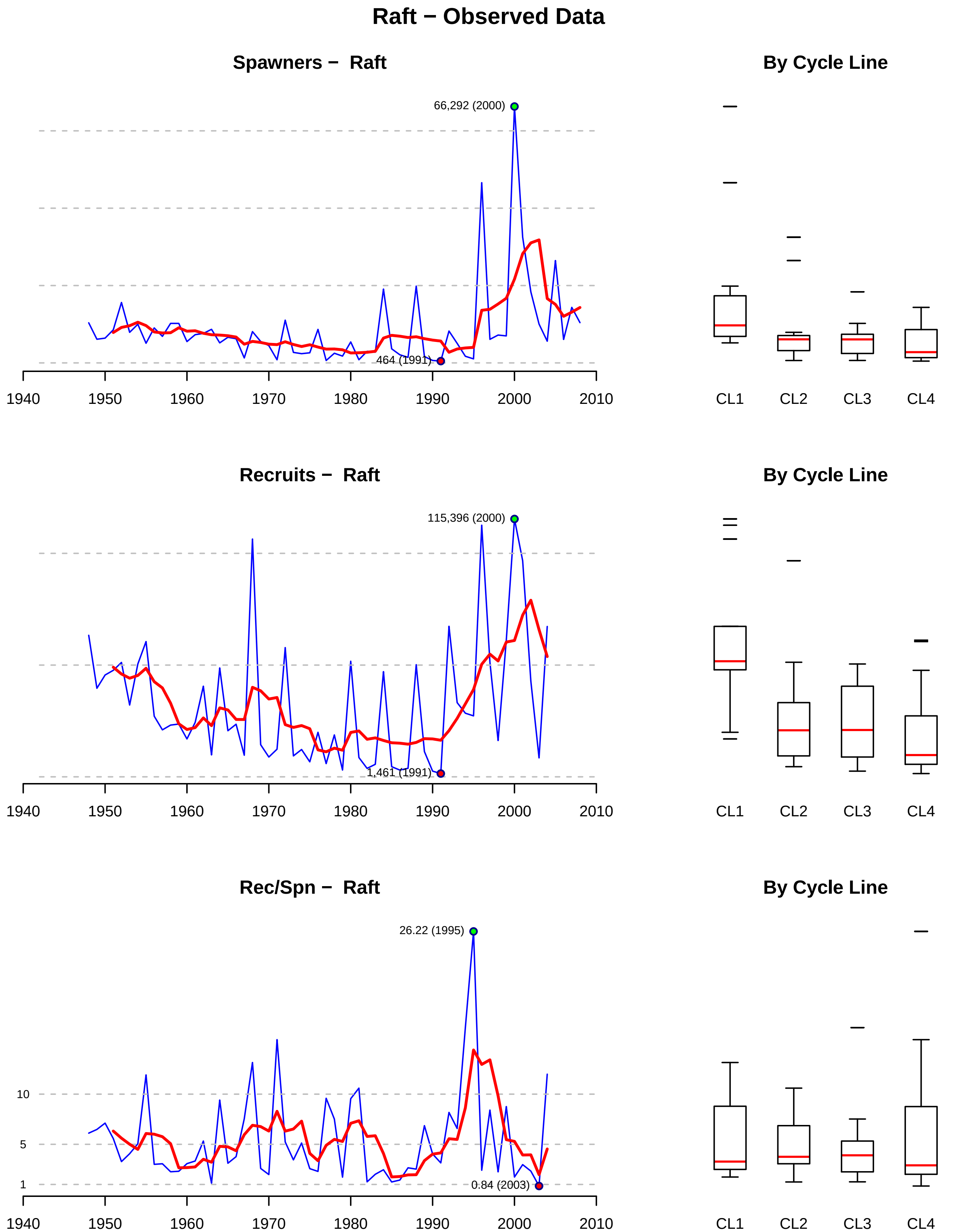


Figure A.8a: Observed Data − Raft

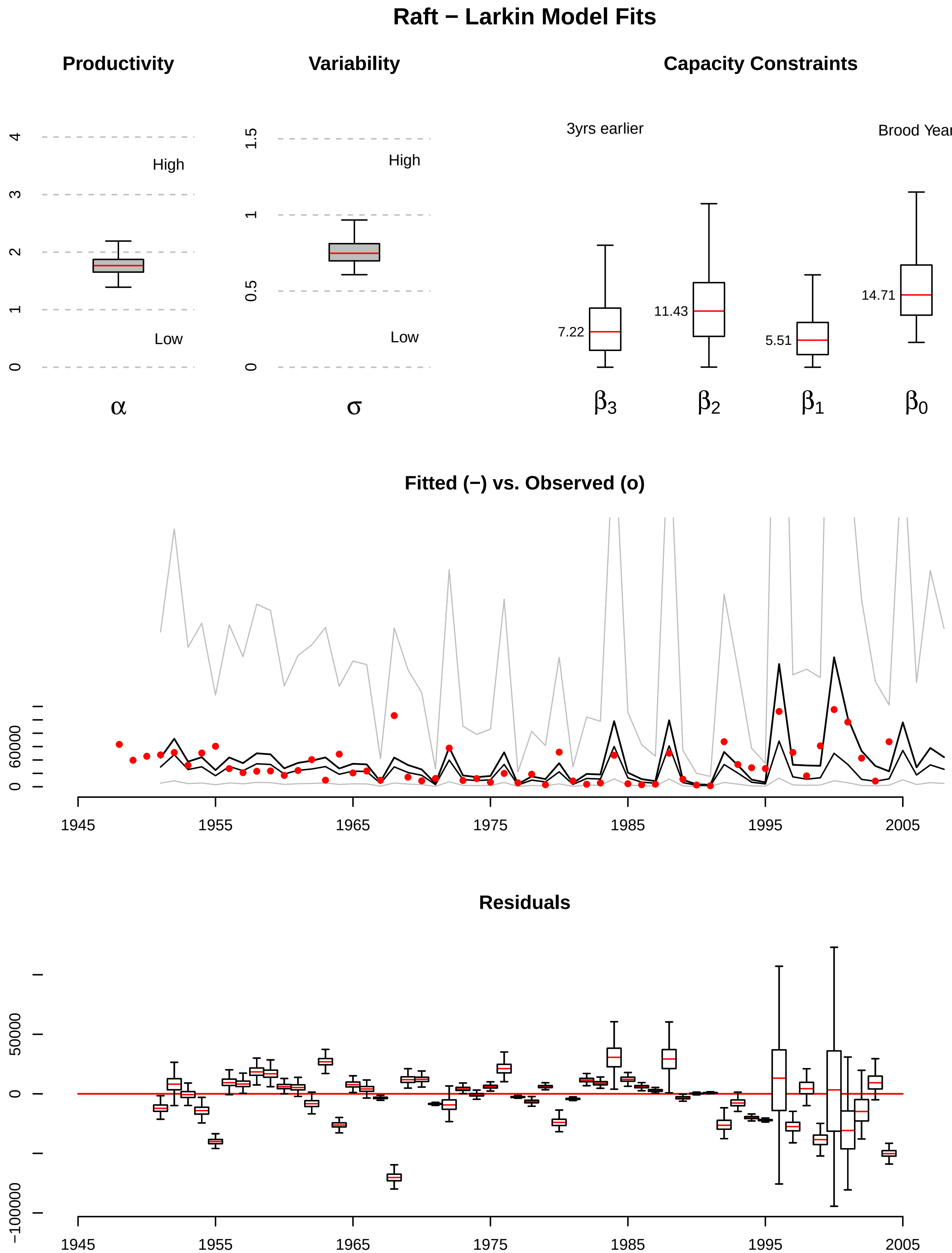


Figure A.8b: Larkin Model Fits − Raft

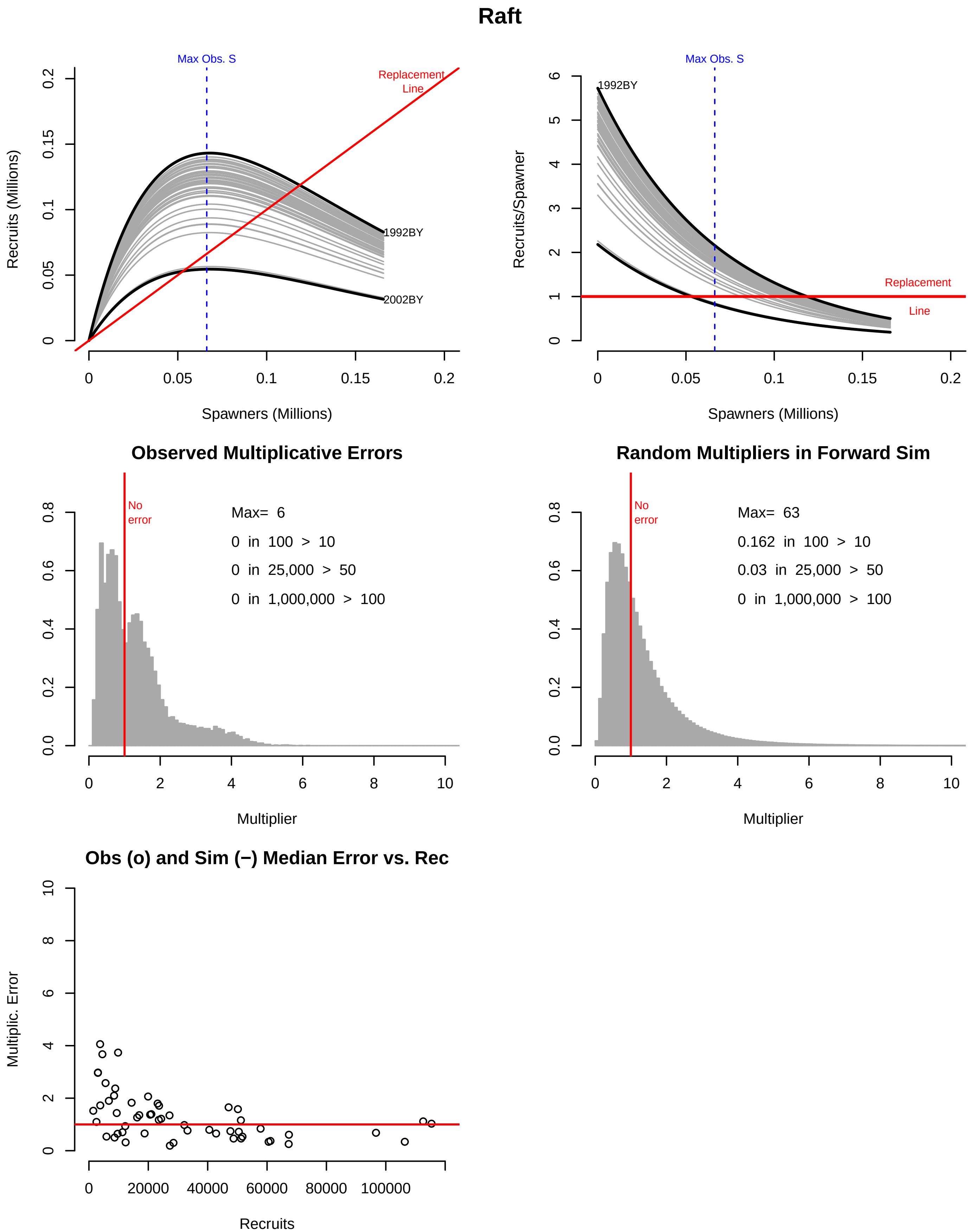


Figure A.8c: Delayed−density effects and error structure − Raft

Stellako − Observed Data

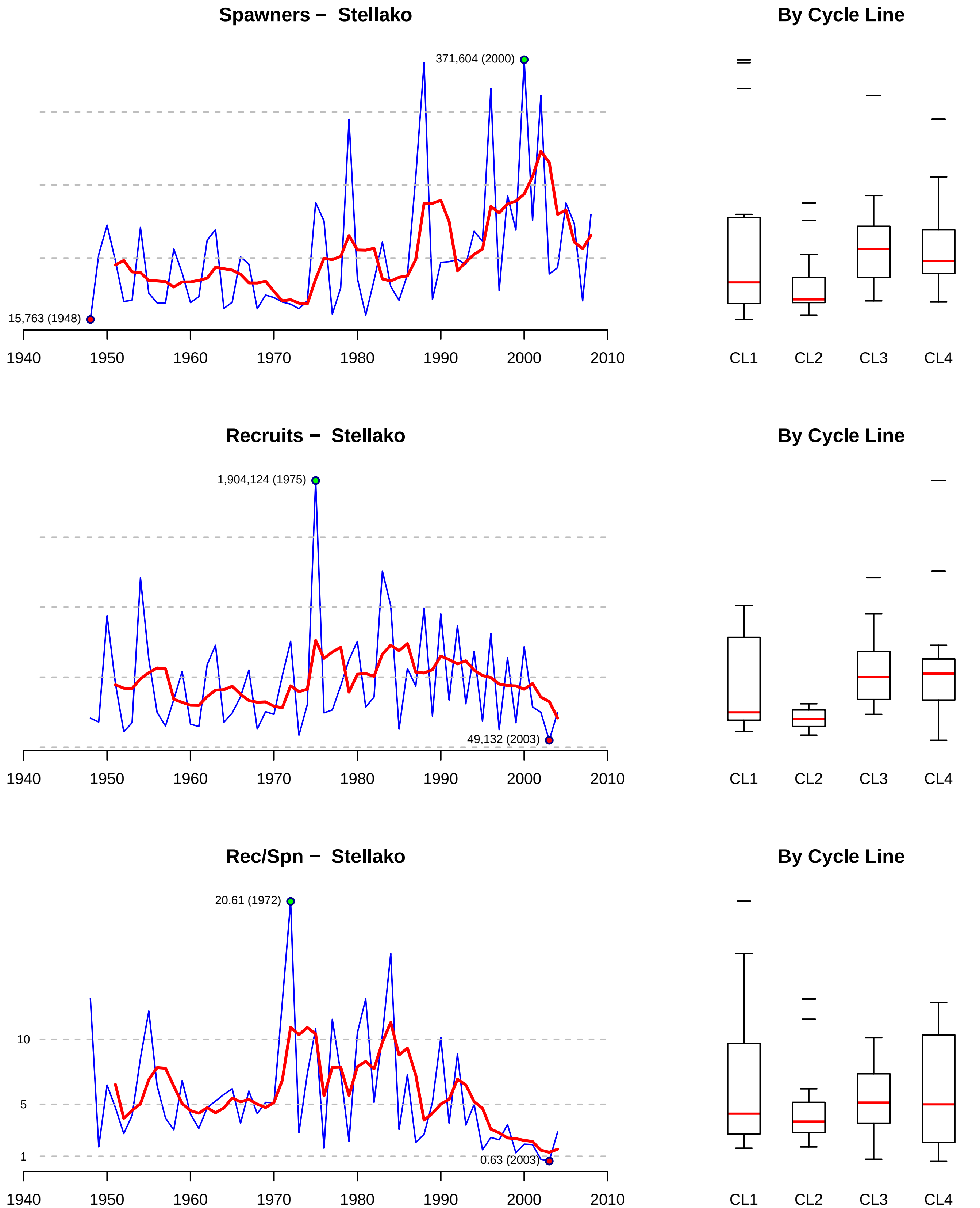


Figure A.9a: Observed Data − Stellako

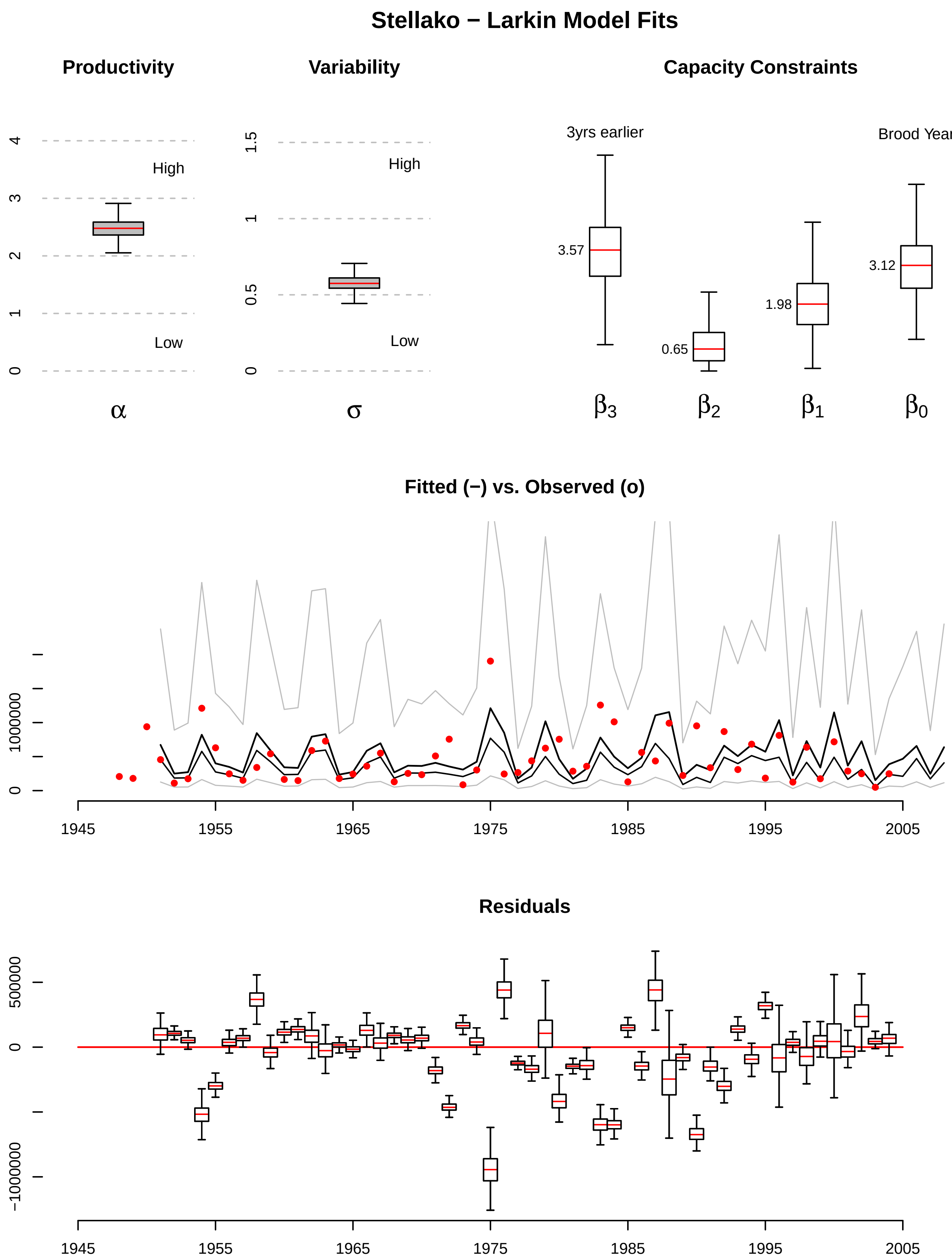


Figure A.9b: Larkin Model Fits − Stellako

Stellako

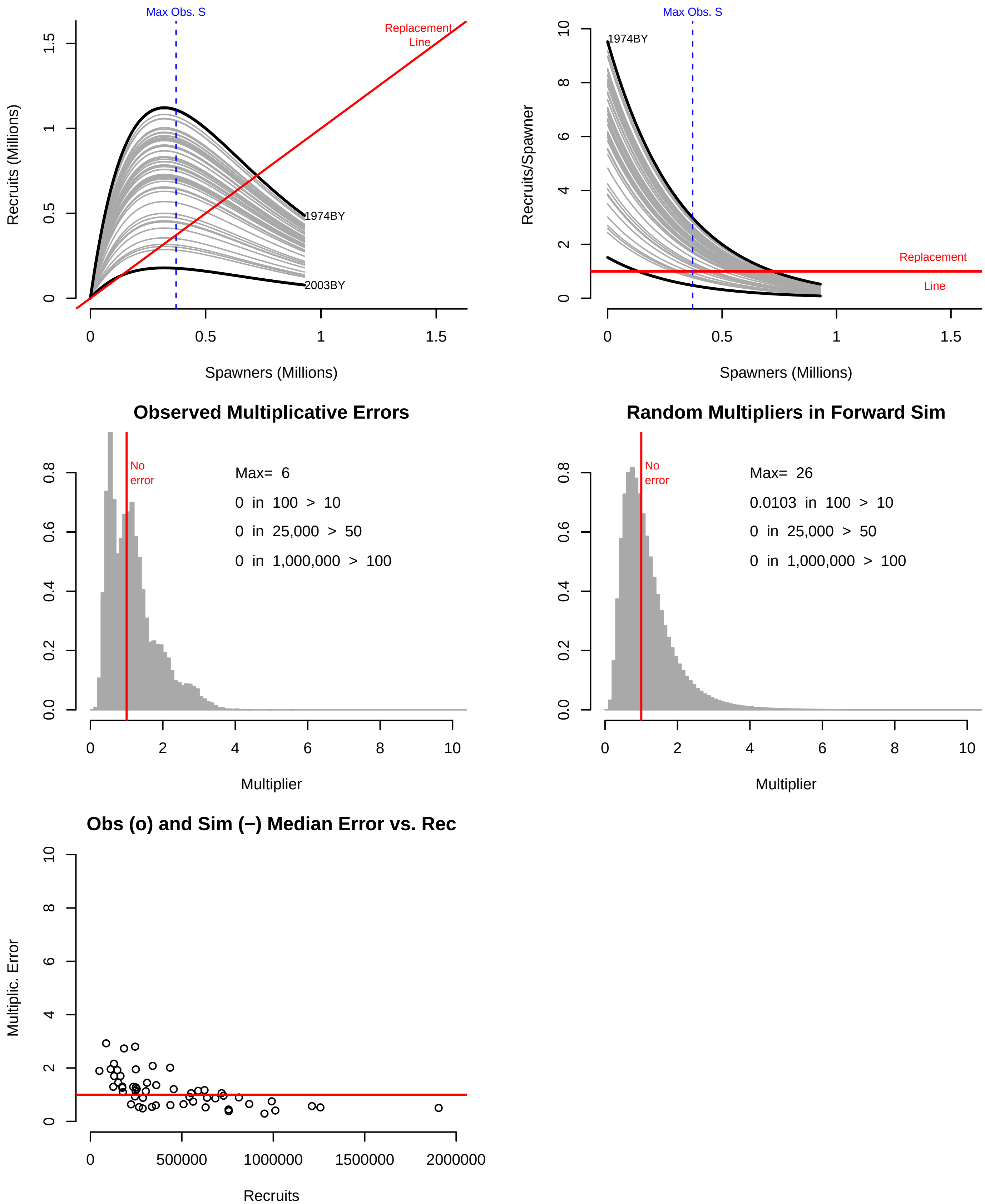


Figure A.9c: Delayed−density effects and error structure − Stellako

Late Stuart − Observed Data

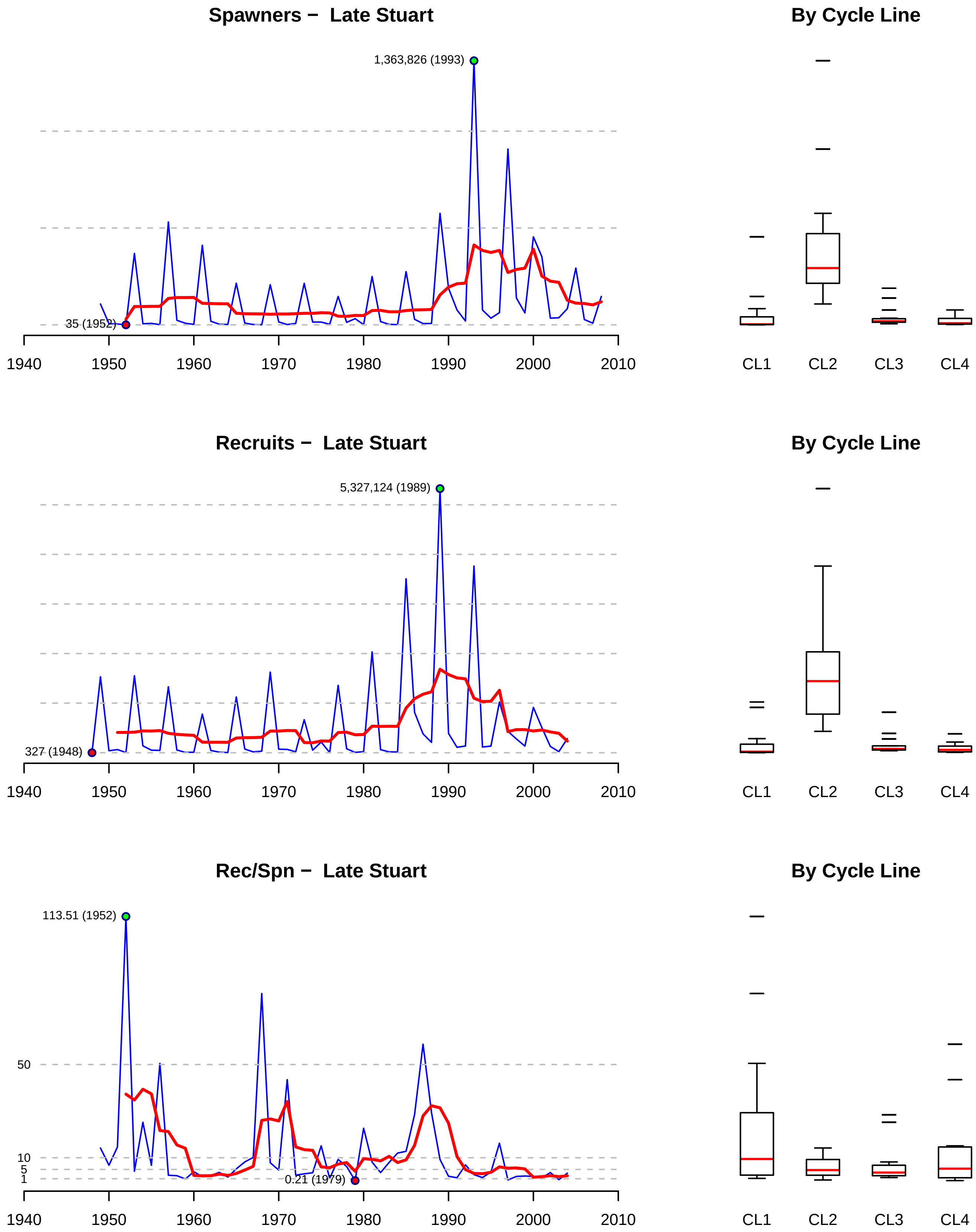


Figure A.10a: Observed Data − Late Stuart

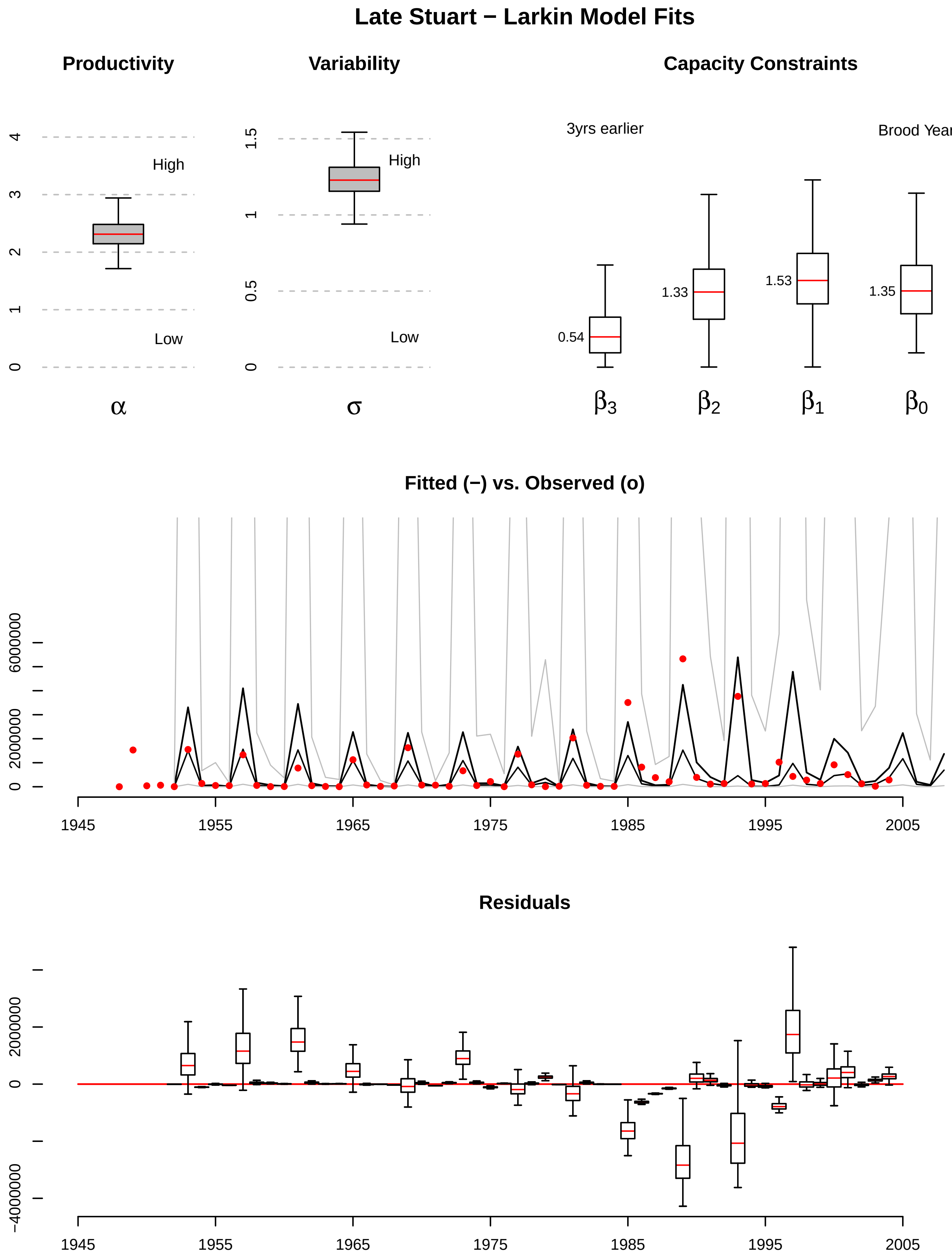


Figure A.10b: Larkin Model Fits − Late Stuart

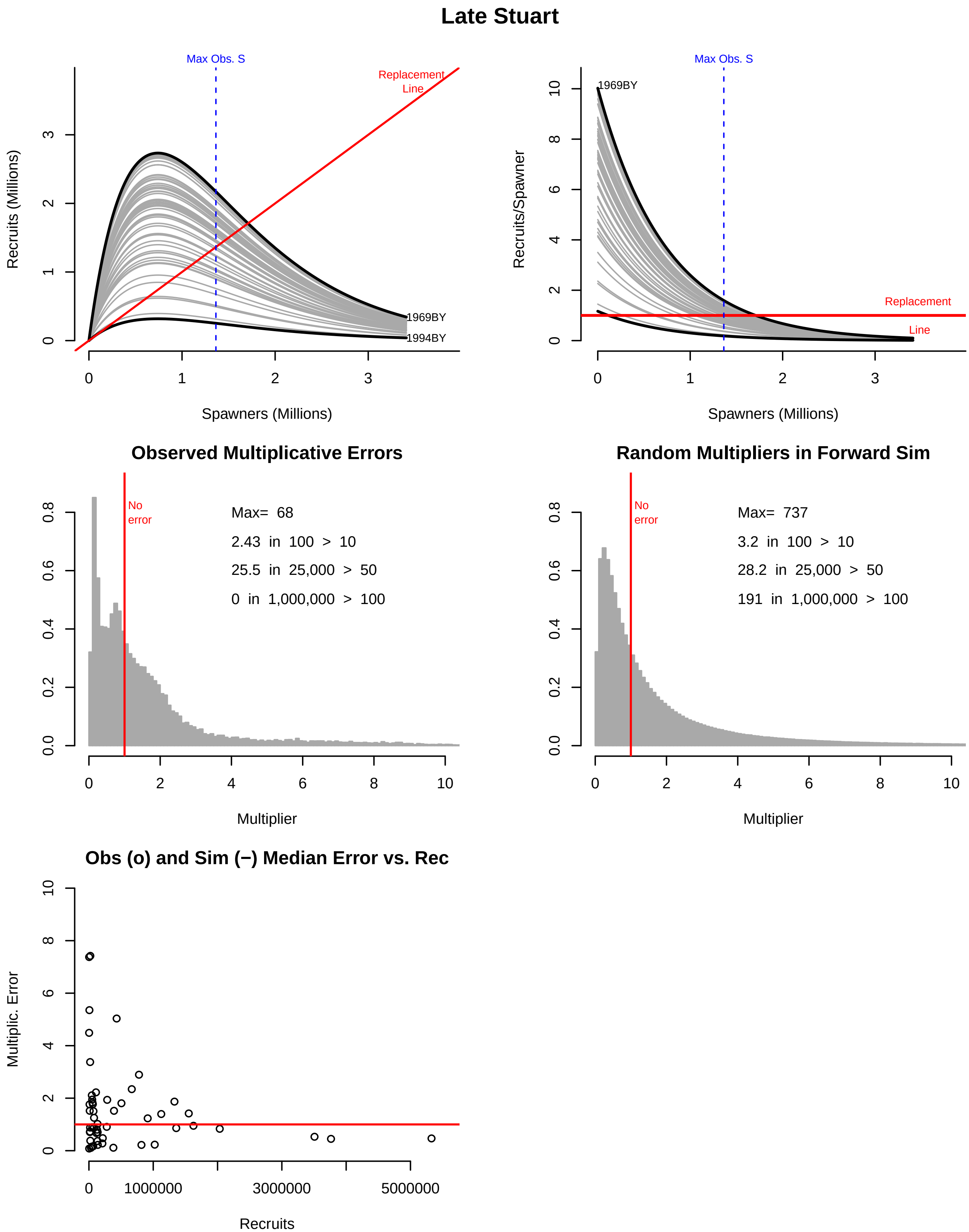


Figure A.10c: Delayed−density effects and error structure − Late Stuart

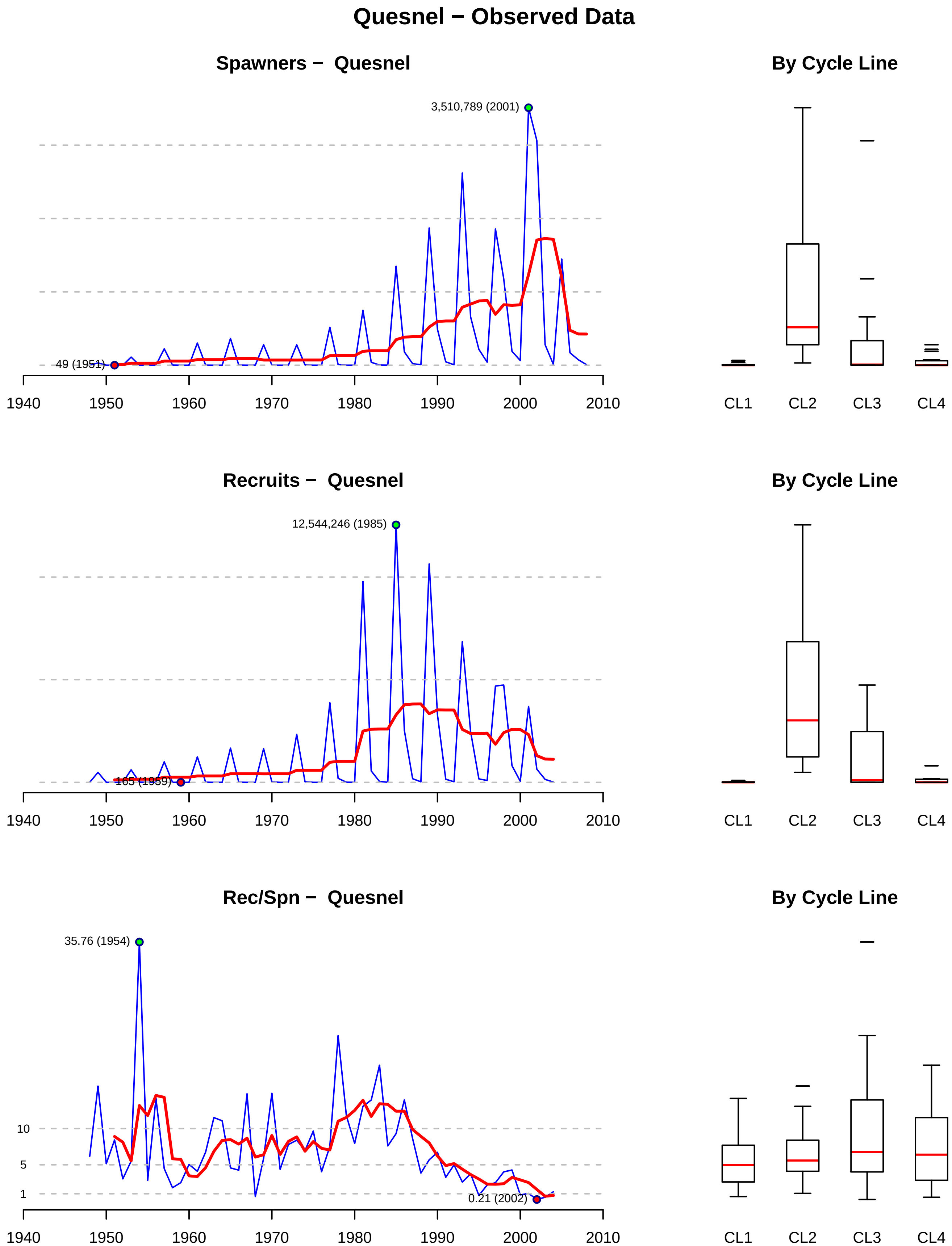


Figure A.11a: Observed Data − Quesnel

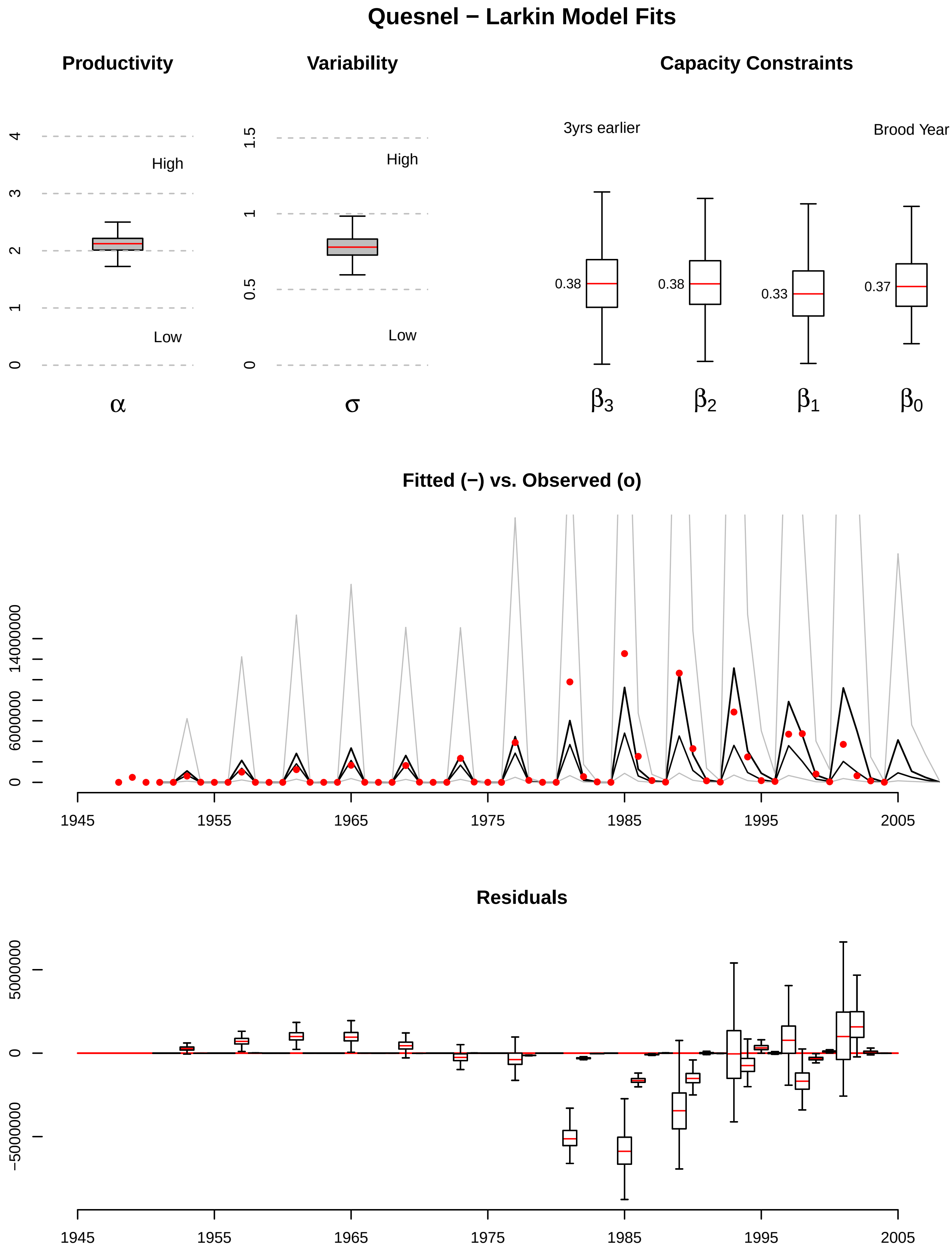


Figure A.11b: Larkin Model Fits − Quesnel

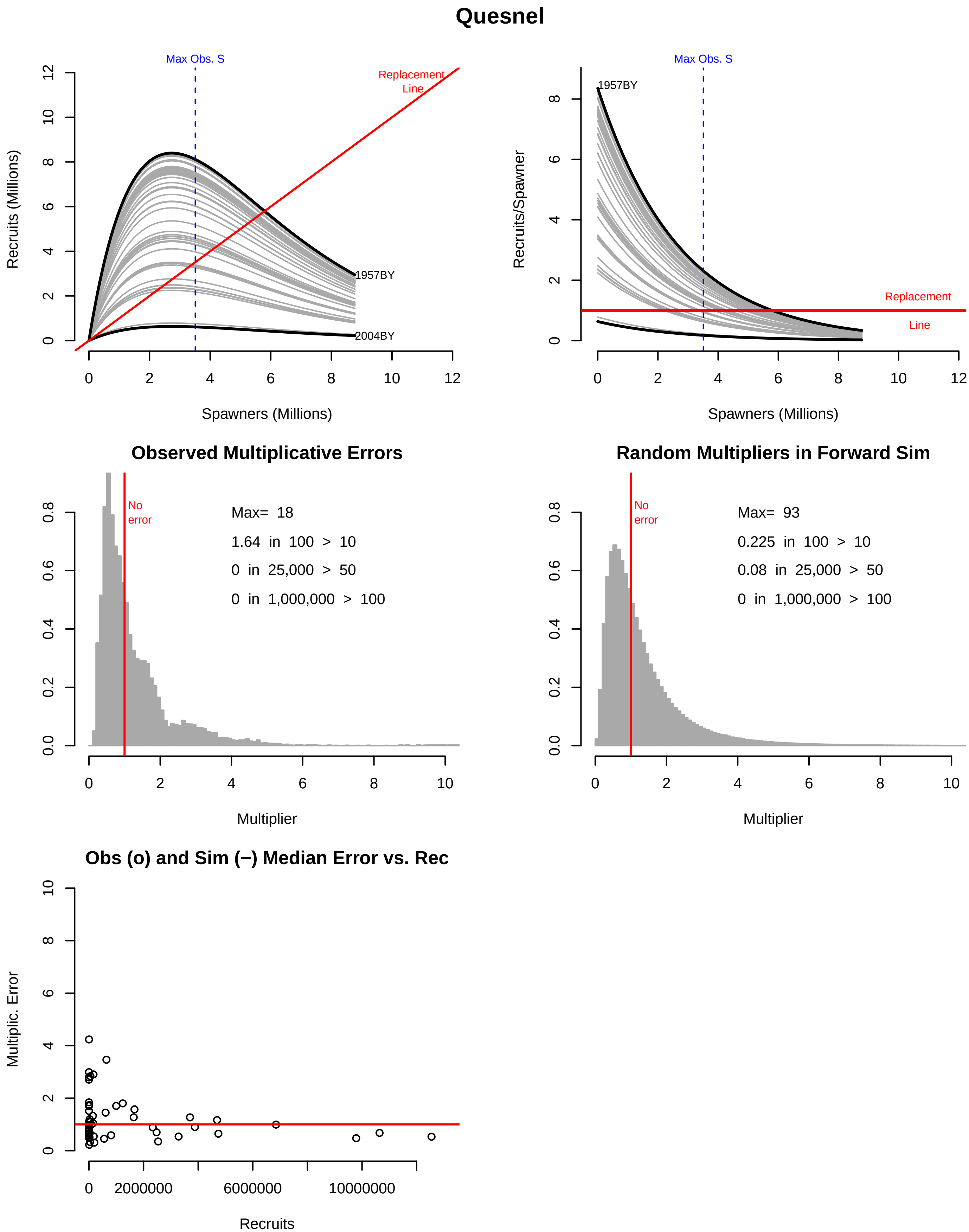


Figure A.11c: Delayed−density effects and error structure − Quesnel

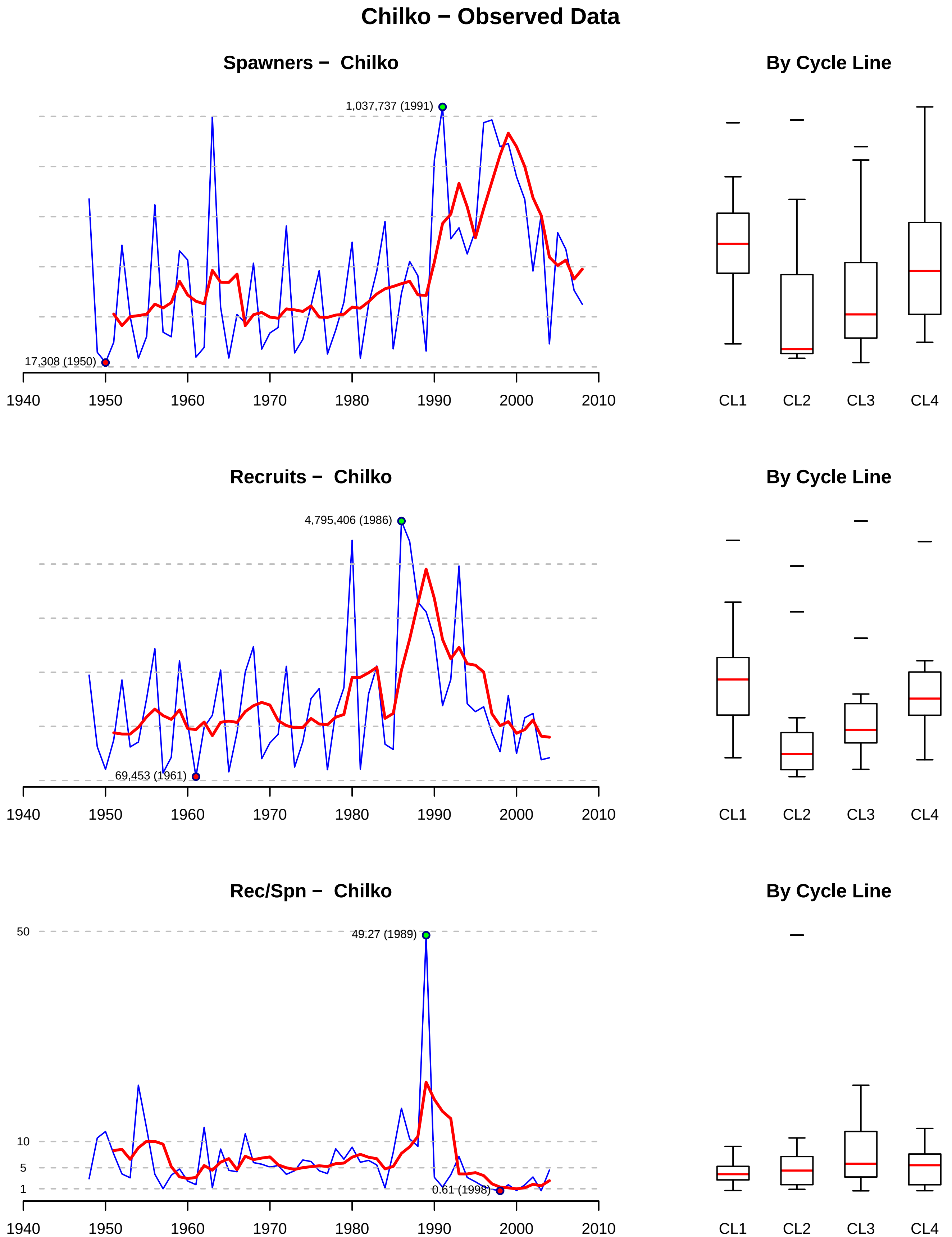


Figure A.12a: Observed Data − Chilko

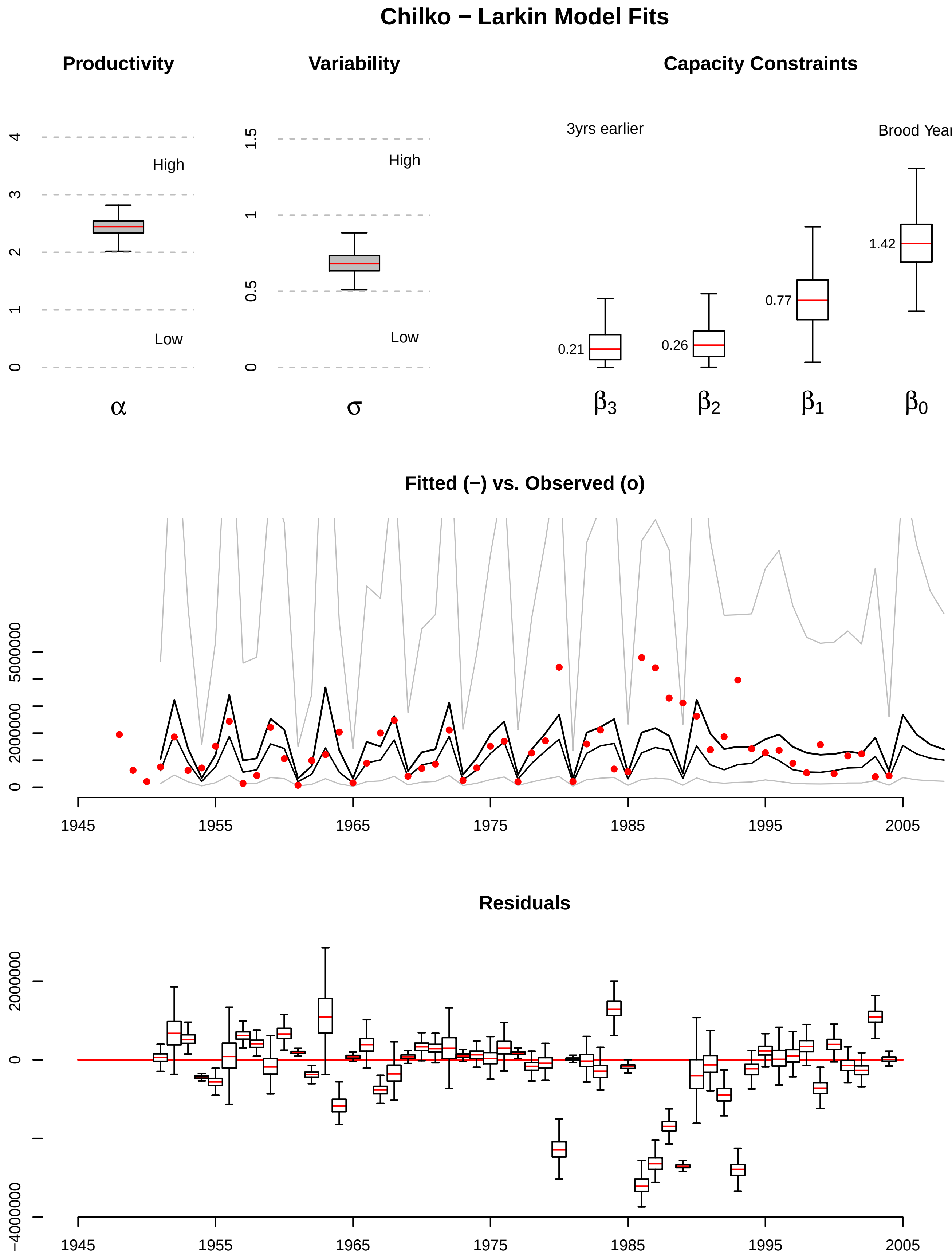


Figure A.12b: Larkin Model Fits − Chilko

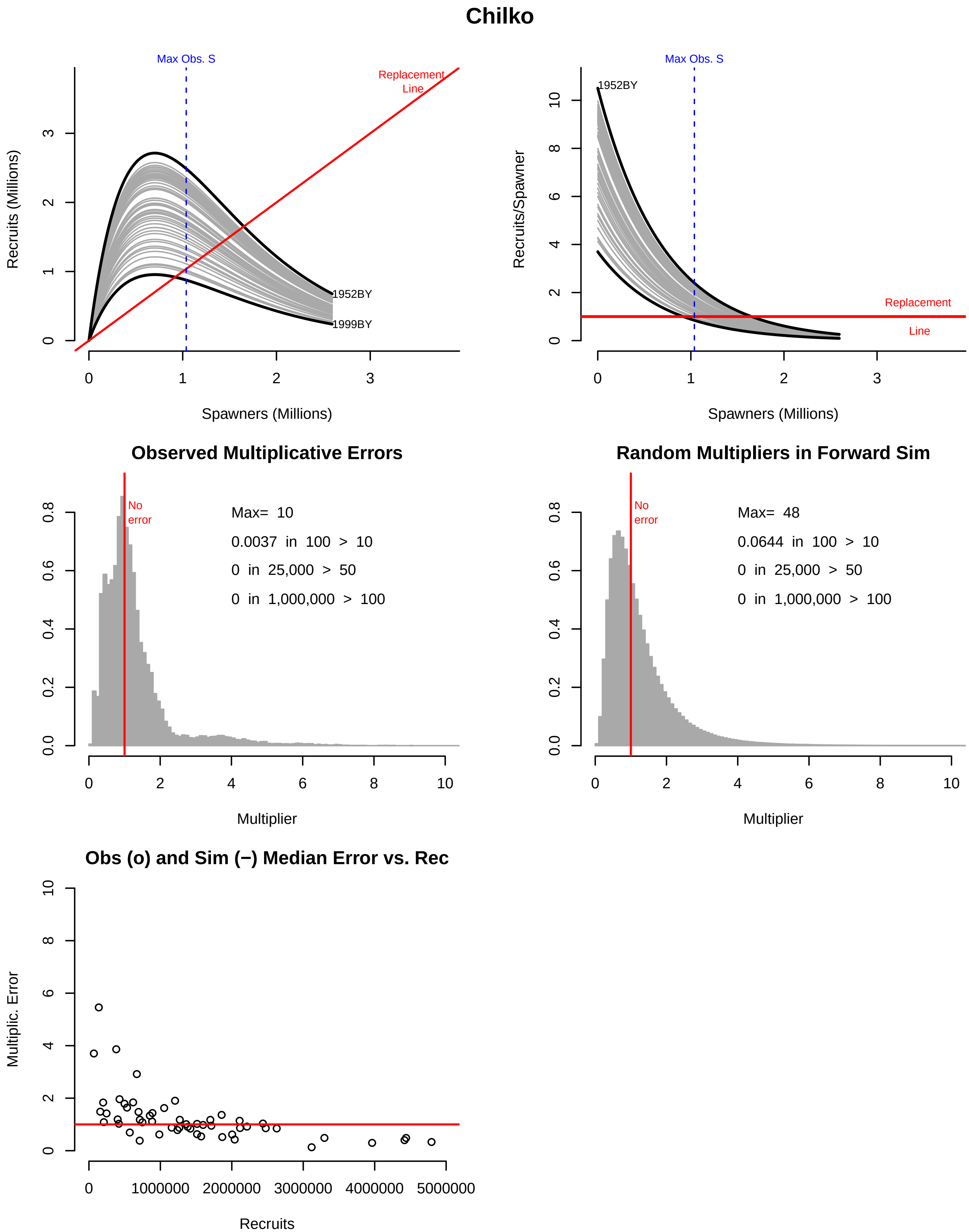


Figure A.12c: Delayed−density effects and error structure − Chilko

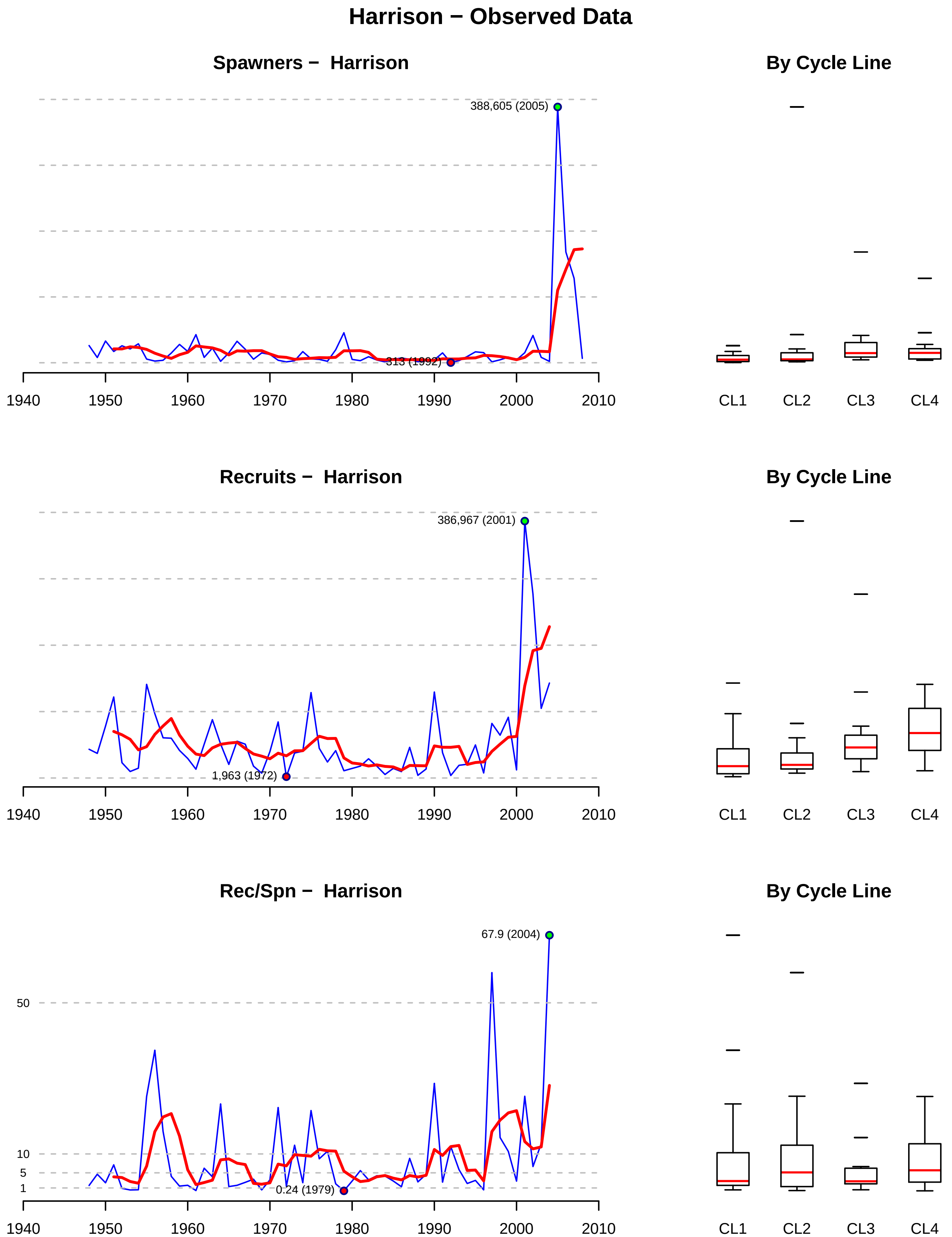


Figure A.13a: Observed Data − Harrison

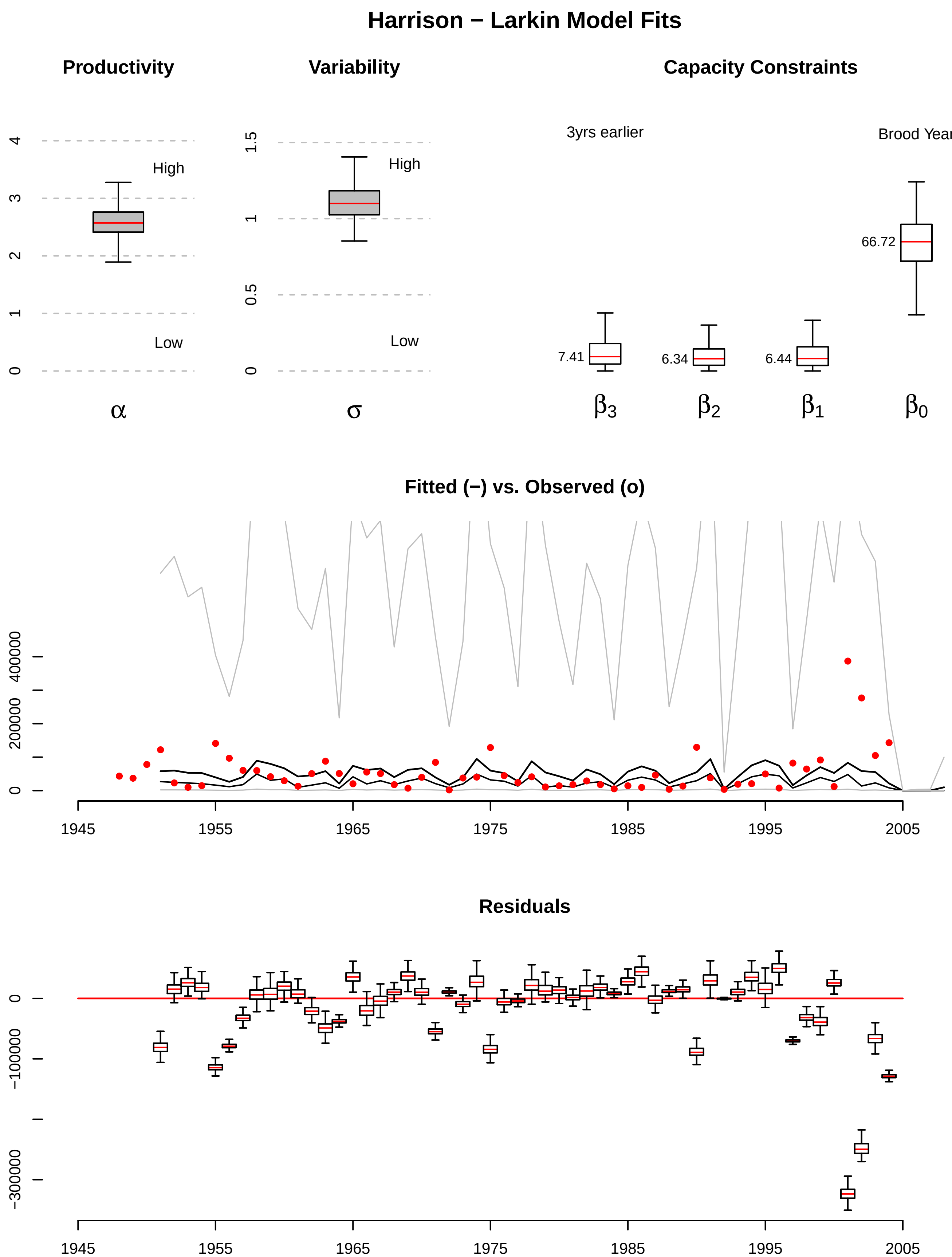


Figure A.13b: Larkin Model Fits − Harrison

Harrison

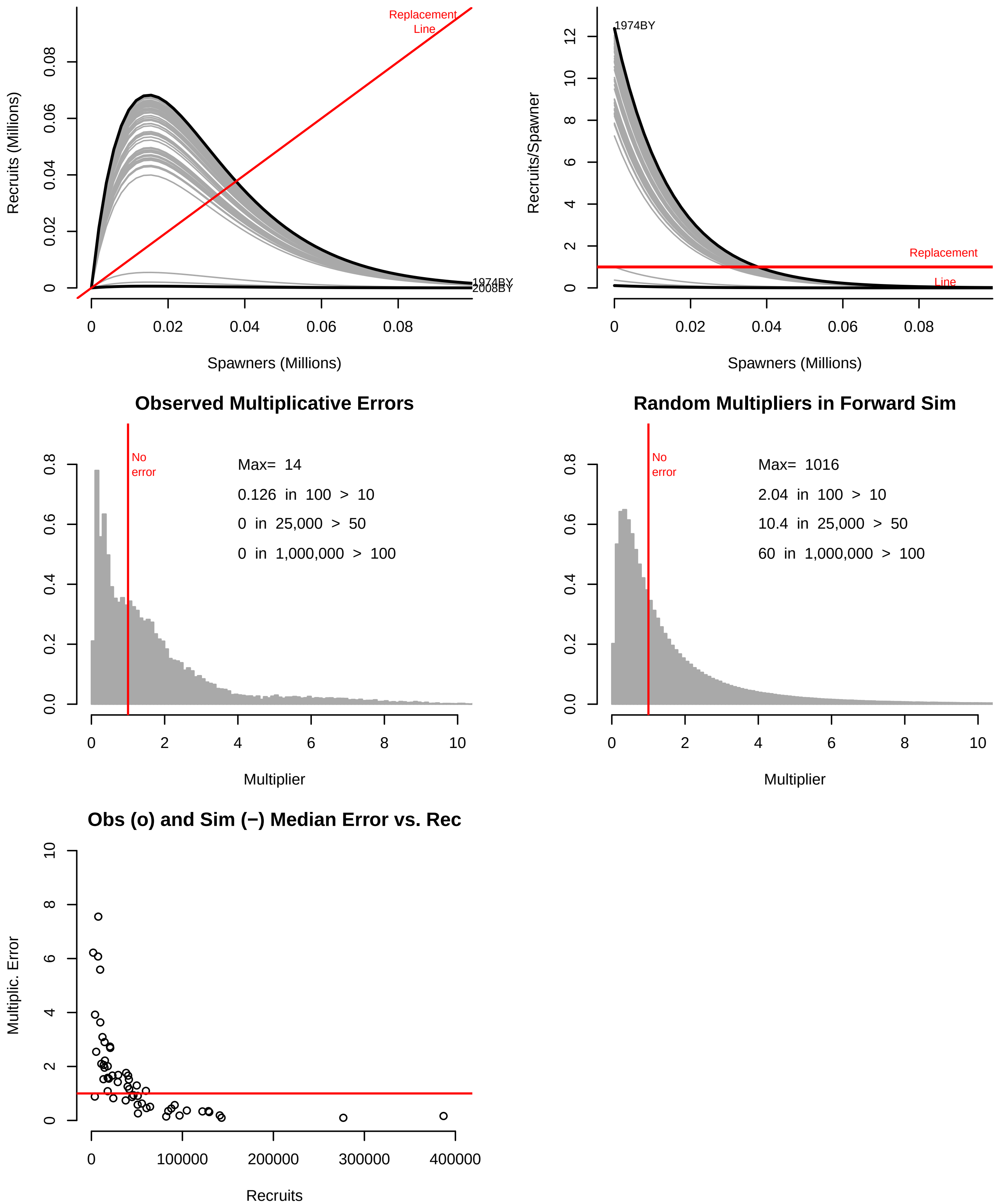


Figure A.13c: Delayed−density effects and error structure − Harrison

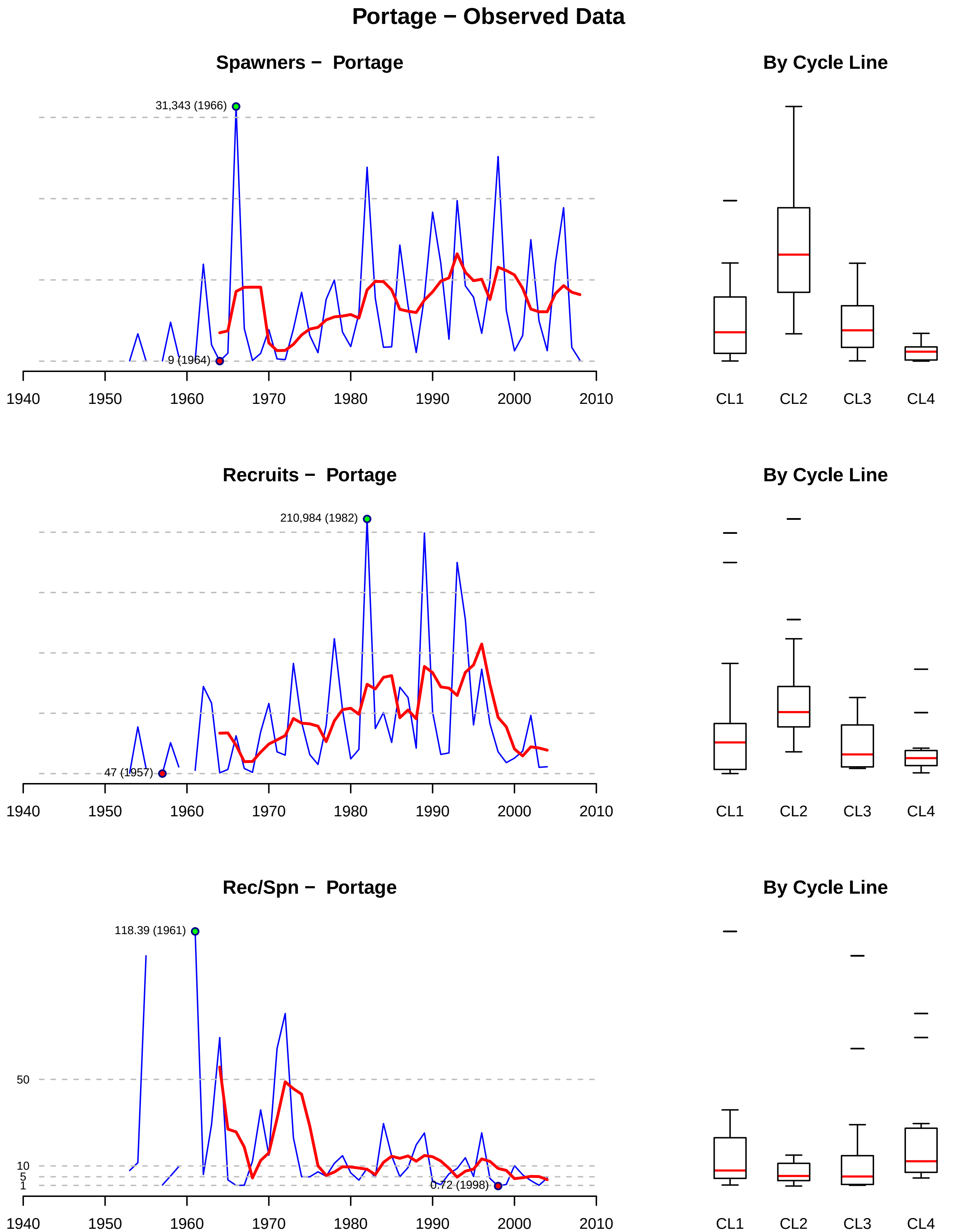


Figure A.14a: Observed Data − Portage

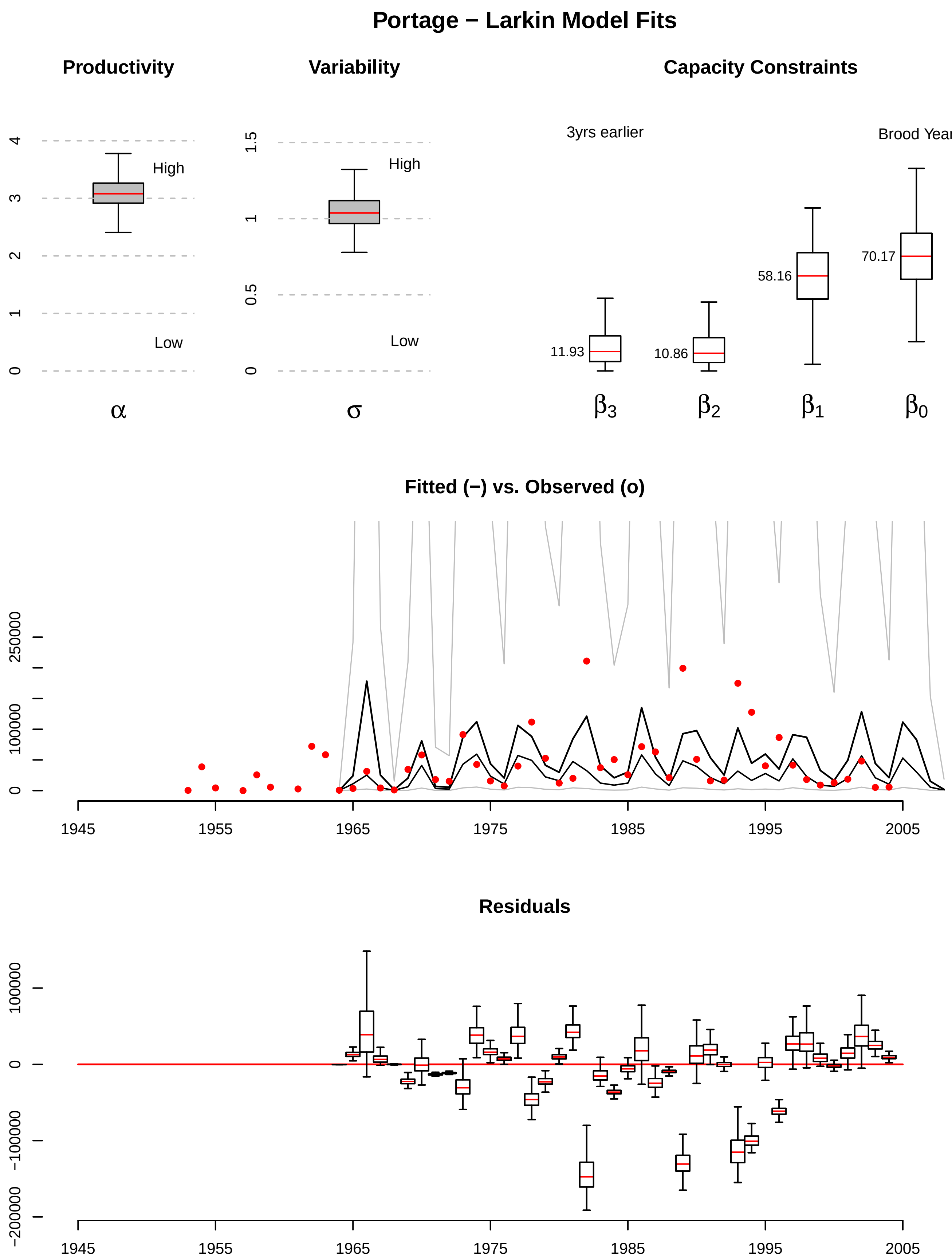


Figure A.14b: Larkin Model Fits – Portage

Portage

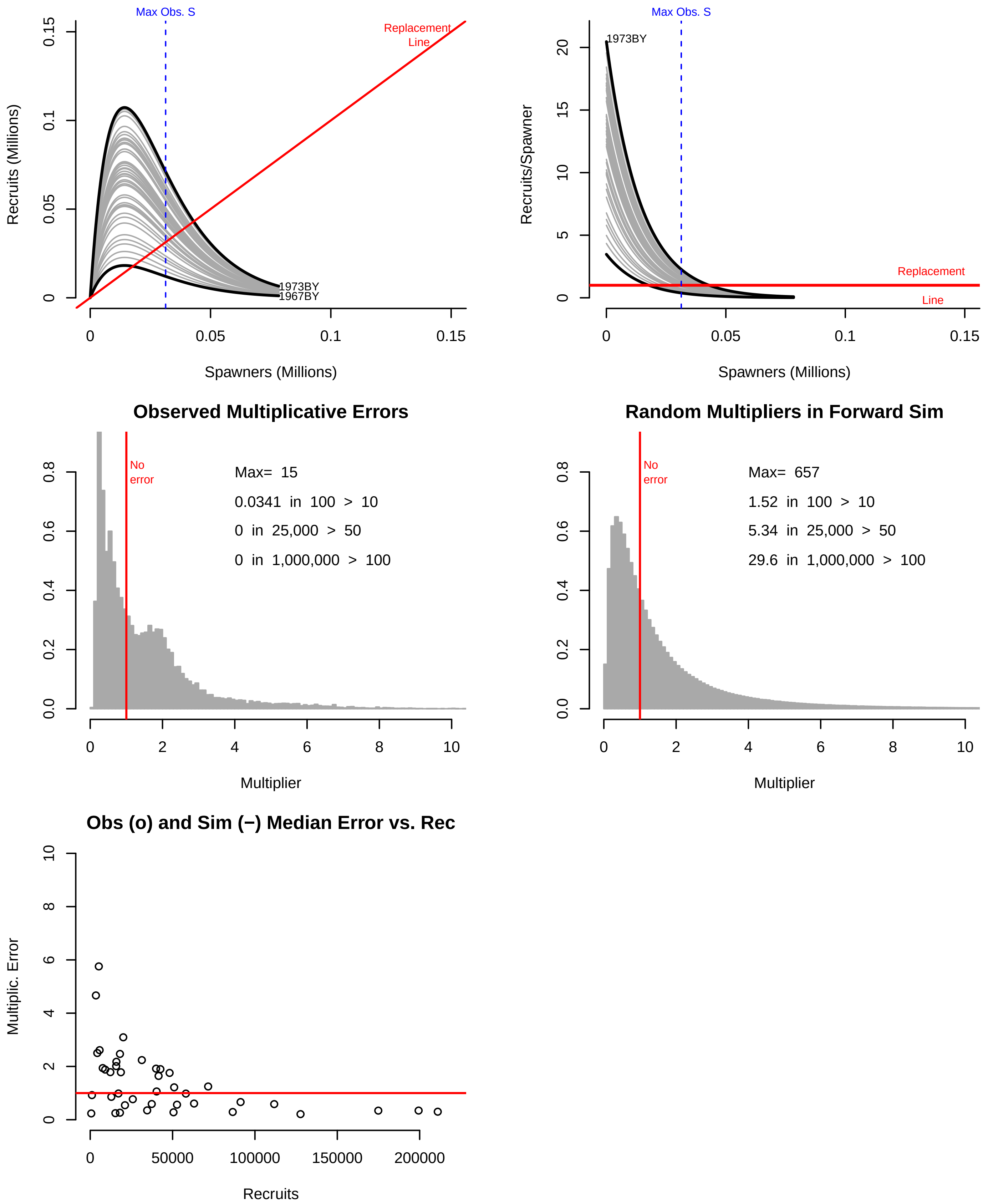


Figure A.14c: Delayed−density effects and error structure − Portage

Late Shuswap − Observed Data

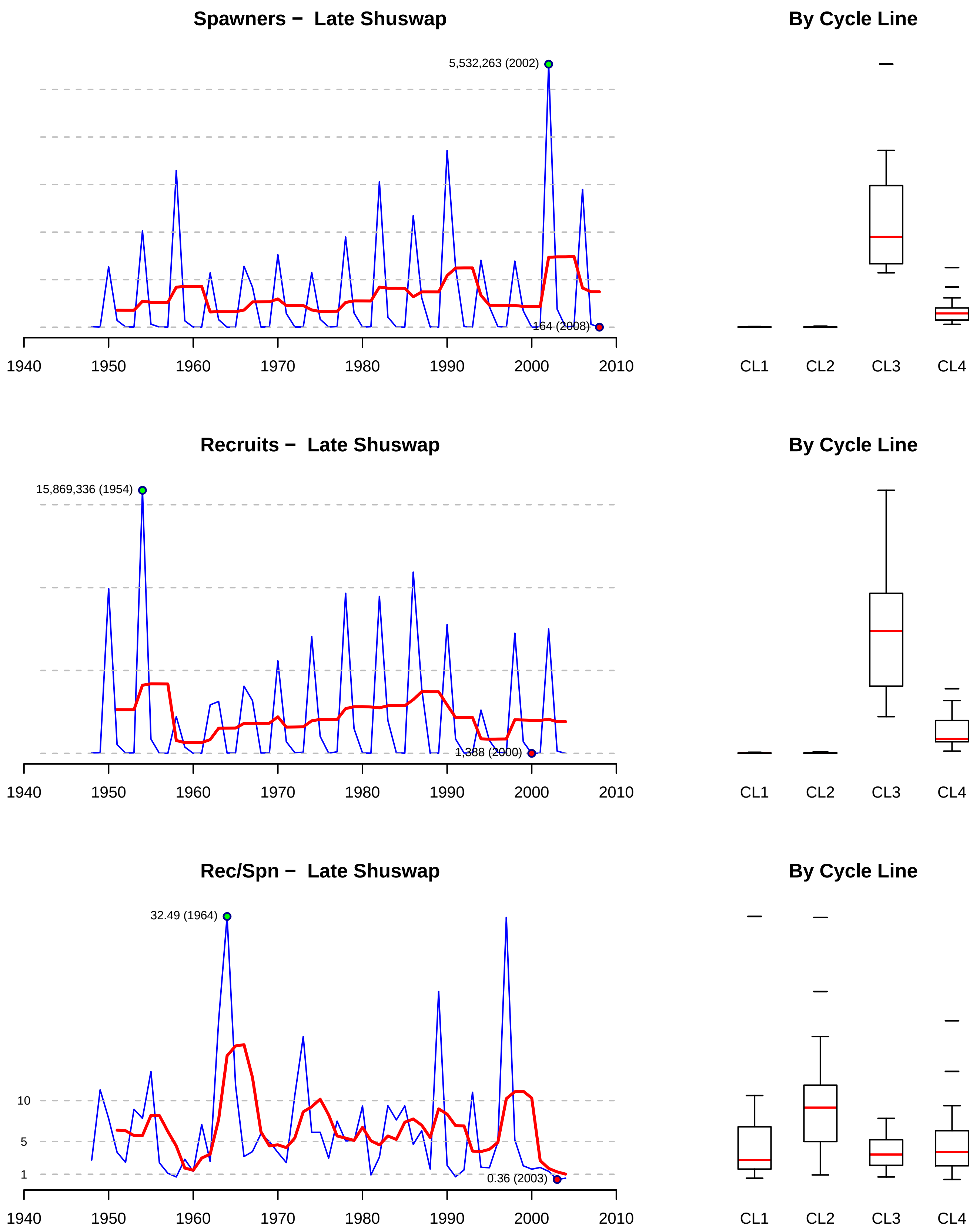


Figure A.15a: Observed Data − Late Shuswap

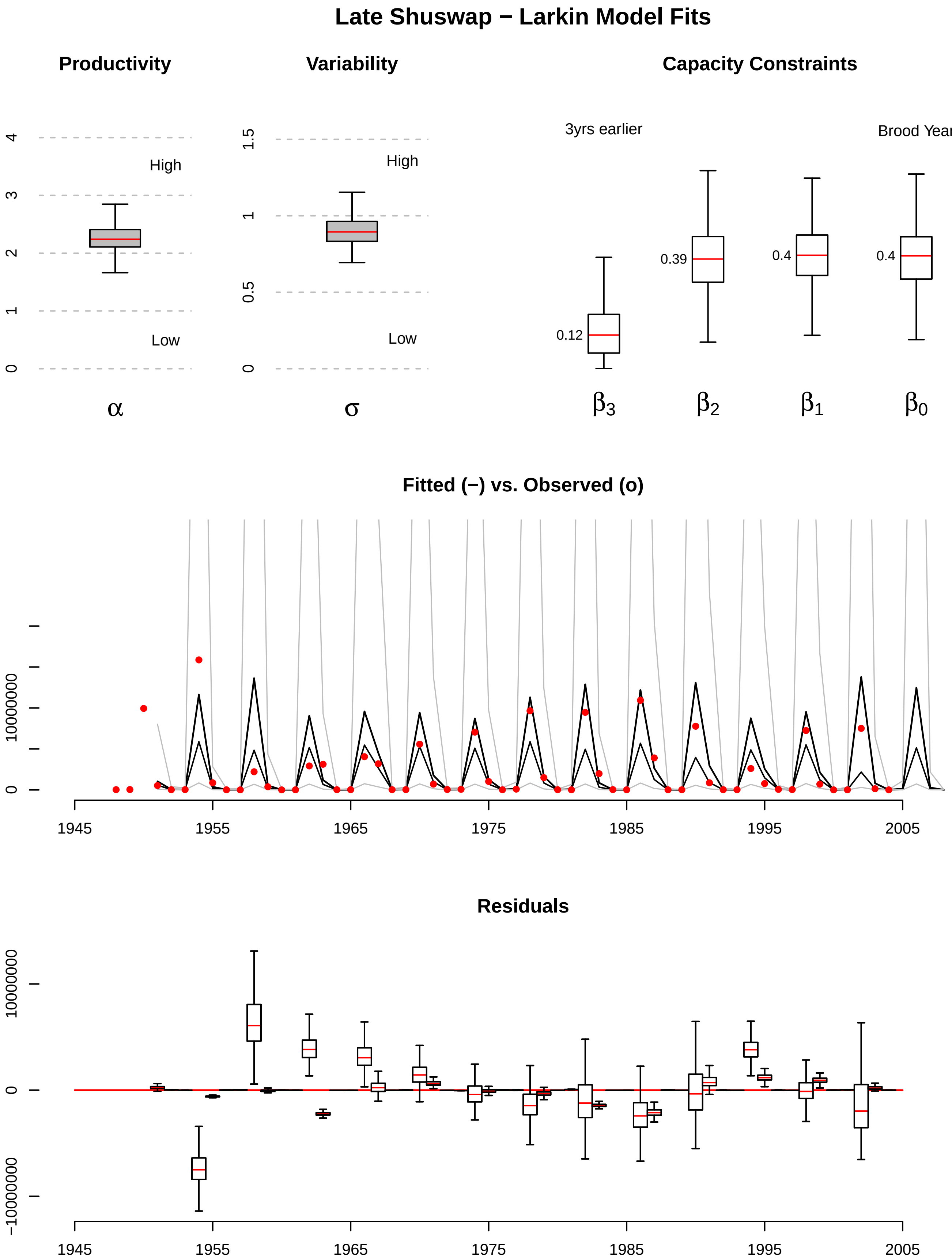


Figure A.15b: Larkin Model Fits − Late Shuswap

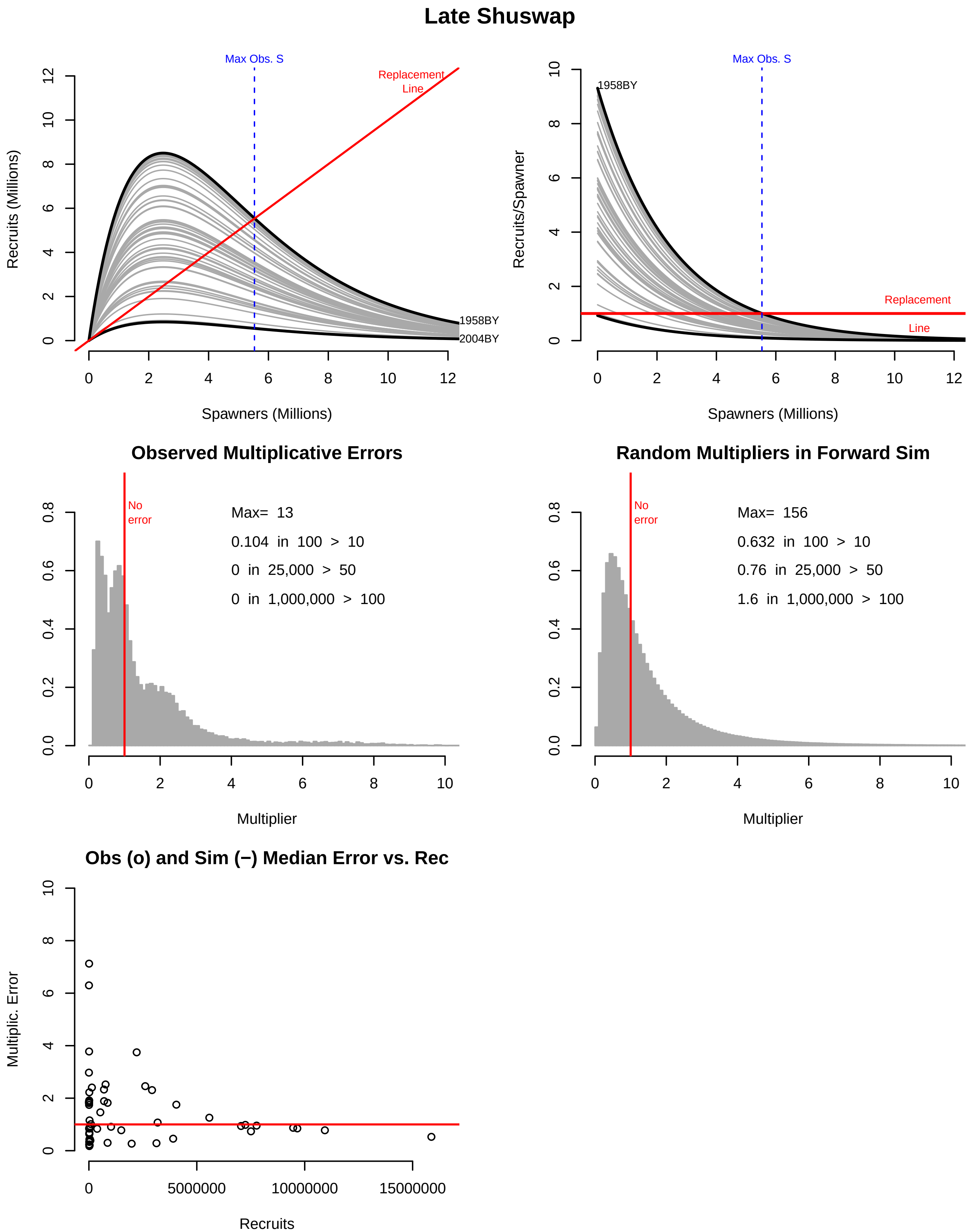


Figure A.15c: Delayed−density effects and error structure − Late Shuswap

Birkenhead − Observed Data

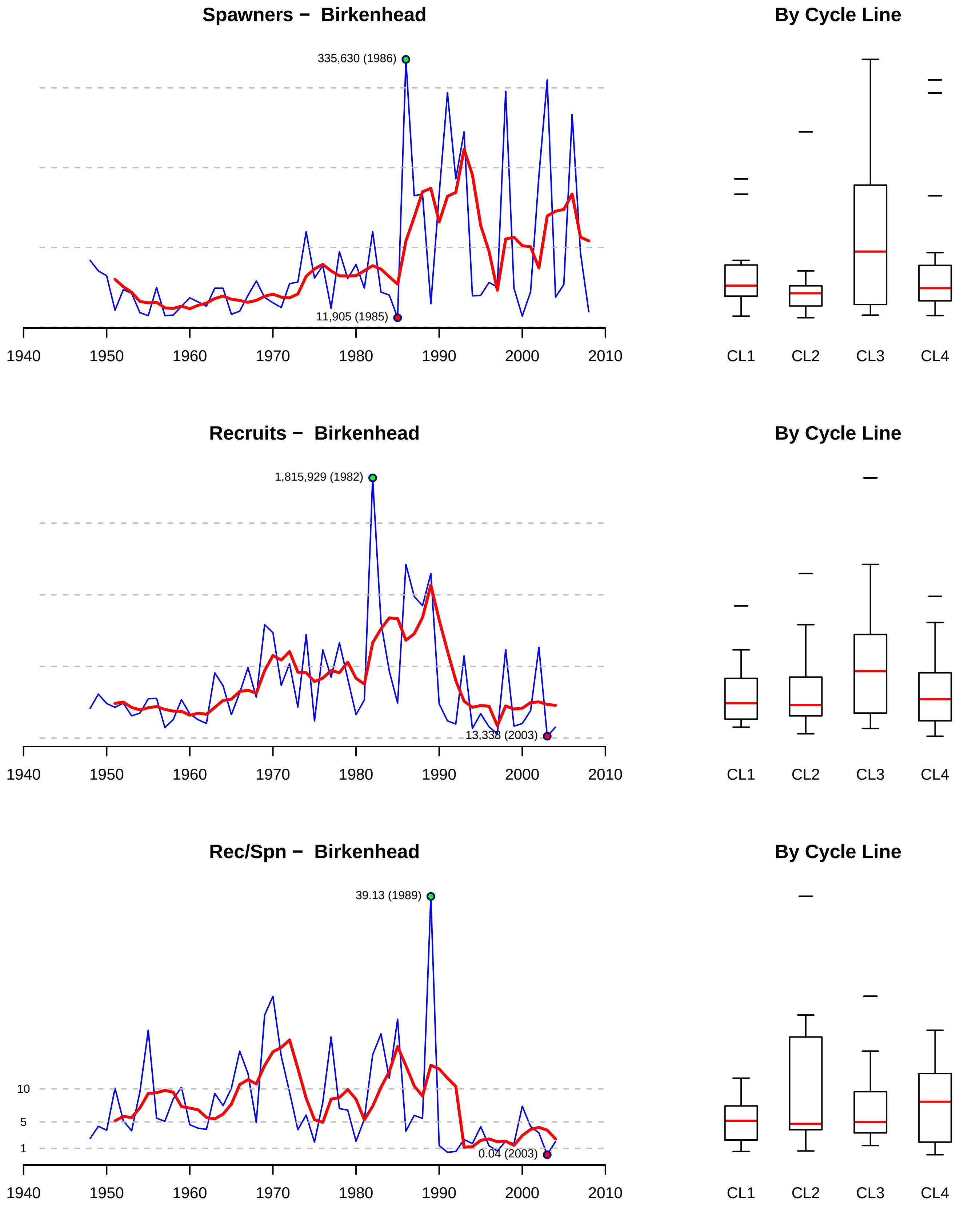


Figure A.16a: Observed Data − Birkenhead

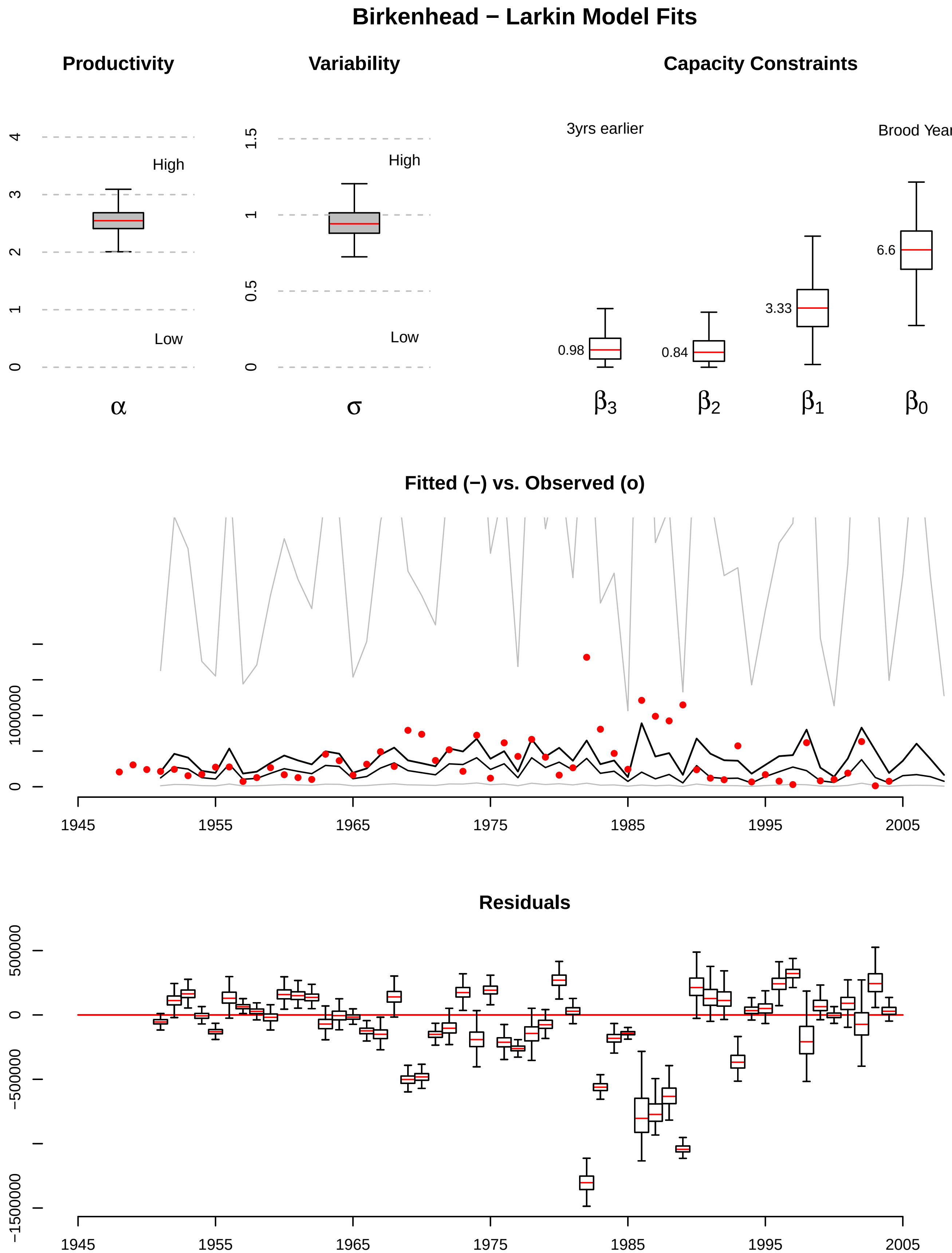


Figure A.16b: Larkin Model Fits − Birkenhead

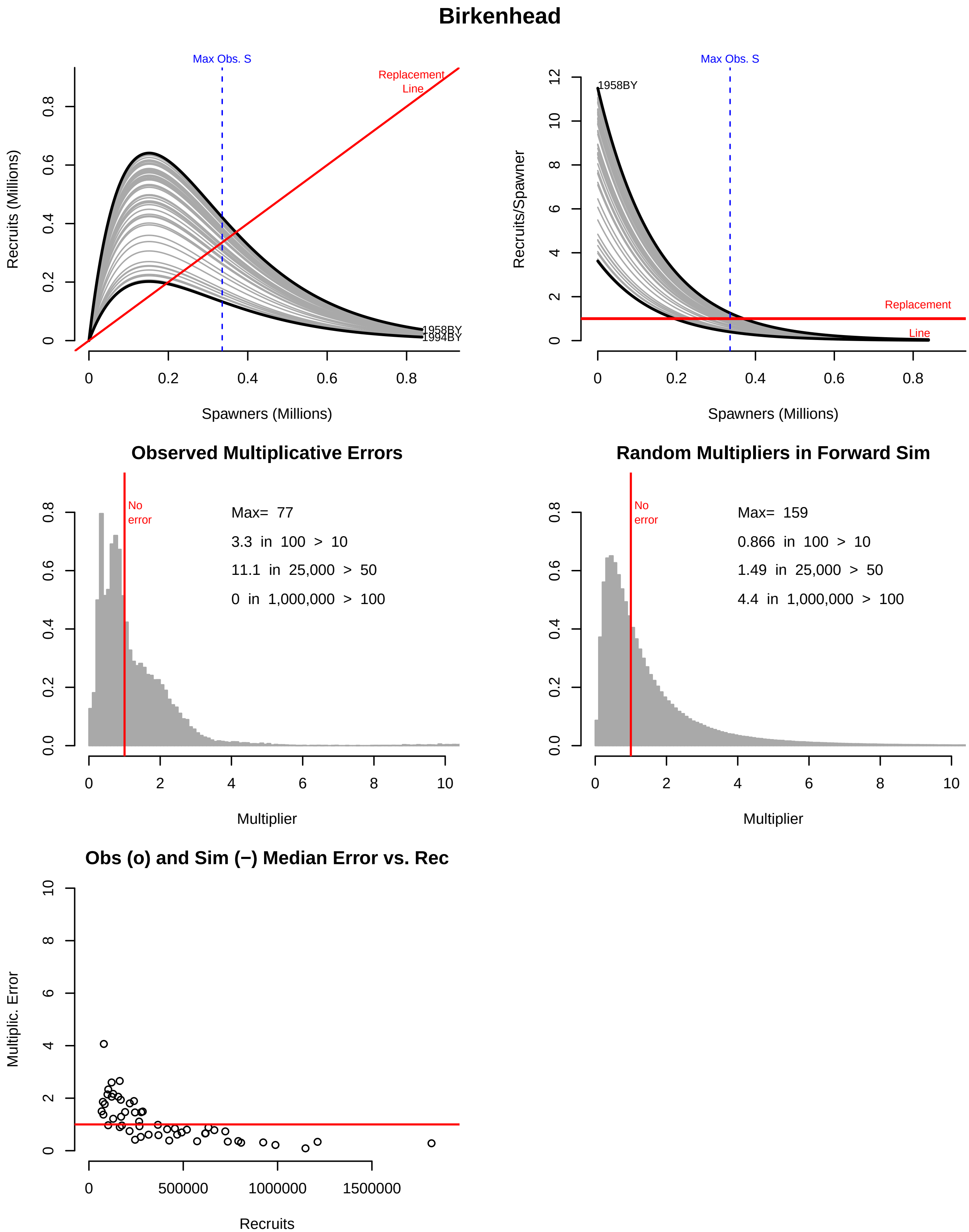


Figure A.16c: Delayed−density effects and error structure − Birkenhead

Weaver Creek − Observed Data

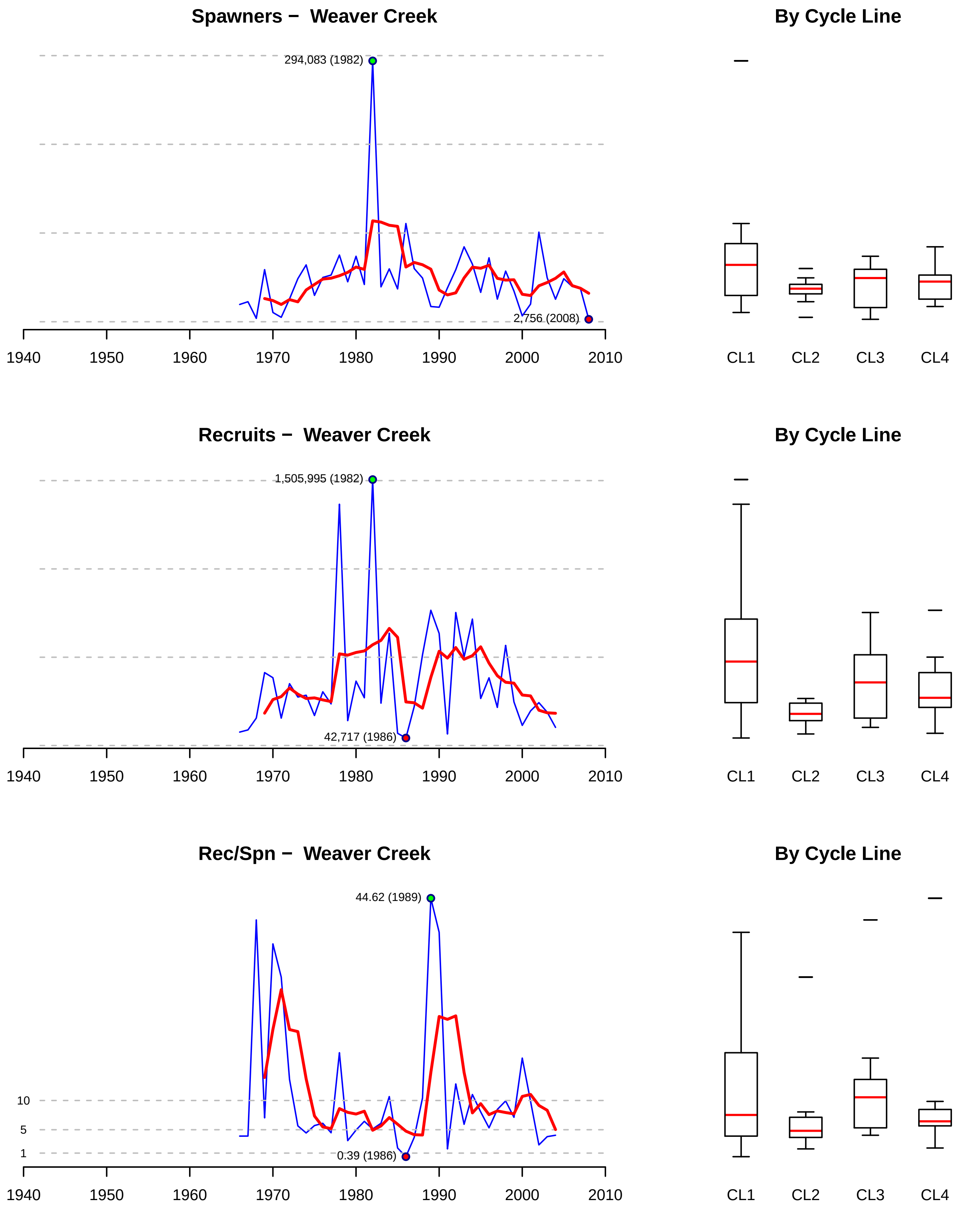


Figure A.17a: Observed Data − Weaver Creek

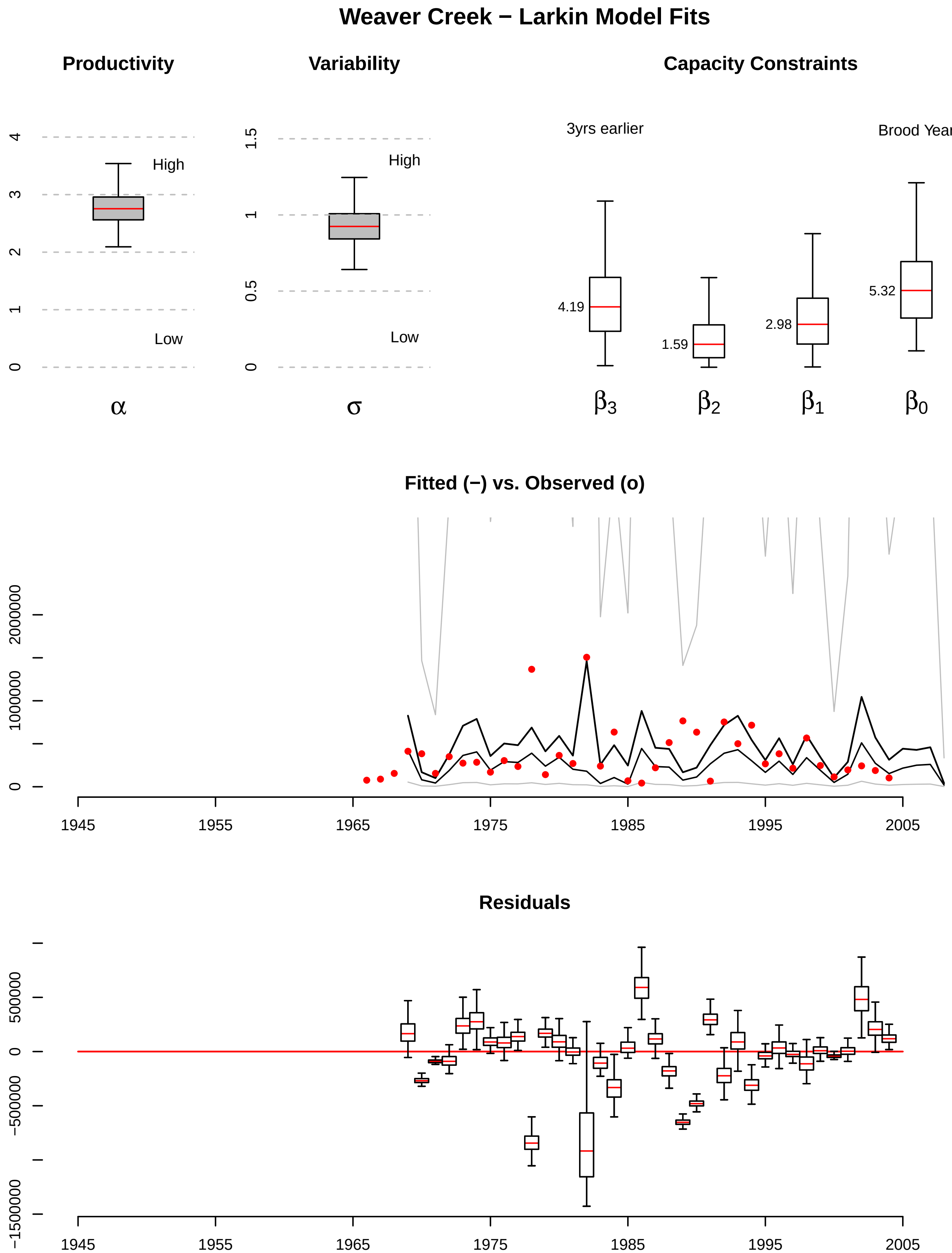


Figure A.17b: Larkin Model Fits − Weaver Creek

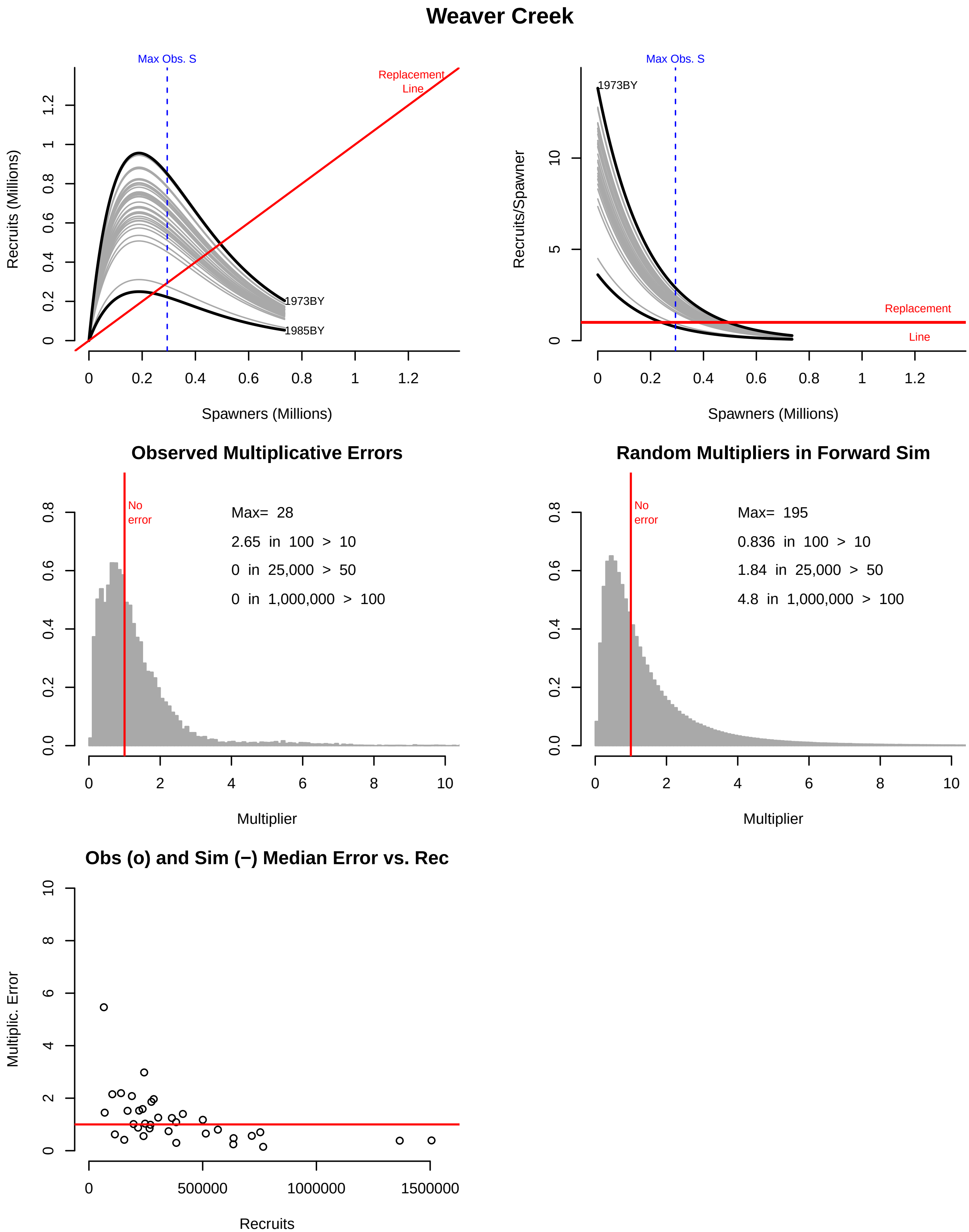


Figure A.17c: Delayed−density effects and error structure − Weaver Creek

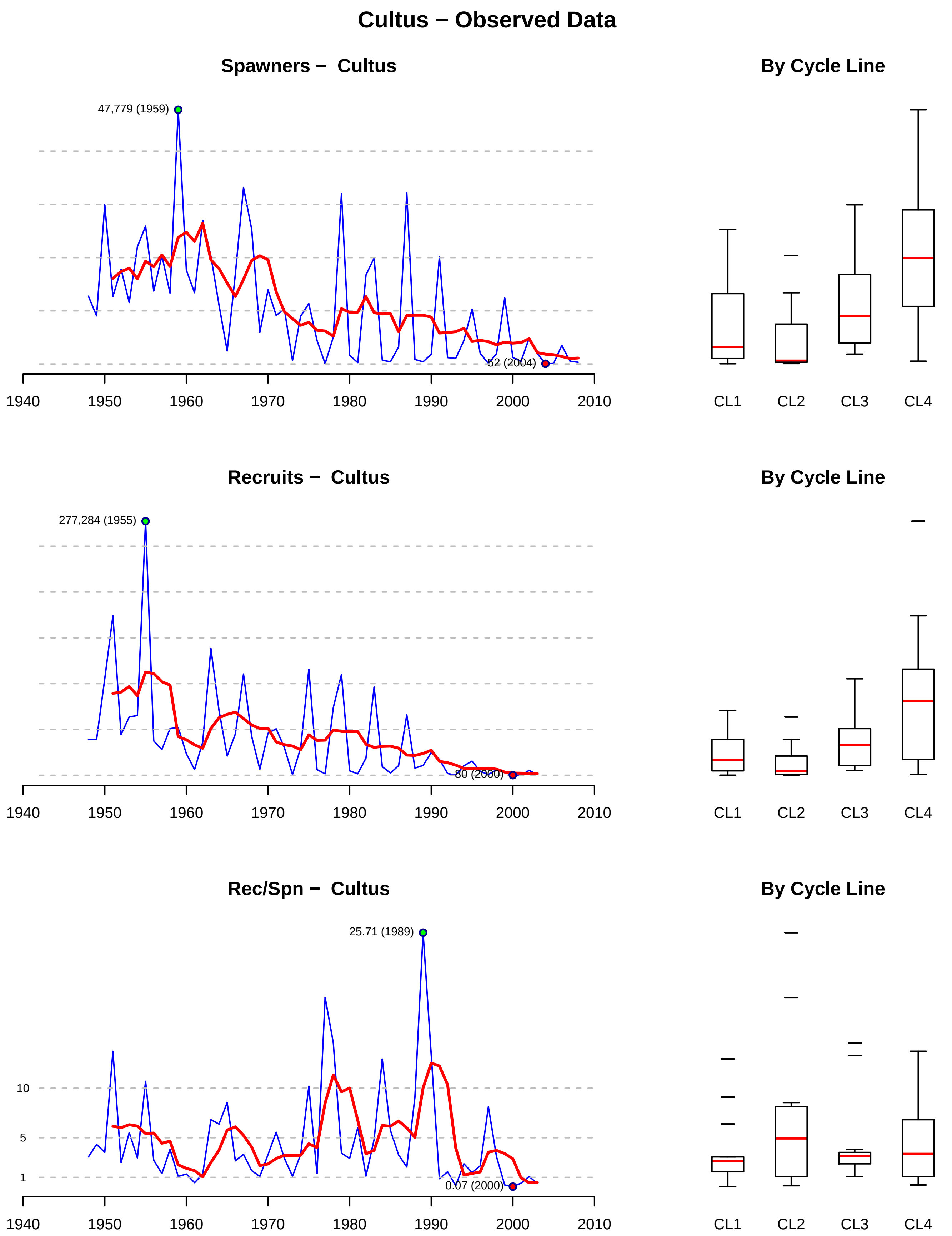


Figure A.18a: Observed Data − Cultus

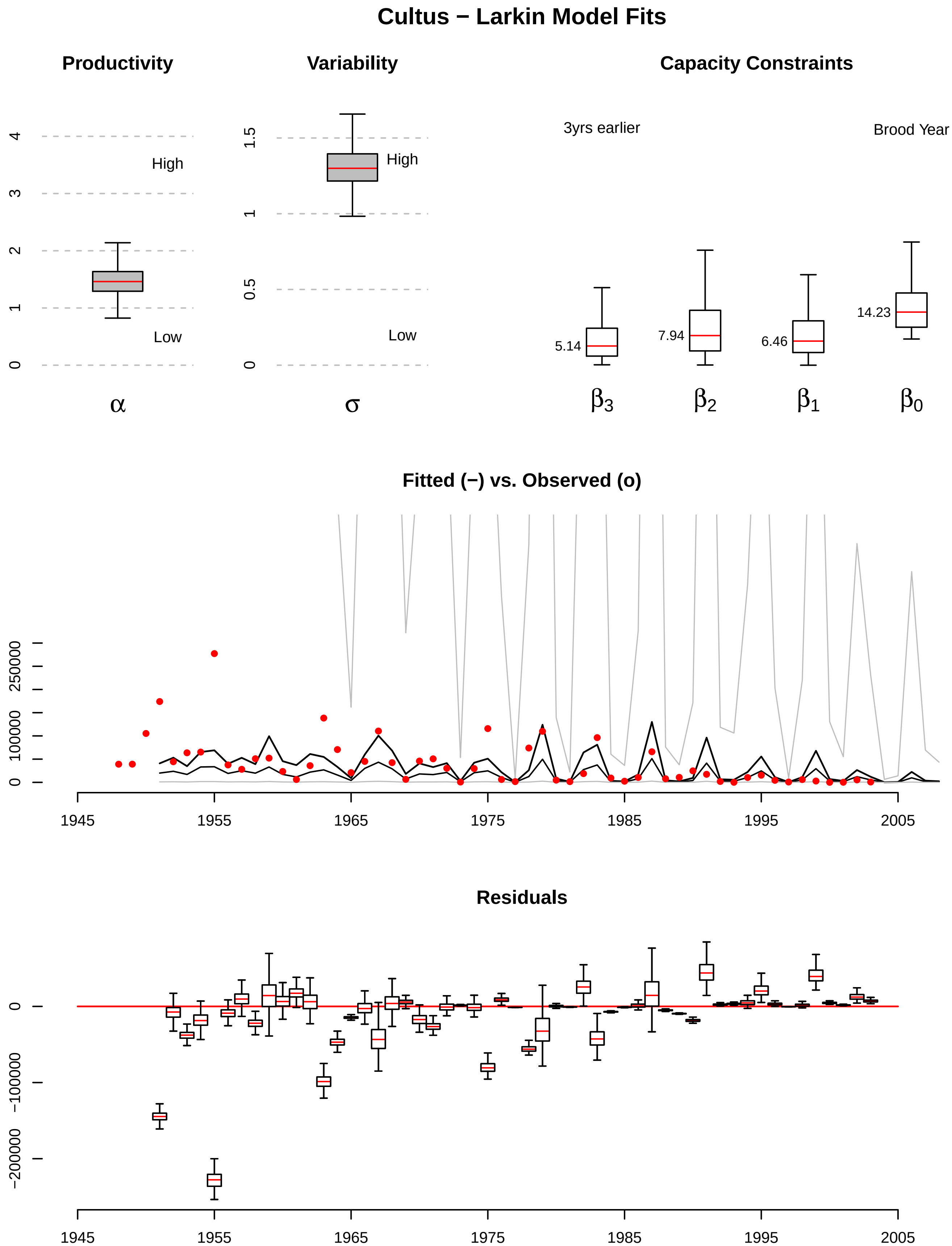


Figure A.18b: Larkin Model Fits − Cultus

Cultus

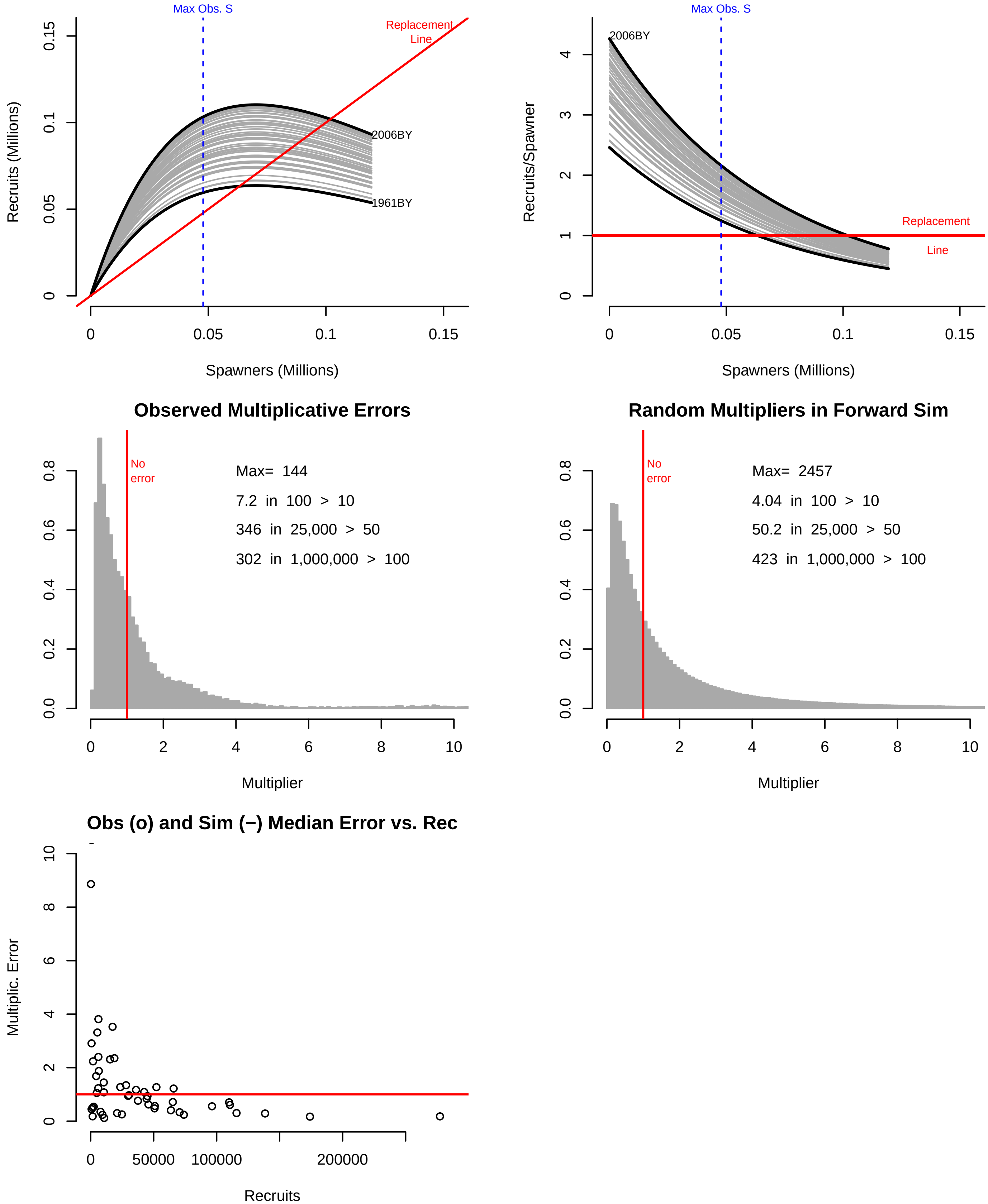


Figure A.18c: Delayed−density effects and error structure − Cultus