Benchmark Analysis for Pacific Salmon

Conservation Units in the Skeena Watershed

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Executive Summary[1]

Background and Approach

Canada's Wild Salmon Policy (WSP[2]) calls for the monitoring and assessment of all geographically, ecologically and genetically distinct populations of wild Pacific salmon, known as Conservation Units (CUs). The Wild Salmon Policy states that CUs will be assessed against specific reference points, or benchmarks, for indicators such as spawning abundance or fishing harvest rate. For each CU, a higher and a lower benchmark are to be defined so as to delimit 'green', 'amber', and 'red' status zones. As numbers of spawning salmon decrease, a CU moves towards the lower status zones and the extent of management actions directed at conservation should increase. The status of a CU does not dictate that any specific action must be taken, but instead serves to guide management decisions in conjunction with other information on habitat, ecology and socioeconomic factors.

Over the past few years, significant headway has been made towards defining benchmarks for CUs in the Fraser River watersheds, however, there has been much less progress towards setting benchmarks for other areas of coastal British Columbia and the Yukon. It is in this context that the Pacific Salmon Foundation (PSF) commissioned the independent analysis presented here. This analysis provides a foundation towards developing abundance-based status benchmarks for CUs that spawn in the Skeena River basin, the second-largest watershed in BC and home to approximately 50 CUs of sockeye, Chinook, chum, coho, and pink salmon[3]. The main objectives of this analysis are:

- derive and explore some possible options for status benchmarks,
- conduct a preliminary independent assessment of the status of Skeena CUs, and
- make available a foundation of computer code for performing stock-recruitment analyses that can be expanded and updated in the future.

While this analysis presents benchmark options, it does not determine which benchmarks should be used for assessing Skeena CUs as that is the responsibility of DFO in consultation with First Nations and other affected parties.

DFO has recommended that Wild Salmon Policy status assessments adopt an approach that combines several different classes of status indicators, including current abundance of spawners, time trends in abundance, geographic distribution of spawners, and fishery harvest levels relative to a CU's productivity. The scope of the analysis presented here is limited to examining benchmark options related to current abundance and harvest levels. The approach used is based on CU-specific 'stock-recruitment models', which describe the relationship between the number of spawning salmon in a parental generation (the 'stock' or 'escapement') and the expected numbers of offspring produced and available for harvest or spawning (the 'recruitment'). By fitting a stock-recruit model to actual data from a CU, one can estimate the average recruitment that is expected from a given number of spawners. The model can be used to estimate a variety

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[1] Executive Summary by the Pacific Salmon Foundation
[2] Canada's Policy for the Conservation of Wild Pacific Salmon can be accessed at: http://www.pac.dfo-mpo.gc.ca/fm-gp/species-especes/salmon-saumon/wsp-pss/docs/wsp-pss-eng.pdf
[3] Conservation Units for Steelhead trout have been developed but were not included in this assessment.

of values that are commonly used as status benchmarks, such as the escapement and harvest rates that are expected to maximize long term fishing yield ('Smsy' and 'Uopt', respectively), and the escapement level that will allow a CU to return to Smsy within one generation in the absence of fishing ('Sgen1').

As a lower benchmark option, this analysis determined Sgen1 for each CU, following recommendations used for Fraser sockeye. A second lower benchmark option, 10% of the virgin stock size ('0.1*So'), is presented as a more intuitive and computationally simpler alternative. Setting reference points as a fraction of the virgin stock size is a common practice in many fisheries throughout the world, and 0.1*So corresponds to the level at which fisheries managed by the US Pacific Fisheries Management Council are closed. For the upper benchmark, Smsy was determined for each CU. Since escapements beyond Smsy may produce additional ecosystem benefits, 'Smax' (the escapement that produces the maximum recruitment) is also presented. As a benchmark for harvest level, Uopt is presented for each CU, as well as 'Umax' which is the harvest rate that exceeds the productivity of the stock and would eventually lead to extirpation.

The current abundance status of each CU was determined by comparing its average escapement for 2006-2010 (the last five years of available estimates) to the Smsy and Sgen1 benchmarks. The current harvest rate status was computed by comparing fishing levels over this period to the Uopt benchmark.

Uncertainty and Bias

There are four major sources of uncertainty and potential bias that affect the evaluation of benchmarks and status. The relative size of these biases will vary between species and CUs depending in part on the amount and quality of data available for the stock-recruit analysis. However, the actual extent of bias is unknown. Each of the four biases is discussed in more detail below.

It is important to be aware of uncertainty and possible bias when considering the results of this analysis, as they can have important consequences for management. This includes the possibility of overestimating productivity and Uopt, setting lower abundance benchmarks too low, and evaluating harvest rate and abundance status as being better than they actually are. If the benchmarks presented here were to be applied without considering this uncertainty, then future policies and management strategies could result in reduced conservation performance and loss of long term fishery yields.

Bias in Estimated Recruitments from Run Reconstructions

The numbers of recruits used for this analysis were determined using annual estimates of the number of salmon caught from each CU. For sockeye, these harvests are estimated by a model that uses information about when the salmon from each CU are thought to be migrating through areas where fisheries are occurring (i.e., a 'run-reconstruction model'). Relatively minor changes to run-timing for sockeye can lead to significant differences in the estimated harvest and, ultimately, the estimated number of recruits. If harvest from a CU has been overestimated, then this would in turn lead to inflated estimates of recruitment and productivity. This type of a bias could lead to the incorrect conclusion that a CU is not overharvested when it really is. All of the available information on sockeye run-timing by CU, harvest timing in all marine and freshwater fisheries has been taken into account so the harvest rates estimated for each Skeena sockeye CU are as accurate as possible. For Chinook and coho, harvest rates in fisheries are estimated directly based on coded-wire tag data for a few tagged stocks ('indicator stocks' assumed to represent other CUs of the same species). The assumption that one tagged stock can be representative of several others is an additional source of uncertainty and possible bias.

Bias Due to Lack of Year-Specific Age-at-Return Data

For most salmon species, fish vary in age-at-maturity, the age at which they mature and return to their natal streams. Salmon returning within a particular year will be from different years of spawning (i.e., brood years), with the exception of pink salmon that have a fixed age-at-maturity of two-years. In order to perform a stock-recruit analysis, the recruits returning in a given calendar year must be apportioned by age so that the correct number of progeny is attributed to the number of parental spawners in a brood year. This is necessary to arrive at the total number of recruits produced by each parental cohort, information which is the foundation of a stock-recruit analysis. However, the proportion of ages among recruits can vary substantially from year-to-year, and it is rare that this information is available for every year. Therefore, stock-recruit analyses frequently uses an average age composition calculated from available data for a CU, and apply this average to all years in order to apportion annual recruitment among the various parental cohorts.

However, the practise of using a single average age composition produces biases in the recruitment reconstruction. Specifically, these biases are expected to lead to productivity estimates that are inflated, Uopt harvest rate is then too large, and Sgen1 would be set too low. These biases would lead to management advice that would lead to overharvest and reduced future production. In the Skeena, this bias potentially affects all CUs except for pink salmon (which all return to spawn at the same age), the Babine system sockeye CUs (for which annual age data are available for every year), and possibly the Kalum-late Chinook CU (for which annual age data is available for returns from 1988 onwards). Age composition-related bias is a potential issue for all other CUs examined in this report. Unfortunately, wide variation in the extent of age-related bias among populations (e.g., Babine vs. Nass, six Columbia Chinook stocks vs. Babine) does not allow one to compute a reliable correction factor.

Measurement Error and Time Series Bias

Measurement error bias leads to overestimation of both stock productivity and the magnitude of density dependence. Like age composition effects, this bias will result in overestimation of the harvest rate benchmark and underestimation of the lower abundance benchmark. The size of the bias will increase with the extent of error in escapement measurements, when the time series is short, and when there is limited contrast in the range of escapements over time. Time series bias will likely result in a slight overestimation of the harvest rate benchmark and potentially larger underestimation of the lower abundance benchmark and other abundance-based benchmarks. The magnitude of measurement error and time series biases in the Skeena-based stock-recruitment estimates is uncertain, however, there are many characteristics of the data which suggest these biases could be quite large.

Bias Due to Unrepresentative Data (Changing Productivity)

Use of the benchmarks developed here for future management assumes that the historical data used to estimate the benchmarks is representative of future conditions. This would not be true if the productivity of a CU is changing over time. This analysis found statistical evidence of declining productivity in the last decade for a few CUs, including important ones such as the Babine sockeye wild runs. The fundamental question is whether such conditions are permanent or temporary. While it is possible that CUs which show recent declines in productivity will continue to show this pattern over the next few years, a longer view of the same data may reveal multiple cycles of decline and recovery.

Results

Several possible abundance and harvest rate benchmark options have been calculated for 34 of the 53 salmon CUs identified for the Skeena watershed. These benchmark values can be found within the main report and accompanying tables. However, for 19 CUs (mainly sockeye), there was insufficient data available to determine benchmarks. In addition, the analysis presents the results of a preliminary status assessment that compares current (2006-2010) escapement and harvest rates to a subset of these benchmarks (Sgen1, Smsy, and Uopt). For many of the 34 CUs where benchmarks have been calculated, the stock-recruit data is poor, and the benchmarks and status assessments presented here are uncertain and potentially biased. The results described here should, therefore, be interpreted with caution until additional studies can be undertaken to verify these results.

Sockeye

Five CUs were assessed as being most likely in the red abundance status zone (i.e., below the Sgen1 benchmark, meaning that it would take more than a generation without fishing for these CUs to return to Smsy levels: Babine late-timing wild (≈ Nilkitkwa CU), Bear CU, Gitanyow (=Kitwancool) CU, Morice CU, and Swan CU. Four CUs are most likely in the amber status zone: Babine early- and mid-timing wild (≈ Babine CU and ≈ Tahlo/Morrison CU, respectively), Lakelse CU, and Motase CU. Seven CUs were most likely in the green status zone (meaning that these CUs are likely at or above levels that would be expected to produce the maximum long term yield): Alastair CU, Azuklotz CU, Damshilgwit CU, Kitsumkalum CU, McDonell CU, Stephens CU, and the Babine enhanced stock. The remaining 12 lake-type and two river-type sockeye CUs could not be assessed due to insufficient data.

Based on recent (2006-2010) harvest rates, the Damshilgwit and perhaps the Babine mid- and late-timed wild CUs are likely being harvested at levels above Uopt. Prior to 1997, three CUs (Bear, Morice, and Babine late-timing wild) appear to have been harvested at rates above Uopt. The average 2006-2010 harvest rate across assessed CUs was 28%, considerably less than the average Uopt (50%). There is very wide variation in productivity among CUs, indicating wide variation in Uopt.

The estimated Uopt for the enhanced Babine stock was 64% compared to 45-47% for the three wild Babine system CUs. Bias for these estimates should be relatively low owing to the long time series, accurate escapement estimates, and use of year-specific age composition data for the recruitment reconstruction. Historical trends (1960-2010) in harvest rates indicate that wild CUs have been overharvested as the Babine aggregate was fished at rates close to Uopt for the enhanced component. Recent (2006-2010) harvest rates are lower than the long-term average (1960-2010) and closer to rates that are appropriate for the wild Babine CUs. However, the three wild CUs show signs of reduced productivity in recent years, which would imply that the Uopt benchmark calculated in this report may be too high.

Chinook

Seven CUs were assessed as most likely being in the green abundance status zone: Ecstall, Kalum-early, Kalum-late, Lower Skeena, Middle Skeena Large Lakes, Middle Skeena Mainstem Tributaries, and Upper Bulkley. An additional four CUs could not be assessed due to insufficient data. In this analysis there was no evidence that any of the seven assessed CUs have been harvested above Uopt. Less productive CUs (Upper Bulkley and Kalum-early) are currently harvested at very low rates (4%). More productive stocks have Uopt ranging from ~60-75% and in recent years have been harvested at approximately 40%.

Coho

The Lower Skeena CU was assessed as most likely being in the amber abundance status zone, while the Middle Skeena and Upper Skeena CUs are most likely in the green zone. The Skeena Estuary CU could not be assessed due to a lack of data. Up to the mid-1990's, all CUs were likely harvested at or above Uopt (53-72%), but recent rates are lower (34% for 2006-2010). Middle Skeena and Upper Skeena CUs have shown positive trends in escapement since harvest rates have been reduced, but the Lower Skeena CU has not recovered, possibly due to declining productivity.

Chum

The Skeena Estuary and Lower Skeena CUs were assessed as most likely being in the red abundance status zone, while the Middle Skeena CU is most likely in the amber zone. Prior to the mid-1990's all CUs were likely harvested at or slightly above Uopt (30-44%), but recent rates have averaged 14%, near or below Uopt. Productivity for the Skeena Estuary and Lower Skeena CUs has apparently declined over time, which may be the reason that these CUs have not recovered despite reductions in harvest. It should be noted that escapement estimates for chum are of low reliability given the poor survey coverage in recent years.

Pink

The Middle-Upper Skeena Even-Years CU was assessed as most likely being in the red abundance status zone. The Nass-Skeena Estuary Even-Years CU is most likely in the amber zone. The three odd-years CUs are likely in the green zone (Nass-Skeena Estuary, Lower Skeena, and Middle-Upper Skeena). Historically, pink salmon CUs were harvested at or slightly above Uopt (42-57%), but recent rates are almost half of this value. This analysis found no evidence of reduced productivity over the last decade.

Conclusion and Future Work

Additional exploration of sources of uncertainty and bias in the benchmarks and status assessments is recommended. As discussed above, biases common to stock-recruit models can potentially lead to overestimating productivity and appropriate harvest rates, and setting the lower abundance benchmark too low. This can result in overharvest, reduced conservation performance, and reduced long term harvest yields. Several of these biases are expected to be larger when data quality and quantity is poor, which is the case for many of the CUs in the Skeena Watershed.

Results from management strategy evaluations can provide considerable guidance on the utility of the various benchmarks computed from this analysis. Management strategy evaluations use simulations to test the expected effectiveness of alternative management approaches for meeting management objectives (such as protecting weak stocks and providing fishing opportunities) under a range of uncertainties. A logical next step in implementing the Wild Salmon Policy in the Skeena is to use the estimated stock-recruitment parameters and benchmarks developed here in a management strategy evaluation to provide an explicit and rational way of setting harvest rates which address a set of agreed management objectives. However, these evaluations are also dependent on the accuracy of the parameters estimated, which further argues for a more quantitative assessment program to validate parameter values estimated for key CUs.

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Glossary of Terms

Bayesian refers to methods in probability and statistics based on degree-of-belief interpretation of probability. In traditional (i.e., frequentist) statistics, a hypothesis can only be true or false and the probability of being incorrect about the true/false designation is computed. Bayesian statistics has the advantage of assigning a 0-1 probability for the hypothesis directly. In stock-recruit analysis, Bayesian statistics allows the computation of probabilities for a wide-range of stock-recruit curves and associated benchmarks for any data set.

Benchmarks are reference points against which the attributes of a stock, such as its spawning abundance or fishing mortality rate, can be measured in order to determine its status. Canada's Wild Salmon Policy requires that the biological status of each Conservation Unit (CU) be assessed relative to higher and lower benchmarks, which will be defined to delimit green, amber, and red status zones. As spawner abundance decreases, a CU moves towards the lower status zone and the extent of management intervention for conservation purposes should increase.

Brood Year is the year that a group or cohort of animals was born in. For example, sockeye salmon that are 4 years old returning in 2010 were from the 2006 brood year.

Carrying Capacity is the maximum population size that can be sustained indefinitely in the absence of harvest. Carrying capacity is sometimes associated with a specific environment but can also be considered over the life of a species (integrates all life stages) as it is in this text.

Exploitation Rate (ER) is the proportion of a population removed by harvest (fishing).

Hierarchical Bayesian Models (HBMs) are a class of Bayesian models well suited to the analysis of data collected at different levels of aggregation. For example, in stock-recruit analysis, we may have data from individual conservation units, but may be most interested in the variation in a parameter (e.g., stock productivity) or derived parameters (e.g., optimal exploitation rate) across units. Standard techniques either assume that the data from each unit are completely independent, or aggregate the data and estimate only one parameter for all units. Hierarchical models provide an efficient way of partially pooling the information from different units without assuming they all have the same parameter estimates.

Maximum Sustainable Yield, or MSY is the largest yield (catch) that can be taken from a stock over an infinite period (i.e., long-term average or expected value). The stock size that produces MSY is referred to as S_{MSY}.

Overfishing occurs when fishing mortality has reached a level where the stock can no longer produce enough juveniles to replace itself. As a result, the abundance of the population will decline but will not necessarily be extirpated. Overfishing has been defined as any exploitation rate (U) that is greater than the rate which maximizes yield ($U > U_{msy}$, note U_{opt} is equivalent to U_{msy}). Negative effects of overharvest on future recruitments increase with the extent to which U is greater than U_{msy}.

Photosynthetic Rate is the rate at which sugars are produced in plants and algae during photosynthesis. For algal production, it is often expressed in units of mg carbon fixed per unit area (e.g. m^2) per unit time (e.g. hr). It this assessment, the photosynthetic rate in lakes has been related to the production of fish within the lake to derive an estimate of the spawning stock size that maximizes recruitment.

Recruitment is the process where juvenile organisms survive and are added to a population of interest. In salmon management, recruitment usually refers to the pre-fishery abundance of adults. Thus recruitment is calculated based on the sum of all catches, estimates of pre-spawn mortality and post-release mortality (if fish are captured and then released), and the escapement.

Sgen1 is the escapement that is sufficient for the population to recover to Smsy (the escapement that maximizes yield) in one generation.

Stock Productivity is the maximum ratio of recruits produced per spawner, and therefore the maximum growth rate for the population. This rate occurs near the origin of the stock-recruit curve where there are no density-dependent effects on mortality. Graphically, stock productivity is the slope of the stock-recruitment curve at the origin. The exploitation rate that maximizes yield is determined solely by stock productivity.

Stock-Recruitment Models are relationships that predict the expected number of individuals in one generation (the recruitment) as a function of the number of reproducing individuals in the previous generation (the stock). There are a variety of model forms, with the Ricker and Beverton-Holt models being some of the most common.

1.0 Introduction

Canada's Policy for Conservation of Wild Pacific Salmon requires that the biological status of each Conservation Unit (CU) is assessed. For each CU, higher and lower benchmarks will be defined that will delimit green, amber, and red status zones (Fig. 1, FOC, 2005). As spawner abundance decreases, a CU moves towards the lower status zone and the extent of management intervention for conservation purposes should increase. The lower benchmark between amber and red zones will be established at a level of abundance high enough to ensure there is a substantial buffer between it and any level of abundance that could lead to a CU being considered at risk of extirpation. The higher benchmark between green and amber zones may be based on the abundance that provides the maximum sustainable yield, although higher values can also be considered if they provide ecosystem benefits.

The majority of metrics that can be used as benchmarks can be derived from CU-specific stock-recruit relationships (Fig. 1). These relationships describe how the total production for a generation (recruitment) varies with the abundance of the parental generation (e.g. the number of spawning salmon). Across years, we would expect considerable variation in the production (recruitment) from the same spawning stock due to environmental variation. By fitting a single relationship to data from a CU, the relationship represents the average recruitment that can be expected for a given escapement.

The intent of this report is to describe the results of a stock-recruit analysis of Pacific salmon data from the Skeena Watershed as a necessary step in the development of benchmarks for status evaluations. This work is an independent analysis commissioned by the Pacific Salmon Foundation. The benchmarks and status assessments presented in this report may change due to inputs from stakeholders and future changes to the data that are the foundation of the analysis.

2.0 Methods

2.1 Modelling

The following form of the Ricker model was used to predict recruitment as a function of escapement,

$$1)\quad R_{i,t} = S_{i,t}\, e^{\alpha_i - \beta_i S_{i,t} + \omega_{i,t}}$$

where, *i* and *t* denote indices for CU and brood year, respectively, R is recruitment, S is the escapement, α is the log of the initial slope of the stock-recruitment curve (recruitment in the absence of density effects, often termed stock productivity which we abbreviate as Prod in this analysis), β is the rate at which recruitment declines with increasing escapement (often called the density-dependent term), and ω is a randomly distributed error term with mean 0 and standard deviation σ_i (Fig. 1). Under this form of the Ricker relationship, $1/\beta$ is the spawning size which maximizes recruitment (i.e., Smax) and α/β is the carrying capacity or expected long-term equilibrium abundance.

Two methods were used to estimate stock-recruitment relationships from the available data. First, the Ricker relationship was re-arranged to predict recruits-per-spawner (R/S) and log-transformed so that linear regression could be used to estimate the parameters,

$$2)\quad \log\left(\frac{R_i}{S_i}\right) = \alpha_i - \beta_i S_i + \omega$$

where, *t* has been omitted here and from subsequent equations for notational simplicity. We term such estimates independent linear-regression based values, since they were generated by linear regression and are independently estimated for each CU. That is, the parameter estimates for each CU have no influence on the parameter estimates for other CUs.

A hierarchical Bayesian model (HBM) was the second method used to estimate stock-recruit parameters. Under this method, equation 2) is used to estimate CU-specific parameters, but the estimation further assumes that α_i estimates for each CU are exchangeable and come from a common log-normal distribution (termed a hyper-distribution). That is,

$$3)\quad \alpha_i \sim \ln(\mu_\alpha, \sigma_\alpha)$$

where, ~ln denotes that α_i is a stochastic variable drawn from a lognormal distribution with mean μ_α and standard deviation σ_α. The parameters of this distribution (μ_α, σ_α), termed hyper-parameters, are estimated along with the CU-specific values. CUs with limited stock-recruit data, or where there is considerable uncertainty in α_i estimates due to the pattern of stock-recruit data (e.g., limited variation in escapement values, few stock-recruitment data points), will contribute less information to the hyper-distribution for α compared to those CUs where α is better defined. The hyper-distribution also affects the CU-specific estimates of α. CUs where α is poorly defined will be 'shrunken' towards the mean of the hyper-distribution to a greater extent than those where α is better defined. The HBM includes the use of uninformative prior distributions for the hyper parameters of α (hyper-priors) and σ_i, and informative priors for CU-specific estimates of β_i based on lake rearing capacity estimates for sockeye salmon. Informative priors for CU-specific estimates of β_i based on measures of habitat capacity for other species (e.g. stream rearing area or spawning ground capacity) can be included in the analysis if that information is available in the future. Priors for β_i were assumed to be lognormal, with the mean determined by the photosynthetic-based estimate of Smax for lake sockeye salmon (PR), and a coefficient of variation (CV) set to a moderately informative value (CV=0.3) for all sockeye CUs except for the four Babine system CUs where CV was instead set to a minimally informative value (CV=1). The CV value for sockeye Smax prior should reflect all aspects of the uncertainty associated with deriving the estimate including variation in photosynthetic rates within- and –among years, and the uncertainty in biostandard values used to convert peak smolt production estimates to required spawners. However, as there was insufficient information to estimate the uncertainty in these elements, we selected a value that reflected a moderate amount of uncertainty. For other species, we assumed that the mean of the prior for Smax was equivalent to the average escapement, and used highly uninformative (CV=10) or minimally informative distributions (CV=1). Our use of the average escapement for a prior on Smax follows Walters et al. (2008). Minimally informative priors were needed for occasional cases where there was insufficient information to estimate the magnitude of the density dependent term. A total of

11,000 MCMC iterations were run to estimate the posterior distribution of parameter estimates for each CU. The final posterior distributions were based on 2,500 samples that were obtained after discarding the first 1,000 simulations and retaining every 4th value. The model was programmed in WinBUGS and called from the R2WinBUGS R library interface.

There are three advantages of the HBM compared to the linear regression method. First, the HBM incorporates prior information on carrying capacity (e.g., via PR-based Smax estimates for lake-rearing sockeye salmon). In most stock-recruit data sets, estimates of α and β are confounded. That is, the data can be almost equally well-described by a productive population (large α) with strong density dependence (large β) or vice versa. This leads to considerable uncertainty in derived parameters used as benchmarks, like the escapement or ER that produces MSY. By including additional information in the stock-recruit estimation via priors on β_i, this uncertainty can be reduced. The second advantage of the HBM is improved estimation of the hyper-distribution of the log of stock productivity (α). One could estimate the parameters of this distribution based on independent estimates of α_i (generated by the independent linear regression method), however that distribution would be 'contaminated' by poorly defined estimates for some CUs. The HBM properly weighs the contribution of each CU to the hyper-distribution based on the amount of information in each α_i estimate. Finally, the HBM has the advantage of providing more reliable estimates of α_i for CUs where this parameter is poorly defined (e.g., has few data points) because the hyper-distribution acts as a prior for the CU-specific estimates.

A variety of benchmarks can be determined from the stock-recruitment parameter estimates for each CU generated from the HBM (Fig. 1). Following recommendations used for Fraser sockeye (Grant et al. 2010), Sgen1, the escapement that allows the stock to recover to the escapement that maximizes yield in one generation, was used for the lower benchmark. Estimates of Sgen1 depend on both the estimated productivity and carrying capacity from the stock-recruit analysis. Sgen1 values were computed by nonlinear estimation using the 'L-BFGS-B' algorithm from the 'optim' nonlinear estimation library within R. We used 10% of the unfished equilibrium escapement ('0.1*So' = $0.1\alpha/\beta$) as a more intuitive and computationally simpler alternative for the lower benchmark. Setting reference points as a fraction of the virgin stock size (i.e. the unfished equilibrium escapement) is a common practice in many fisheries throughout the world. We used the 10% level because this is the percentage of virgin biomass where fisheries managed by the US Pacific Fisheries Management Council are closed at (Hilborn 2002). The upper abundance-based benchmark was computed as the escapement that maximizes yield (Smsy) which was calculated using the approximation $\alpha/\beta(0.5\text{-}0.07\alpha)$ (Hilborn and Walters 1992). Escapements beyond Smsy may produce additional ecosystem benefits. To account for this, we used Smax ($1/\beta$) as an alternative for the upper benchmark. We computed the ER that would maximize yield for each CU for which stock-recruit data are available, calculated as $0.5\alpha–0.07\alpha^2$ (Uopt). We also computed the ER that exceeds the productivity (e^{α}) of the stock, and would therefore eventually lead to extirpation, calculated as $1 - e^{\alpha}$ (Umax). Stock status was determined by comparing the average escapement from 2006-2010 (last five years of available estimates) with Sgen1 and Smsy, and exploitation status was computed by comparing the average ER over this period with Uopt.

2.2 Data

The stock-recruit data we used was based on available escapement and recruitment estimates from 1954-2008 brood years prepared by LGL (English et al. 2012, English 2013) working in consultation with S. Cox-Rogers and D. Peacock (DFO). CU names and delineations were provided by B. Holtby (DFO) and represent a provisional update to those identified by Holtby & Ciruna (2007). CU names and delineations match those used in English 2013 (see English et al. 2012, English 2013 and Appendix 1 for more details). Recruitment associated with each brood year escapement was determined based on estimates of total ER by return year and the age composition of returning fish. Due to missing escapement data in some years, recruitment for some brood years (especially latter ones) was incomplete. Only brood years where 95% or more of the age composition was included in the recruitment estimate was used in this analysis. Only CUs with three or more stock-recruitment pairs were included in the analysis.

Sockeye

Originally, 28 CUs were identified for lake-reared sockeye salmon in the Skeena Watershed but not all these CUs have stock-recruit data (Table SX.1, Appendix 1). We were able to include 17 CUs in our stock-recruit analysis (Table SX.1). Based on discussions with DFO and stakeholders, we analyzed the Babine system CUs as a single enhanced- (Pinkut +Fulton) plus three wild- (early-, middle-, and late-timed) run components. The three wild-run components correspond approximately to the 'Babine' CU (early run; includes Onerka Lake), 'Tahlo/Morrison' CU (middle run) and 'Nilkitkwa' CU (late run) (see Appendix 1). Recruitment for each of these four Babine system CUs was computed by expanding estimated escapements by CU-specific ERs based on differences in run-timing for the four Babine groups included in the run reconstruction analyses (Alexander et al. 2013; English et al. 2013). Escapement estimates for each of the Babine system CUs were derived from Babine fence counts, spawning ground estimates and run-timing for each of the Babine system CUs. Our enhanced Babine CU time series excludes surplus escapement from the spawning stock size used in the stock-recruit analysis because these fish are not permitted to enter the spawning channels and thus they are not part of the spawning population for the enhanced Babine CU. These surplus returns are part of the total return of enhanced Babine CU so are included in the recruitment values. All sockeye recruitment reconstructions were based on across-year average age composition data with the exception of the four Babine CUs where year-specific data were available for the Babine aggregate. Recruitment reconstruction for CUs without any age composition data are based on ageing data for neighbouring CUs thought to have similar age composition (English et al. 2012, English 2013). Recruitment reconstructions include harvests within the Skeena River (English et al. 2013).

Data on photosynthetic rate (PR) and other information (predators, smolt size) was used as auxiliary information in the stock-recruit analysis for all CUs except the four Babine system CUs. Babine Lake is the only Skeena sockeye rearing lake with multiple CUs. Smax estimates based on Babine Lake rearing capacity for juvenile sockeye would need to be divided into four separate components, one for each CU, to be included in the stock-recruit analysis. Since we lacked information on how to divide the capacity of Babine Lake, we set the CV value for the Smax prior to a minimally informative value (CV=1) for the four Babine sockeye CUs, to eliminate any effects of the prior on estimated stock recruit parameters and resulting benchmarks. For all other CUs, estimates for the mean of the prior on Smax (the escapement that maximizes recruitment) were determined by estimating the maximum number of smolts that each lake could produce based on the photosynthetic rate (PR) model (Shortreed et al. 1999). These estimates were then converted to an escapement required to produce them based on biostandard values. Estimates of Smax were provided to the authors by S. Cox-Rogers (DFO) in 2011 (updated from Cox-Rogers et al. 2010). The reliability of the Smax estimates based on photosynthetic rate and other characteristics of the lake will depend on quality of the information available for each lake. However, there was insufficient data to estimate this uncertainty. We used a CV of 0.3 for the Smax prior for all CUs except for the four Babine system CUs. Estimates of Smax from the PR model are shown in Table SX.1.

Chinook

There is a relatively consistent number of stock-recruitment pairs (18-25) across the seven Chinook CUs in the Skeena with the exception of Ecstall which has only six pairs (Table CN.1). All of these CUs (with the exception of Ecstall) have information on age-at-return, but in most cases not enough to allow age-at-return to vary across years. Therefore, we generally used the average age-at-return across years in the recruitment reconstruction, as done for other species. There was enough age composition data for returns in 1989 and later (except for 1996) to use these annual values in the computation of recruitment for the Kalum-late CU. We did not attempt to use an informative prior on the escapement needed to maximize recruitment based on habitat capacity because these estimates are not available for Skeena Chinook CUs (Parken et al. 2006). Following Walters et al. (2008) approach for the Skeena Independent Science Review Panel (ISRP) analysis, we used the historic mean escapement as the mean for the prior on Smax. However, we used a highly uninformative prior (CV=10) for five of the seven CUs. A minimally informative prior (CV=1) was needed to achieve convergence for the Ecstall and Kalum-late CUs.

Coho

Two of three coho CUs in the Skeena have 53 stock-recruitment pairs over the 1954-2008 period, and the third CU has 14 pairs (Table CO.1). As for other species, average age composition across years was used for the recruitment reconstruction. The average escapement was used as a prior on the escapement that maximizes recruitment (Smax) because Smax estimates based on habitat capacity have not been computed for Skeena coho CUs. An uninformative prior (CV=10) was used for the Smax prior for lower Skeena CU, but minimally informative priors (CV=1) were needed to achieve convergence for middle and upper Skeena CUs.

Chum

The three chum CUs in the Skeena have 17-45 stock-recruitment pairs over the 1954-2008 period (Table CM.1). We used the average age composition across years for the chum recruitment reconstruction, as done for other species. The average escapement was used as a prior on the escapement that maximizes recruitment (Smax) because Smax estimates based on habitat capacity have not been computed for Skeena chum CUs. An uninformative prior (CV=10) was used for the Smax prior for lower Skeena CU, and minimally informative priors (CV=1) were needed to achieve convergence for the Skeena estuary and middle Skeena CUs.

Pink

There are five pink CUs in the Skeena watershed (two even-year CUs and three odd-year CUs) with 27-28 stock-recruitment pairs (Table PK.1). The recruitment reconstruction assumed all fish return at age 2. The average escapement was used as a prior on the escapement that maximizes recruitment (Smax). A minimally informative prior (CV=1) was needed to achieve convergence for all CUs. Note that the HBM jointly estimated CU-specific stock-recruitment parameters using data from both even- and odd-year CUs in the same analysis. However, as shown below, because of the limited number of CUs, there was no distinguishable effect of the HBM assumption that α estimates are exchangeable among CUs. As a result, stock-recruit estimates from the HBM were virtually identical to those from independent estimation using linear regression. Thus, combing odd- and even-year CUs in the same HBM analysis is inconsequential.

3.0 Results

3.1 Sockeye

Stock-recruit plots for Skeena lake sockeye CUs show typical 'shotgun' patterns in the data (Fig. SX.1). Given this pattern, it is not surprising that there was large uncertainty in the shape of the stock-recruit curves , even when they were estimated from the HBM which included prior knowledge about Smax and exchangeability in α_i estimates (note wide credible intervals in Fig. SX.1). Stock-recruit curves based on independent and linear estimation (gray lines) were similar to those estimated from the hierarchical Bayesian model (HBM) for most CUs because the stock-recruit based-estimates of Smax were consistent with estimates from the PR model (e.g. Azuklotz, Kitsumkalum). However, the PR-based estimates of Smax were much greater for other CUs (e.g. Morice, Bear), which led to lower estimates of productivity from the HBM relative to estimates from the linear independent model.

Estimates of α_i and β_i were partially confounded, which is not surprising given the limited information about productivity and density dependence in the stock-recruit data (Fig. SX.2). Use of informative priors for β_i reduced the extent of the correlation between parameters (results not shown for brevity). The posterior distributions of β_i were generally very close to the prior distributions (Fig. SX.3), either because the prior means and stock-recruit based estimates were consistent, or because there was limited information in the data about β_i estimates. We examined the temporal trend in residuals from the stock-recruitment curves to evaluate whether there was evidence for temporal changes in productivity (Fig. SX.4). Eleven of 17 CUs showed a negative trend in residuals through time indicating that productivity has declined, however a significant negative slope was only found for the three wild-run Babine system CUs. Statistical evidence for temporal changes in productivity was therefore quite limited, however the sample size for many of the CUs was low and the extent of variation in residuals was often very high, so statistical power to detect such trends was poor (see Big River Analytics 2013 for an alternative analysis of temporal changes in the productivity of Skeena CUs).

Stock productivity (e^{α}, the initial slope of the stock-recruit curve) is a key management parameter as it determines the ER that maximizes yield. There was considerable uncertainty in α_i

estimates from the HBM for many CUs (e.g. Johnston, Kitwancool), though some were well defined (e.g., Alastair, Fig. SX.5). Most independent estimates of α_i were shrunk towards the mean of the hyper-distribution, and the extent of shrinkage was quite large for many CUs where information to estimate stock-recruit parameters was limited (e.g., Kitwancool). This shrinkage is not surprising considering the uncertainty in α_i estimates. The hyper-distribution of α from the HBM and a lognormal distribution fit to independent estimates was similar, although the latter had a slightly lower mean and showed less variation among CUs (solid and dashed lines in Fig. SX.5). Thus, the effect of the hierarchical α-exchangeability assumption appears to be quite modest. Based on random draws from hyper-parameters, 95% of α estimates for lake-reared sockeye within the Skeena watershed were between 0.40 and 3.2 with a median of 1.2 (Fig. SX.6, top). Optimal ERs translated from random draws of α produced a distribution with a median of 0.48 and a 95% credible interval of 0.19-0.86 (Fig. SX.6, bottom). The wide range in optimal rates reflects the considerable variation in productivity among CUs estimated by the HBM.

Benchmarks for the 17 lake sockeye salmon CUs with stock-recruitment data are presented in Table SX.2. These estimates were determined based on posterior distributions of α_i and β_i and reflect the uncertainty in these estimates. Optimal ERs ranged from a low of 0.23 (Damshilgwit) to a high of 0.70 (Johnston, Stephens) with an average of 0.50. There was very large uncertainty in optimal ERs for most CUs due to uncertainty in α_i. We compared the results of computing benchmarks based on data from 1954-2008 brood years versus only using data from 1980-2008, as escapements and catch estimates after 1980 are likely more reliable than older estimates (English et al. 2013). In the vast majority of CUs, key benchmarks, such as the optimal ER and Sgen1, were very similar based on these two periods (Fig. SX.7). We considered recomputing benchmarks using the most recent data (1998-2008) as this period of record may be most representative of near future conditions. However, we could not conduct this analysis because of the very limited sample sizes which preclude reliable estimation of stock-recruit parameters from which benchmarks are based. The four Babine system CUs were the only ones with ten stock-recruit points over this short period, with the remaining CUs having sample sizes typically ranging from three to five points (Table SX.1).

Status for 16 of the lake-reared sockeye salmon CUs with stock-recruitment data was determined by comparing the average escapement and total ER between 2006 and 2010 with estimates of Sgen1 (lower), Smsy (upper), and Uopt benchmarks (Table SX.3). Probabilities of being in red (below Sgen1), amber (Sgen1-Smsy), and green (>=Smsy) status zones for each CU reflect the uncertainty in Sgen1 and Smsy values generated from the posterior distributions of α_i and β_i from the HBM. Similarly, the probability of over-fishing between 2006 and 2010 was computed by comparing the average ER over this period relative to the posterior distribution of Uopt values. Status for the Johnston CU could not be computed because escapement data and ER estimates for the 2006-2010 period were not available. Thus status could only be assessed for a little more than 50% (16) of the original 28 CUs.

Five of 16 CUs had a probability of 0.5 or higher of being in the "red" status zone (Babine Late-Wild, Bear, Kitwancool, Morice, Swan) with the remaining having highest probabilities in amber zone (Babine-early-wild, Babine-mid-wild, Lakelse, Motase, Swan) or green zone (Alastair, Azuklotz, Babine-enhanced, Babine-mid-wild, Damshilgwit, Kitsumkalum, McDonell, Stephens). Three of the CUs potentially in the red zone (Bear, Kitwancool and Swan), one in the amber zone (Motase) and one in the green zone (Damshilgwit) had either very few stock-recruitment points or few observations at high escapements (Fig. SX.1). Consequently, there was considerable uncertainty in the density dependent stock-recruitment parameter and, in most cases, the priors on Smax from the PR model had a strong influence on estimates for these CUs (Fig. SX.3). Based on other CUs with more information about Smax, the ratio of average historical escapement to the Smax estimate was 0.52, compared to 0.13 for the five CUs in the red zone. This suggests that the mean of the prior on Smax for red zone CUs may be overestimated. This could occur due to overestimation of smolt capacity of the lake (Rmax), or due to problems with the biostandard values that are used to convert Rmax to the required number of spawners. The biostandards are not specific to individual lakes in the Skeena, and therefore do not account for unique factors like limitations in spawning habitat in some systems. It is also possible that these CUs have been overfished for a long period which has driven down the escapement, but there is little support for this based on recent trends in the ERs (Fig. SX.8) and escapements (Fig. SX.10) relative to the estimated Uopt and Smsy values, respectively. However, it is possible that these stocks were overharvested and depleted prior to the start of the record used here (1960 for ERs and 1954 for escapements).

The probability that the 2006-2010 ERs exceed the rate that produces MSY was very low (<0.05) for 10 of 16 CUs, with high probabilities of over exploitation (>0.4) for Babine-Late-Wild and Damshilgwit (Table SX.3). Time trends in ERs relative to the benchmarks show that about eight of 16 CUs have been fished near the estimated optimal ERs and are currently fished at well below these values (Fig's SX.8 and SX.9). CUs such as Bear and Babine- Mid- and Late-Wild show that historical ERs have exceeded the estimated optimal ERs, indicating that these stocks were over exploited. Others, such as Stephens, Lakelse, and McDonell, have been fished well below estimated optimal rates. Comparison of time trends in escapement relative to abundance benchmarks indicate that most CUs have been above the Sgen1 lower benchmark (Fig. SX.10 and SX.11, and Table SX.3). Notable exceptions include Babine-Late-Wild, Bear, Kitwancool, Lakelse, Motase, Morice and Swan.

3.2 Chinook

Stock-recruit relationship for Chinook salmon CUs show less scatter compared to other species in the Skeena Watershed (Fig. CN.1). Due to limited sample size and few observations at low stock size, there is considerable uncertainty about the productivity of the Ecstall CU; thus, caution should be used when delineating benchmarks for this CU. However the confidence region is relatively narrow for other CUs. The patterns in the stock-recruit pairs for Ecstall and upper Bulkley required the use of minimally informative priors on Smax (CV=1 vs. 10 for other CUs) to avoid unrealistically large Smax estimates and unrealistic benchmarks that depend on the Smax estimate (0.1*So,Sgen1, and Smsy). The independent and HBM-based estimates of the expected stock-recruit curves were very similar, which is not surprising considering that the amount of information in the stock-recruitment data was similar for most CUs (Table CN.1). Distributions of β are shown in Figure CN.2 in comparison with the uninformative priors on β (converted from Smax). The slightly more informative priors for Ecstall and upper Bulkley are apparent, but do not appear to dominate the estimated posterior distributions. The CV=1 priors for these CUs reduced the prior probability of very low β values, which was sufficient to substantially lower the probability of obtaining very low β estimates in the posterior (equivalent to very high estimates of Smax).

Significant negative trends in stock-recruit residuals over time were observed for Middle Skeena Large Lakes and mainstem tributary CUs ($p<0.05$, Fig. CN.3), and the Upper Bulkley CU had a significant positive trend. A cyclic trend in residuals was apparent for all CUs except Ecstall, which is a data-poor CU. This pattern could be caused by using average- rather than year-specific age composition data to estimate brood year recruitment (see discussion, Zabel and Leven 2002). The Kalum-late CU stock-recruit dataset was based on annual age compositions after return year 1988 (except 1996), and still shows the same cyclic pattern seen in the Kalum-early CU. There was very limited shrinkage in the HBM-based estimates of α based on a comparison of independently-derived values for all CUs except Ecstall (Fig. CN.4). This is not a surprising result, as all CUs except Ecstall have relatively long and informative time series. The higher estimate of α for Ecstall is pulled down towards mean of the hyper-distribution, and the shrunken estimate has greater uncertainty than for other CUs where there is more information.

The hyper-distribution for α had large variance (Fig. CN.4) because the sample size to define the hyper-distribution (n=7 CUs) was low. As a result, the hyper-distribution had little effect on CU-specific estimates, which is why independent linear- and HBM-based values were the same. This same dynamic applies to all other species we analyzed (except sockeye) because they are also represented by few CUs.

Benchmarks and stock status are provided in Tables CN.2 and CN.3, respectively. Time-series trends in ER and abundance status are shown in Figures CN.5 and CN.6, respectively. Estimated optimal ERs ranged from a low of 0.56 (Kalum-early) to a high of 0.79 (Ecstall). Average 2006-2010 ERs (0.04-0.41) are well below these optimal values, so the current probability of over-exploitation was near zero (Table CN.3). The probability that the 2006-2010 average escapement was below the Sgen1 benchmarks was at or below 1% for all CUs except Ecstall (Table CN.3), where there were no recent escapement or ER estimates to evaluate status.

3.3 Coho

There was considerable scatter in the stock-recruitment plots for all coho CUs (Fig. CO.1); thus, considerable caution should be used when delineating benchmarks. The HBM-based stock-recruit curves were virtually identical to those based on linear regression-independent estimation. As for Chinook CUs, this occurred because the prior on Smax used in the HBM was highly uninformative (Fig. CO.2), and because there was minimal shrinkage in the productivity estimates owing to the limited number of CUs available for the analysis. There was a significant ($p<0.001$) negative trend in stock-recruitment residuals for the lower Skeena coho CU, and a significant ($p<0.05$) positive trend in residuals for the middle Skeena CU (Fig. CO.3). Lower and middle Skeena CUs were exploited above the mean estimate of the optimal ER (~0.5-0.6) until the mid-1990's, but ERs since then have been reduced and are well below the estimated optimal values (Fig. CO.4, Table CO.2). Escapement of lower Skeena CU has been near or at the lower benchmark (Sgen1) for the entire period of record (Fig. CO.5). This same pattern occurred for the middle Skeena CU up to the late-1990s. Middle and upper Skeena CUs have shown a recovery in escapement since then, with escapements well above the upper Smsy benchmark. The lower Skeena CU is likely in the amber abundance status category, while middle and upper Skeena CUs are most likely in the green status category (Table CO.3); but again, there is high uncertainty in the estimates. There was a 0% probability that these stocks are currently overexploited given average 2006-2010 ERs of 34% and estimated optimal ERs ranging from 53-72% (Table CO.3).

3.4 Chum

There was considerable scatter in the stock-recruitment plots for all chum CUs (Fig. CM.1), thus, considerable caution should be used when delineating benchmarks. The HBM-based stock-recruit curves were virtually identical to those based on linear regression-independent estimation. This occurred because the prior on Smax used in the HBM was highly uninformative (Table CM.1), and because there was minimal shrinkage in the productivity estimates owing to the limited number of CUs available for the analysis. There were near significant ($p<0.1$) and significant ($p<0.005$) negative trends in stock-recruitment residuals for Skeena estuary and lower Skeena chum CUs, respectively (Fig. CM.2). The relationship for the middle Skeena CU was not significant, but the last eight stock-recruit residuals (brood years >1990) are all negative, indicating reduced productivity since the early 1990s. All chum CUs were exploited at rates above (Skeena Estuary) or equal to estimated optimal ERs (~0.3-0.45, Table CM.2) until the mid-1990's (Fig. CM.3). Recent ERs have ranged from 11-14% and are well below estimated optimal rates. Escapement for most of the period of record has been at or below the lower benchmarks for Skeena estuary and lower Skeena CUs, and below lower and above upper benchmarks for the middle Skeena CU (Fig. CM.4). There is no evidence of rebuilding of any CUs in spite of reduced ERs, likely due to reduced productivity in the last decade (Fig. CM.2). All CUs are currently (2006-2010 average) harvested at rates well below estimated optimal values, and the most probable abundance status for the 2006-2010 period is red for the Skeena estuary and lower Skeena CUs and amber for the middle Skeena CU (Table CM.3).

Sgen1 estimates and abundance-based benchmark status delineations for all chum CUs are tenuous at best given the poor data quality. For example, run-reconstruction estimates are based, at times, on expansion factors as large as 157. Additionally, the largest known chum spawning area in the Skeena, the Ecstall River, has not been enumerated since 2002. These CUs have likely been depressed over the time-series used in this analysis (i.e., 1954-2010), and there is evidence to suggest that historical abundance was much higher (Peacock and Spilsted 2010; Price et al. 2013).

3.5 Pink

There was considerable scatter in the stock-recruitment plots for all pink CUs (Fig. PK.1). Some CUs (e.g. Nass-Skeena Estuary odd year) did not exhibit any evidence of reduced recruitment at higher densities. The HBM had difficulty converging to reasonable stock-recruit parameter estimates in this case because the density dependent term (β_i) approached zero. This problem was addressed by using a CV for the prior on Smax of 1 (relative to 10 for most other species except sockeye). There was little effect of this prior as seen by the similarity in the linear regression-independent estimates (gray lines in Fig. PK.1) compared to the HBM-based estimates. This prior also had little influence on the β_i estimates based on a comparison of posterior and prior distributions for this parameter (Fig. PK.2). No temporal trends in stock-recruitment residuals were evident (Fig. PK.3). None of the brood-year residual plots were significant ($p>0.05$) and the only CU which approached significance ($p=0.07$, Nass-Skeena

Estuary odd year) had a positive trend. All pink CUs were exploited at rates equal to or above estimated optimal ERs (0.42-0.57, Fig. PK.4, Table PK.2) until the late-1990's. Recent (2006-2010) ERs have averaged about 0.22 and are well below estimated optimal rates (Table PK.3). Escapement for most of the period of record (Fig. PK.5) has often been below the lower benchmark (Nass-Skeena Estuary odd year), between lower and upper benchmarks (Nass-Skeena estuary even year, lower Skeena odd year, middle and upper Skeena odd year), or above the upper benchmark (Nass-Skeena estuary even year). Based on recent escapements (2006-2010), one CU is most likely in the red (middle-upper Skeena even year) or amber zones (Nass-Skeena estuary even year), and three are most likely in the green zone (Table PK.3).

4.0 Summary

4.1 Lake Sockeye

1. Five of 16 CUs (31%) where status could be assessed based on recent average escapement (2006-2010) were most likely in the red status zone (below lower benchmark Sgen1);
2. Most lake-reared sockeye CUs have not been overfished as defined in this report. The average ER for 2006-2010 exceeded the estimated optimal rate for one of 16 CUs. The average of the most recent ERs (2006-2010) across CUs (0.28) was considerably less than the estimated average optimal rate across CUs (0.5). The Damshilgwit and perhaps the Babine late wild-run CUs are likely currently overexploited. Prior to 1997, three CUs (Bear, Morice and Babine late-wild) appear to have been overfished;
3. There is very wide variation in productivity among CUs, indicating wide variation in ERs that optimize yield. Reduced ERs for mixed-stock fisheries implemented to protect weaker sockeye stocks have resulted in smaller harvest shares for these fisheries and a larger portion of the total harvest taken in terminal fisheries where only the most productive stocks are harvested.
4. The estimated optimal ER for the enhanced Babine CU (Pinkut + Fulton) was 0.64 compared to 0.45-0.47 for the three wild Babine system CUs. Bias for these estimates should be relatively low owing to the long time series, accurate escapement estimates, and use of year-specific age composition data for the recruitment reconstruction. Historical trends (1960-2010) in ERs indicate that wild CUs have been overexploited as the Babine aggregate was fished at rates close to the estimated optimal for the enhanced component. Current (2006-2010) ERs are lower than the long-term average (1960-2010) and closer to rates that we estimate are optimal for the wild-run. However, the three Babine system wild CUs have significant negative trends in stock-recruitment residuals, indicating that the Uopt benchmark is likely too high for current productivities (see also Big River Analytics 2013). Thus, it is likely that -mid- and late-timed wild Babine CUs continue to be slightly overexploited.

4.2 Chinook

1. None of the seven Chinook CUs are likely in the red abundance status zone. All CUs are most likely in the green zone and recent escapements (2006-2010) are greater than the estimated requirement for MSY.

2. There was no evidence from our stock-recruit analysis that any Skeena Chinook CUs have been overfished. Less productive CUs that had lower estimated optimal ERs of about 51-56% (Upper Bulkley and Kalum-early, respectively) are currently exploited at very low rates (4%). More productive stocks have estimated optimal ERs ranging from ~60-75% and are exploited at approximately 40%.

4.3 Coho

1. It is likely that none of the three coho CUs are in the red abundance status zone. The lower Skeena CU has a probability of 0.25 of being in the red abundance status zone but is most probably in the amber zone. The remaining CUs (middle and upper Skeena) are most probably in the green zone; however, there is considerable uncertainty in benchmark estimates.
2. All CUs were likely harvested at or above estimated optimal ERs up to the mid 1990's, but current ERs (34%) are well below estimated optimal rates (53-72%). Middle and upper Skeena CUs have shown positive trajectories in escapement since ERs have been reduced, but the lower Skeena CU has not recovered.
3. The lower Skeena CU shows a significant negative trend over time in stock-recruitment residuals. This indicates the productivity of this CU has declined, which is the likely cause for the failure of the CU to recover after ERs were reduced in the mid 1990's.

4.4 Chum

1. Two (Skeena Estuary and lower Skeena) of three chum CUs are most likely in the red abundance zone (probability of 0.93), while the middle Skeena CU is most likely in the amber zone; however, these status delineations are tenuous at best given the poor data quality.
2. Prior to the mid 1990's, all CUs were fished at or slightly above estimated optimal ERs. Current ERs (2006-2010) have averaged about 14% which is near or well below estimated optimal values (0.30-0.44).
3. Productivity for Skeena estuary and lower Skeena CUs has declined through time, which may be the reason for continued depressed escapements in spite of substantive reductions in harvest.

4.5 Pink

1. One of the five pink CUs (middle-upper Skeena even year) is likely in the red abundance status zone. All other CUs are most likely in the amber (Nass-Skeena Estuary) and green abundance classes.
2. Historically, pink salmon CUs were fished at or slightly above the estimated optimal ERs (0.42-0.57). Recent ERs are almost half of the estimated optimal rates.
3. Based on the temporal trend in stock-recruitment residuals, there is no evidence of reduced productivity over the last decade.

4.6 General Conclusions

Status of the vast majority of the 35 CUs that we evaluated was good; however, there remains considerable uncertainty associated with stock-recruitment parameter estimates for most

Skeena CUs. There were nine CUs where the historical average ER exceeded the estimated values that maximized yield (Uopt) and two CUs where the 2006-2010 average ERs exceeded Uopt (Fig. S.1). However, due to the considerable uncertainty in Uopt values for many CUs, there were many more cases where there was a substantial probability that the historical average ER exceeded optimal values. Similarly, abundance status across CUs was generally good. There were three CUs of 35 that had an average escapement over the period of record that we examined less than the expected Sgen1 estimate and six CUs where the 2006-2010 average escapement was less than Sgen1 (Fig. S.2). Due to considerable uncertainty in some Sgen1 estimates, there were 11 CUs with a substantial probability that recent escapements were less than Sgen1.

There are four major sources of uncertainty in the estimated benchmarks that in turn affect our evaluation of CU status and have implications for future management. The first relates to potential bias in estimated recruitments associated with run reconstructions. The second is on potential biases in stock-recruitment parameters associated with error in recruitment estimates owing to the assumption that the age composition for each CU does not change across years. The third concern relates to the potential effects of time series and measurement error bias on stock-recruitment estimates. The fourth and perhaps greatest concern is whether stock-recruitment parameters estimated from historical data will be representative of future conditions. We discuss each of these issues below.

Bias in Estimated Recruitments

The annual recruitment values used in this analysis are based on sometimes uncertain estimates of ER (English et al. 2012, 2013). Uncertainty in ERs will add additional uncertainty to the stock-recruit analysis presented here. For example, previous analyses (Cox-Rogers, unpublished data) indicate that relatively minor changes to run-timing for sockeye can lead to significant differences in ERs and hence reconstructed recruitments. ERs for Chinook and coho are based on CWT return data for a few tagged stocks. Overestimation of the ER for a CU would lead to higher estimates of recruitment which in turn imply greater productivity. Such a bias would lead to overestimation of the ER that maximizes yield (Uopt) and potentially the wrong conclusion that a CU is not overexploited when it really is. To address this issue, alternate versions of the stock-recruitment dataset used here would need to be generated under different assumptions of run-timing for sockeye CUs or CU-specific ERs for Chinook and coho CUs to determine the extent to which this uncertainty could bias benchmarks and status assessments.

Bias Due to Lack of Year-Specific Age-at-Return Data

Estimating the number of recruits produced from a given brood year requires data on the age of return in both the catch and escapement. If the stocks within a CU return at multiple ages (say 50% age 4, 50% age 5), recruitment for a brood year is calculated by multiplying the total recruitment in each year by the proportion of fish of the appropriate age, and then summing such estimates (e.g. recruits for the 2000 brood = total recruitment in 2004 * proportion of age 4 fish in 2004 + total recruitment in 2005 * proportion of age 5 fish in 2005). This calculation requires a sufficient sample of age estimates in each return year. In the case of the Skeena salmon data, only the Babine sockeye aggregate (comprising four CUs) has age composition data for each year. The Kalum-late Chinook CU recruitment estimates were derived using annual age composition values for returns later than 1988 (except 1996, which lacked age data). In all other cases, there is only enough data to estimate the average proportions of age-at-return across years, and these averages are used to estimate the brood year recruitment. Zabel and Levin (2002) examined the potential effects of using average age proportions by comparing Ricker stock-recruit parameter estimates for Chinook salmon stocks from the Columbia River where annual age proportions were available for the entire 20 year record. They found that:

1. The resulting time series of recruits based on average age proportions was smoother and had higher autocorrelation than the series based on year-specific proportions. This occurred because recruits from strong brood years were incorrectly assigned to neighbouring brood years, and weak brood years were artificially bolstered by adjoining years.
2. Use of average age proportions led to higher estimates of α and β compared to variable age proportions. We converted their parameter estimates into our Uopt, Sgen1, and Smsy benchmarks. Across the six stocks, the benchmarks were overestimated by 36%, underestimated by 64%, and overestimated by 8%, respectively. Thus, not accounting for variable age-at-return would lead to ER benchmarks that are potentially too high, and lower abundance benchmarks that are too low.
3. Simulation testing revealed that the extent of age-related bias in stock-recruitment parameters increased with the extent of variability around the stock-recruitment relationship. In addition, there was less bias when age-at-return was dominated by a single age compared to multiple ages.

In the Skeena, age composition-related bias will vary across species and would likely be greatest for Chinook where the majority of returns are spread among three age classes, intermediate for sockeye, coho and chum, where the majority of returns are spread among two age classes, and inconsequential for pink, where the majority or all returns are from one age class, respectively. There should be no age composition-related bias for the four Babine sockeye CUs which are the only ones where year-specific ageing data are available for all years of the time series.

In a previous analysis of available Skeena lake sockeye data from 1980-2008 brood years, we compared benchmarks derived from average- and year-specific age compositions for the aggregate Babine and the Nass CUs (Table SX.4). Using the average age composition relative to the year-specific ones led to an increase in Uopt of 13%, and a decrease in Sgen1 of 36% for the Babine aggregate, but there was very little difference among estimates for the Nass CU. The biases for Babine were of the same direction but of much lesser magnitude than for the six Chinook stocks evaluated by Zabel and Levin (2002). We also compared benchmarks for the Kalum-late CU based on the average age composition and with annual age composition for returns later than 1988 (except 1996). The annual age composition benchmarks were similar to those based on the average. The 0.1*So, Smsy, Smax, Uopt, and Umax values were within 5% of each other. Productivity was 10% lower using the annual age composition data, and this led to a 17% increase in Sgen1. However, since escapement is well above all revised abundance benchmarks, and ER is well below the exploitation benchmarks, these differences had no effect on the status assessment.

Clearly, lack of year-specific age composition data has the potential to result in overestimation of Uopt and underestimation of Sgen1. These biases would lead to the conclusions that ER and abundance status is better than it really is, and future policies that would lead to overharvest and reduced conservation performance. Unfortunately, wide variation in the extent of age-related bias among populations (e.g. Babine vs. Nass, six Columbia Chinook stocks vs. Babine) does not allow one to compute a reliable correction factor. Management simulations that evaluate the performance of various benchmarks could perhaps adjust the driving stock-recruitment relationships downward by the levels associated with age composition bias reported by Zabel and Levin (2002) or based on what was observed for Babine.

Measurement Error and Time Series Bias

Measurement error bias leads to overestimation of both stock productivity and the magnitude of density dependence (i.e., underestimation of Smax, Hilborn and Walters 1992). This occurs because error in the measurement of escapement spreads the stock-recruitment observations along the x-axis, making recruitment appear less dependent on spawning stock than it really is. Like age composition effects, this bias will result in overestimation of Uopt and underestimation of Sgen1. The magnitude of the bias will increase with the extent of error in escapement measurements, when the time series is short, and when there is limited contrast in the range of escapements over time. Published estimates of the extent of measurement error bias are unreliable because they are contaminated by time series bias effects (Caputi 1988, see below) so are not reported here.

Time series bias occurs because the 'independent' variable in the stock-recruitment regression (stock or escapement) is actually dependent on the process errors around the relationship; positive errors (better than expected recruitment for a given stock size) lead to higher spawning stocks later in time, and negative errors lead to lower stocks (Hilborn and Walters 1992). Like the other biases reviewed above, time series bias will lead to overestimation of both α and β stock-recruitment parameter estimates, however the bias in the latter parameter is much more severe (Korman et al. 1995). Based on simulations which represented conditions for 30 sockeye salmon stocks in southern BC and Alaska, Korman et al. (1995) found that bias in α ranged from 0-3% while bias in β ranged from 1-52%. The larger biases in β estimates were from simulations based on low productivity stocks with high autocorrelation. These results indicate that time series bias will likely result in a slight overestimation of the Uopt benchmark and potentially larger underestimation of Sgen1 and other abundance-based benchmarks. Other studies have shown that time series bias will be greatest when time series are short, when there is a strong relationship between recruitment and resulting escapement in the same years (due to implementation of fixed ER policies), when there is greater variation around the stock-recruitment relationship (i.e., greater process error), and when that variation is correlated through time (e.g., higher lag-1 autocorrelation, Caputi 1988, Hilborn and Walters 1992).

The potential magnitude of measurement error and time series biases in the Skeena-based stock-recruitment estimates is uncertain. On a positive note, most of the time series are quite long (Fig. S.3). Of the 35 CUs with three or more stock-recruitment pairs that were included in the analysis, only six had less than 15 data points where biases would be greatest. However, there are many characteristics of the data which suggest biases could be quite large. There has been a long history of fixed harvest policies as seen in the time series of ERs (e.g., Fig. SX.8), leading to potentially higher time series bias. The extent of measurement error is unknown but could be quite high for the many CUs where a limited number of stream walks is the primary method for estimating annual escapements. There is certainly considerable variation around the stock-recruitment curves, though some of this variation may be artificial and caused by measurement errors. There is also quite a bit of evidence for autocorrelation in stock-recruit residuals, though some of this could be due to using across-year average age proportions in the estimation of recruitment.

While we recognize that measurement and time series biases are a potential serious problem in our analysis, we do not have a viable method of correcting for them. More advanced state space modelling techniques have been touted as potentially addressing these bias issues, but successful implementation and testing is still lacking (Walters and Martell 2004). Hawkshaw and Walters (unpublished data) recently attempted to develop such a model for Skeena salmon data, but to-date, have not been able to obtain reliable stock-recruitment parameter estimates. It appears that there is not enough information in the data to separate process and observation error variability, even when relatively restrictive assumptions on the ratio of observation to process error are used. There is a long history of using simulation testing to quantify the magnitude of measurement error and time series bias. The results of these exercises, which are reviewed above, demonstrate that the extent of the bias depends on many conditions, like the productivity of the stock, the extent of variation around the stock-recruitment curve, and the extent of autocorrelation in residuals. The extent of bias will also depend on the extent of contrast in escapement over the time series. CUs that are heavily exploited and depleted prior to the start of the time series, and which do not recover, will have little information about the equilibrium stock size and productivity. We cannot reliably estimate all the important parameters and CU history in the first place because of potential biases, and therefore cannot determine which simulated bias level to use for a correction.

A simulation-based bias analysis for Skeena CUs would be further complicated by our use of a Hierarchical Bayesian Model that includes a potentially informative prior on Smax. This modelling approach resulted in larger differences in parameter estimates compared to the independent linear regression method for lake sockeye salmon compared to other species because the prior on Smax was more informative and there were more CUs (so the assumption of exchangeability of α estimates had a larger effect). Our HBM approach would reduce the potential bias in both α and β parameters, but only if the priors of Smax are reliable and the assumption that productivities among CUs are exchangeable holds. A simulation analysis of bias would be more complex because it would be based on the HBM and would therefore have to simulate a number of conditions where we deviate from the key HBM assumptions to varying degrees. Again, the selection of the appropriate results across these deviations to use for bias corrections would be highly uncertain. We have begun this exercise to at least demonstrate the relative benefits of an HBM approach for reducing bias, since the measurement error and time series bias from such a model has never been explored (Fig. S.4). Preliminary simulations do confirm reduced bias using an HBM. The ratio of α estimated by independent linear regression to the true simulated values averaged 1.33 across 15 CUs (i.e. productivity was biased high), while the ratio based on an HBM with a CV=0.3 on the prior for Smax was 1.11. The ratio of Smax estimated by independent linear regression to the true simulated values averaged 0.74 across CUs (i.e. Smax was underestimated), while the ratio based on an HBM was 0.92. When uninformative priors on Smax were used in the HBM (CV=1.0), biases in α (1.27) and Smax (0.79) were only slightly better than those from the independent linear model.

Bias Due to Unrepresentative Data

The use of benchmarks developed in the analysis for future management depends on the assumption that the historical data used to estimate them is representative of future conditions. The temporal trend in stock-recruitment residuals provides evidence of decreased productivity in the last decade for only a limited number of CUs (3 of 17 lake sockeye, 2 of 7 Chinook, 1 of 3 coho, 1 of 3chum, and 0 of 5 pink CUs). For most CUs, there does not appear to be strong evidence that historic conditions will not be representative of the future. However, for some CUs, especially important ones such as Babine sockeye wild runs, there is evidence of declining productivity. The fundamental question is whether such conditions are permanent or temporary. If the change in productivity is permanent, then use of benchmarks developed in this analysis for future management is not appropriate because they are based on data from an era that does not represent future conditions. One could argue that, in the absence of convincing scientific data suggesting that the productivity change is permanent, there is no reason to assume that it is, and therefore that benchmarks developed in this analysis can be used for future management. However, based on the precautionary principle, one could also argue that we should assume that a permanent drop in productivity has occurred and benchmarks should be adjusted to reflect this fact. While this latter argument is also logical, we do not know of any defensible methodology to determine which data are representative of future conditions and which are not. Time series methods, like the Kalman filter approach, provide estimates of how much productivity could be changing over the historical time series (conditional on some very restrictive assumptions) but do not provide a reliable means of forecasting what productivity will be in the future. We considered recalculating benchmarks using only recent data (say > 1995-1998), but such an approach reduces the number of stock-recruit pairs to ten or less for most CUs. This would lead to very unreliable stock-recruit parameter and benchmark estimates due to limited sample sizes, and potentially much greater levels of time series and measurement error bias.

Stock-recruitment parameter estimates developed from this analysis need to be integrated in a management strategy evaluation framework to determine the conservation and fishery performance of the various benchmarks that were used here. A key requirement in such an analysis will be definition of the planning horizon over which performance is evaluated. Typically those horizons range from 50-100 years. Shorter time frames will be very sensitive to initial conditions, will not capture long-term benefits of rebuilding strategies, and will show extreme variation among trials, leading to large uncertainty about the benefits and drawbacks of various management options. The question of how well the historic data represent future conditions must be viewed over the same time horizon used for management strategy evaluations. It is highly probable that CUs which show recent declines in productivity are likely to continue to exhibit this pattern over the next few years. However, a longer view of the same data shows multiple cycles of decline and recovery. Thus, there does not appear to be a strong rationale for using only the most recent data (say last decade) to represent future conditions, even if such an analysis were feasible.

Future Work

Results from published management strategy evaluations can provide considerable guidance on the utility of the various benchmarks computed from this analysis. For example, if performance is measured by a risk-averse utility function which penalizes very low catches or fisheries closures in any year, then a constant ER rule (a fixed proportion of returns are harvested in each year) will outperform an abundance-based rule like a fixed escapement policy, where fisheries are closed if escapement is below the target (Walters and Martell 2004). This conclusion holds even without accounting for the additional complications of implementing abundance-based harvest rules, which require a method of forecasting abundance or accurate in-season estimation of abundance. Fixed ER strategies can be implemented without any knowledge of abundance, through time and area closures given knowledge of run timing and location. Other studies have shown that outcome uncertainty, which measures our ability to accurately implement a given policy (i.e. obtain a specified ER or catch), can have a large effect on performance (Collie et al. 2012). Considering the uncertainty in escapement estimates for most of the CUs in the Skeena, and uncertainty in estimating abundance prior to the fishery, it seems that accurate implementation of fixed escapement policies will be very difficult and could lead to reduced fisheries and conservation performance relative to implementing a fixed ER rule. Thus, the ER benchmarks will likely provide more utility for fisheries management than abundance-based benchmarks. However, for species where the run strength can be estimated in-season (e.g. sockeye), fisheries could be managed using rules where maximum ERs vary with abundance (typically increasing with abundance). It is uncertain whether fixed ER policies or abundance-based harvest rules should be adjusted over time to account for variation in stock productivity. Simulations of slow changes in productivity through time indicate very limited benefits of reduced ERs during periods of low productivity in single stock fisheries (Walters and Martell 2004, Collie et al. 2012), however there may be greater benefits in mixed-stock fisheries where weak stock conservation is a high priority. Furthermore, if the priority is to conserve weak stocks in mixed-stock fisheries, abundance-based rules for harvest based on returns of the weaker stocks may have better performance than fixed exploitation strategies. The logical next step in implementation of the Wild Salmon Policy in the Skeena is to use the estimated stock-recruitment parameters and benchmarks developed here in a management strategy evaluation to provide an explicit and rational way of setting ERs which strike a reasonable balance between protecting weak stocks and providing fishing opportunities. Additional exploration of sources of uncertainty and bias in the benchmark and status assessments presented here is also recommended.

5.0 References

Alexander, R., K.K. English, D. Peacock, and G. Oliver. 2010. Assessment of the Canadian and Alaskan Sockeye Stocks harvested in the northern boundary fisheries using run reconstruction techniques, 2004-08. Draft report for Pacific Salmon Comm. Northern Boundary Technical Committee.

Big River Analytics. 2013. Application of Regime Change Detection Methods to Productivity Analysis of Skeena Salmon Conservation Units. Draft report prepared for Skeena Wild Conservation Trust, July 23, 2013.

Collie, J.S., Peterman, R.M., and B.M. Zuehike. 2012. A fisheries risk-assessment framework to evaluate trade-offs among management options in the presence of time-varying productivity. Canadian Journal of Fisheries and Aquatic Sciences 69:209-223.

Caputi, N. 1988. Factors affecting the time series bias in stock-recruitment relationships and the interaction between time series and measurement error bias. Canadian Journal of Fisheries and Aquatic Sciences 45:178-184.

Cox-Rogers, S., Hume, J.M.B., Shortreed, K.S., and B. Spilsted. 2010. A risk assessment model for Skeena River Sockeye Salmon. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2920.

Cox-Rogers S., and B. Spilsted. 2012. Update Assessment of Sockeye Salmon Production from Babine Lake, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 2956: viii + 65 p.

English, K.K., Noble, C., and A. Blakley. 2013. Skeena sockeye in-river run reconstruction analysis model and analysis results for 1982-2009. Report prepared for the Pacific Salmon Foundation by LGL Limited, May 2013.

English, K.K., Mochizuki, T., and D. Robichaud. 2012. Review of north and central coast salmon indicator streams and estimating escapement, catch and run size for each salmon conservation unit. Report prepared by LGL Limited for the Pacific Salmon Foundation by LGL Limited, 18 April 2012.

English, K.K. 2013. Extended time-series of catch and escapement estimates for Skeena sockeye, pink, chum, coho and Chinook salmon Conservation Units. Report prepared for Pacific Salmon Foundation by LGL Limited, May 2013.

Fisheries and Oceans Canada (FOC). 2005. Canada's policy for conservation of wild pacific salmon. ISBN 0-662-40538-2.

Grant, S.C.H., MacDonald, B.L, Cone, T.E., Holt, C.A., Cass, Al. Porszt, E.J., Hume, J.M.B., and L.B. Pon. 2010. Fraser sockeye wild salmon policy evaluation of stock status: State and Rate. Working Paper 2010/P14.

Hilborn, R. 2002. The dark side of reference points. Bulletin of Marine Science 70:403-408.

Hilborn, R., and C.J. Walters. 1992. Quantitative fisheries stock assessment. Chapman and Hall.

Holtby, L.B. and K.A. Ciruna. 2007. Conservation units for Pacific salmon under the wild salmon policy. Canadian Science Advisory Secretariat, Research Document 2007/070.

Korman, J. Peterman, R.M., and C.J. Walters. 1995. Empirical and theoretical analyses of time-series bias in stock-recruitment relationships of sockeye salmon (Oncorhynchus nerka). Canadian Journal of Fisheries and Aquatic Sciences 52:2174-2189.

Parken, C. K., R. E. McNicol, and J. R. Irvine. 2006. Habitat-based methods to estimate escapement goals for data limited Chinook salmon stocks in British Columbia, 2004. Canadian Science Advisory Secretariat Research Document 2006/083.

Peacock, D., and B. Spilsted. 2010. Skeena River chum (Oncorhynchus keta) stock status. Canadian Science Advisory Secretariat Draft Report 2010/059.

Price, M.H.H., Gayeski, N., and J.A. Stanford. 2013. Abundance of Skeena River chum salmon Oncorhynchus keta, during the early rise of commercial fishing. Transactions of the American Fisheries Society. in press.

Shortreed. K.S., J.M.B. Hume and J.G. Stockner. 1999. Using photosynthetic rates to estimate the juvenile sockeye rearing capacity of British Columbia lakes, p.502-521. In E.E. Knudsen, C.R. Steward, D.D. MacDonald, J.E. Williams, and D.W. Reiser [eds.]. Sustainable Fisheries Management: Pacific Salmon. CRC Press LLC, Boca Raton, New York.

Walters, C.J., Lichatowich, J.A., Peterman, R.M. and Reynolds, J.D. 2008. Report of the Skeena Independent Science Review Panel. A report to the Canadian Department of Fisheries and Oceans and the British Columbia Ministry of the Environment. May 15, 2008, 144 p.

Walters, C.J., and S.J.D. Martell. 2004. Fisheries ecology and management. Princeton University Press.

Zabel, R.W., and P.S. Levin. 2002. Simple assumptions on age composition lead to erroneous conclusions on the nature of density dependence in age-structured populations. Oecologia 133:349-355.

6.0 Tables and Figures

Table SX.1. List of Skeena lake sockeye salmon Conservation Units (CUs) and available data for stock-recruit analysis for three different brood year periods. Values in the "# of age samples" column denote the total number of age samples, with values in parentheses denoting the number of years where age data are available. CUs with *'s denote those where year-specific age composition data were used to estimate recruitment. PR-based Smax values are estimates of the spawning stock size that produces maximum recruitment based on the photosynthetic rate model and other factors (updated from Cox-Rogers et al. 2010). These estimates are used as priors on β_i in the stock-recruit analysis.

Conservation Unit	# of Stock-Recruit Points			# of Age Samples	PR-based Smax Estimate
	1954-2008	1980-2008	1998-2008		
Alastair	47	22	4	151 (2)	23,437
Asitika	2	0	0		
Azuklotz	20	13	1		5,933
Babine-Enhanced*	48	28	10	17,489 (21)	
Babine-Early-Wild * (= Babine CU)	48	28	10		
Babine-Mid-Wild * (= Nilkitkwa CU)	48	28	10		
Babine-Late-Wild * (= Tahlo-Morrison CU)	48	28	10		
Bear	16	6	0	46 (1)	40,532
Bulkley					
Damshilgwit	5	5	5	67 (1)	2,000
Ecstall/Lower					
Footsore/Hodder					
Johanson					
Johnston	12	4	0		4,125
Kitsumkalum	45	21	6		20,531
Kitwancool	6	5	5	299 (4)	36,984
Kluartantan					
Kluyaz					
Lakelse	39	15	2	194 (1)	35,916
Mcdonell	28	8	3		4,072
Morice	42	17	4	98 (1)	191,362
Motase	12	12	7		1,764
Sicintine					
Slamgeesh					
Spawning					
Stephens	35	14	5		7,069
Sustut					
Swan	22	12	5	100 (1)	21,432

Table SX.2. Preliminary benchmarks for Skeena lake sockeye salmon Conservation Units (CU) based on all available stock-recruit data from across 1954-2008 brood years. The 0.1*So and Sgen1 statistics are two alternatives that could be used as the lower benchmark. They are the escapement that is 10% of the unfished equilibrium escapement, and the escapement that will allow the population to recover to the stock size that maximizes catch (Smsy) in one generation, respectively. Smsy and Smax are two alternatives for the upper benchmark, the latter being the escapement that maximizes recruitment. Prod is equivalent to e^{α}, which is the initial slope of the stock recruitment curve (maximum recruits/spawner). Uopt is the exploitation rate which maximizes catch (i.e., the exploitation rate at Smsy) and Umax is the exploitation rate that will lead to extirpation. Benchmark statistics are based on the CU-specific stock-recruit parameter values from the HBM (mean), as well as the lower and upper 95% credible intervals (LCL and UCL, respectively).

Table SX.2. Con't.

Stat	Mean	LCL	UCL		Stat	Mean	LCL	UCL		Stat	Mean	LCL	UCL
Alastair					Bear					Mcdonell			
0.1*So	3,171	2,533	3,972		0.1*So	2,623	986	5,610		0.1*So	513	440	594
Sgen1	5,710	3,672	8,124		Sgen1	6,212	2,892	11,926		Sgen1	508	334	754
Smsy	13,345	10,846	16,715		Smsy	11,561	4,596	23,851		Smsy	2,009	1,740	2,354
Smax	28,562	22,077	38,495		Smax	33,730	16,321	63,018		Smax	3,355	2,686	4,307
Prod	3.11	2.30	4.20		Prod	2.25	1.50	3.60		Prod	4.75	3.40	6.50
Uopt	0.47	0.37	0.57		Uopt	0.35	0.18	0.52		Uopt	0.60	0.51	0.69
Umax	0.68	0.56	0.76		Umax	0.54	0.31	0.72		Umax	0.79	0.70	0.85
Azuklotz					Damshilgwit					Morice			
0.1*So	853	529	1,327		0.1*So	75	28	179		0.1*So	24,520	12,001	45,071
Sgen1	891	390	1,657		Sgen1	232	114	471		Sgen1	49,447	25,015	89,522
Smsy	3,350	2,155	5,174		Smsy	343	134	807		Smsy	98,908	50,031	179,043
Smax	5,766	3,493	9,416		Smax	1,477	759	2,788		Smax	182,777	94,603	324,992
Prod	4.75	2.60	8.00		Prod	1.70	1.20	2.60		Prod	3.96	2.50	6.10
Uopt	0.59	0.41	0.74		Uopt	0.23	0.10	0.41		Uopt	0.54	0.40	0.67
Umax	0.78	0.61	0.88		Umax	0.40	0.19	0.61		Umax	0.74	0.60	0.84
Babine-Enhanced					Johnston					Motase			
0.1*So	116,637	70,087	251,773		0.1*So	856	384	1,452		0.1*So	121	78	197
Sgen1	225,389	122,067	515,552		Sgen1	493	96	1,099		Sgen1	232	128	421
Smsy	450,778	244,134	1,031,104		Smsy	2,973	1,645	4,755		Smsy	520	342	848
Smax	745,384	318,114	1,997,920		Smax	4,317	2,654	6,707		Smax	1,240	746	2,233
Prod	5.74	3.10	10.40		Prod	9.63	2.40	30.20		Prod	2.80	1.80	4.00
Uopt	0.64	0.48	0.79		Uopt	0.70	0.38	0.89		Uopt	0.43	0.28	0.56
Umax	0.82	0.68	0.90		Umax	0.87	0.58	0.97		Umax	0.64	0.46	0.75
Babine-Early-Wild					Kitsumkalum					Stephens			
0.1*So	11,479	7,298	21,851		0.1*So	2,618	1,811	3,902		0.1*So	1,249	936	1,666
Sgen1	24,453	14,497	48,168		Sgen1	4,457	2,550	7,963		Sgen1	800	281	1,685
Smsy	49,207	30,586	96,336		Smsy	10,967	7,596	16,224		Smsy	4,546	3,382	6,321
Smax	119,790	55,707	314,955		Smax	22,978	15,041	35,045		Smax	6,639	4,342	10,361
Prod	2.97	1.80	4.60		Prod	3.21	2.40	4.20		Prod	7.42	3.60	14.30
Uopt	0.45	0.28	0.60		Uopt	0.48	0.38	0.58		Uopt	0.70	0.52	0.84
Umax	0.65	0.46	0.78		Umax	0.68	0.58	0.76		Umax	0.86	0.72	0.93
Babine-Mid-Wild					Kitwancool					Swan			
0.1*So	6,161	2,990	22,218		0.1*So	4,559	1,602	9,560		0.1*So	2,407	1,366	4,197
Sgen1	12,128	3,243	49,852		Sgen1	7,407	2,972	16,627		Sgen1	3,869	1,846	7,375
Smsy	26,518	12,409	99,703		Smsy	18,608	7,238	36,016		Smsy	10,019	5,848	17,289
Smax	68,691	22,138	315,431		Smax	38,082	20,310	65,470		Smax	20,929	11,638	36,265
Prod	3.18	1.85	5.00		Prod	3.56	1.70	7.50		Prod	3.33	2.10	5.10
Uopt	0.47	0.28	0.62		Uopt	0.49	0.25	0.72		Uopt	0.49	0.33	0.63
Umax	0.67	0.46	0.80		Umax	0.70	0.42	0.87		Umax	0.69	0.52	0.80
Babine-Late-Wild					Lakelse								
0.1*So	66,038	38,230	146,714		0.1*So	2,709	2,012	3,610					
Sgen1	140,260	78,620	320,453		Sgen1	5,355	3,382	7,702					
Smsy	280,521	157,240	640,906		Smsy	11,602	8,798	15,380					
Smax	647,487	278,120	1,797,877		Smax	27,182	19,193	39,834					
Prod	3.15	2.00	4.95		Prod	2.80	2.00	3.80					
Uopt	0.47	0.30	0.62		Uopt	0.43	0.31	0.54					
Umax	0.67	0.49	0.80		Umax	0.64	0.50	0.74					

Table SX.3. Status of Skeena lake sockeye salmon CUs based on comparing the average escapement between 2006 and 2010 relative to Sgen1 (lower) and Smsy (upper) benchmarks (benchmarks computed from all available brood year 1954-2008 data). The probabilities associated with each abundance status level were determined from the posterior distributions of Sgen1 and Smsy predicted from the HBM. Also shown is the average total exploitation rate (ER) between 2006 and 2010 relative to the average optimal exploitation rate (Uopt) and the probability that the 2006-2010 average has exceeded the optimal exploitation rate (Prob. OverExp.). Also shown are the ratios of the current average escapement to the unfished equilibrium (Avg. Esc/So) and the current exploitation rate relative to the optimal rate (Avg. ER/Uopt). Status could not be computed for the Johnston CU because no escapement or exploitation rate data are available between 2006 and 2010.

	Abundance Status				Exploitation Rate Status				
CU	Avg. Esc. ('06-10)	Red (<Sgen1)	Amber (<Smsy)	Green (>=Smsy)	Avg. ER ('06-10)	Avg. Uopt	Prob. OverExp.	Avg.Esc /So	Avg. ER /Uopt
Alastair	18,787	0.00	0.00	1.00	0.20	0.47	0.00	0.59	0.41
Azuklotz	4,724	0.00	0.06	0.94	0.27	0.59	0.00	0.55	0.45
Babine-Enhanced	530,328	0.02	0.20	0.78	0.42	0.64	0.00	0.45	0.66
Babine-Early-Wild	32,672	0.10	0.83	0.07	0.36	0.45	0.13	0.28	0.79
Babine-Mid-Wild	12,452	0.20	0.78	0.03	0.38	0.47	0.18	0.20	0.82
Babine-Late-Wild	99,899	0.76	0.24	0.00	0.45	0.47	0.40	0.15	0.95
Bear	3,735	0.90	0.09	0.01	0.16	0.35	0.02	0.14	0.45
Damshilgwit	350	0.10	0.25	0.66	0.30	0.23	0.83	0.47	1.32
Johnston	NA	NA	NA	NA	NA	0.70	NA	NA	NA
Kitsumkalum	28,920	0.00	0.00	1.00	0.26	0.48	0.00	1.10	0.55
Kitwancool	6,087	0.56	0.43	0.01	0.34	0.49	0.10	0.13	0.69
Lakelse	7,529	0.04	0.96	0.00	0.14	0.43	0.00	0.28	0.31
Mcdonell	3,315	0.00	0.00	1.00	0.14	0.60	0.00	0.65	0.24
Morice	22,209	0.99	0.01	0.00	0.31	0.54	0.00	0.09	0.57
Motase	304	0.15	0.85	0.01	0.35	0.43	0.11	0.25	0.81
Stephens	11,874	0.00	0.00	1.00	0.24	0.70	0.00	0.95	0.34
Swan	3,321	0.60	0.40	0.00	0.24	0.49	0.00	0.14	0.49

Table SX.4. Comparison of benchmarks for the Babine aggregate and Nass CUs computed using the across-year average age compositions, and year-specific values. Sgen1 is the escapement that will allow the population to recover to the stock size that maximizes catch (Smsy) in one generation. Smax is the escapement that maximizes yield and recruitment, respectively. Prod is equivalent to e^{α}, which is the initial slope of the stock recruitment curve (maximum recruits/spawner). Uopt is the exploitation rate which maximizes catch (i.e., the exploitation rate at Smsy).

	Average Age Composition (Avg)	**Year-Specific Age Composition (Yr)**	**Bias = 100*(Avg-Yr)/Yr**
Babine			
	Mean	**Mean**	
Sgen1	240,879	375,605	-36%
Smsy	898,155	1,001,734	-10%
Smax	1,539,444	2,090,271	-26%
Prod	4.51	3.69	22%
Uopt	0.59	0.52	13%
Nass			
	Mean	**Mean**	
Sgen1	67,558	66,706	1%
Smsy	229,575	221,080	4%
Smax	316,629	306,962	3%
Prod	8.51	8.44	1%
Uopt	0.74	0.74	0%

Table CN.1. List of Skeena Chinook salmon Conservation Units (CUs) and available data for stock-recruit analysis. N-SR denotes the number of stock-recruit data points for CUs with escapement and recruitment data (across 1954-2008 brood years). N-Age denotes the total number of age samples, with values in parentheses denoting the number of years where age data are available. PrSmax is the mean of the lognormal prior (pr) for the escapement that maximizes recruitment, and pr CV is the approximate relative variation in that prior. PrSmax values were based on the mean escapement over the period of record.

CU	N - SR	N - Age	pr Smax	pr CV
Ecstall	6	NA	11,636	1
Lower_Skeena	22	156 (1)	1,872	10
Mid_Skeena_Large_Lakes	25	3358 (19)	28,180	10
Mid_Skeena_Main_Tribs	24	215 (8)	7,757	10
Upper_Bulkley	18	533 (13)	1,208	10
Kalum-early	24	327 (6)	1,197	10
Kalum-late	25	8566 (22)	10,921	1

Table CN.2. Preliminary benchmarks for Skeena Chinook salmon Conservation Units (CU) based on all available data from brood years 1954-2008. The 0.1*So and Sgen1 statistics are two alternatives that could be used as the lower benchmark. They are the escapement that is 10% of the unfished equilibrium escapement, and the escapement that will allow the population to recover to the stock size that maximizes catch (Smsy) in one generation, respectively. Smsy and Smax are two alternatives for the upper benchmark, the latter being the escapement that maximizes recruitment. Prod is equivalent to e^{α}, which is the initial slope of the stock recruitment curve (maximum recruits/spawner). Uopt is the exploitation rate which maximizes catch (i.e., the exploitation rate at Smsy) and Umax is the exploitation rate that will lead to extirpation of the CU. Benchmark statistics are based on the CU-specific stock-recruit parameter values from the HBM (mean), as well as the lower and upper 95% credible intervals (LCL and UCL, respectively).

Stat	Mean	LCL	UCL		Stat	Mean	LCL	UCL
Ecstall					Mid_Skeena_Large_Lakes			
0.1*So	634	410	1,758		0.1*So	5,509	4,705	6,774
Sgen1	323	55	1,640		Sgen1	3,880	1,976	6,941
Smsy	2,164	1,206	6,822		Smsy	20,457	16,654	26,480
Smax	2,994	1,390	11,311		Smax	30,343	21,968	44,723
Prod	12.65	4.30	24.21		Prod	6.48	4.30	9.50
Uopt	0.79	0.58	0.88		Uopt	0.68	0.58	0.77
Umax	0.91	0.77	0.96		Umax	0.84	0.77	0.89
Kalum-early					Mid_Skeena_Main_Tribs			
0.1*So	151	132	172		0.1*So	1,877	1,631	2,218
Sgen1	178	113	271		Sgen1	846	497	1,424
Smsy	607	535	695		Smsy	6,542	5,478	8,103
Smax	1,090	857	1,435		Smax	8,727	6,878	11,645
Prod	4.16	2.80	5.90		Prod	8.87	6.30	12.25
Uopt	0.56	0.45	0.67		Uopt	0.75	0.68	0.81
Umax	0.76	0.65	0.83		Umax	0.89	0.84	0.92
Kalum-late					Upper_Bulkley			
0.1*So	2,328	1,993	2,844		0.1*So	205	132	379
Sgen1	1,461	685	2,947		Sgen1	316	118	758
Smsy	8,496	6,903	11,128		Smsy	850	531	1,629
Smax	12,293	8,783	18,902		Smax	1,774	872	3,976
Prod	7.16	4.20	11.30		Prod	3.55	2.20	5.60
Uopt	0.70	0.57	0.80		Uopt	0.51	0.36	0.66
Umax	0.86	0.76	0.91		Umax	0.71	0.55	0.82
Lower_Skeena								
0.1*So	336	285	411					
Sgen1	302	186	480					
Smsy	1,299	1,068	1,637					
Smax	2,093	1,553	2,893					
Prod	5.14	3.80	6.80					
Uopt	0.63	0.55	0.70					
Umax	0.80	0.74	0.85					

Table CN.3. Status of Skeena Chinook salmon CUs based on comparing the average escapement between 2006 and 2010 relative to Sgen1 (lower) and Smsy (upper) benchmarks (benchmarks computed from all available brood year1954-2008 data). The probabilities associated with each abundance status level were determined from the posterior distributions of Sgen1 and Smsy predicted from the HBM. Also shown is the average total exploitation rate (ER) between 2006 and 2010 relative to the average optimal exploitation rate (Uopt) and the probability that the 2006-2010 average has exceeded the optimal exploitation rate (Prob. OverExp.). Also shown are the ratios of the current average escapement to the unfished equilibrium (Avg. Esc/So) and the current exploitation rate relative to the optimal rate (Avg. ER/Uopt). Status of the Ecstall CU could not be assessed because there are no escapement or exploitation rate estimates available between 2006 and 2010.

	Abundance Status				**Exploitation Rate Status**				
	Avg. Esc.	**Red**	**Amber**	**Green**	**Avg. ER**	**Avg.**	**Prob.**	**Avg.Esc**	**Avg. ER**
CU	**('06-10)**	**(<Sgen1)**	**(<Smsy)**	**(>=Smsy)**	**('06-10)**	**Uopt**	**OverExp.**	**/So**	**/Uopt**
Ecstall	NA	NA	NA	NA	NA	0.79	NA	NA	NA
Kalum-early	1,006	0.00	0.00	1.00	0.04	0.56	0.00	0.67	0.08
Kalum-late	13,424	0.00	0.00	1.00	0.41	0.70	0.00	0.58	0.59
Lower_Skeena	1,386	0.00	0.24	0.76	0.39	0.63	0.00	0.41	0.62
Mid_Skeena_Large_Lakes	27,532	0.00	0.02	0.98	0.41	0.68	0.00	0.50	0.61
Mid_Skeena_Main_Tribs	12,672	0.00	0.00	1.00	0.41	0.75	0.00	0.68	0.55
Upper_Bulkley	1,138	0.01	0.10	0.89	0.04	0.51	0.00	0.56	0.08

Table CO.1. List of Skeena coho salmon Conservation Units (CUs) and available data for stock-recruit analysis. N-SR denotes the number of stock-recruit data points for CUs with escapement and recruitment data (across 1954-2008 brood years). N-Age denotes the total number of age samples, with values in parentheses denoting the number of years where age data are available. pr Smax is the mean of the lognormal prior (pr) for the escapement that maximizes recruitment, and pr CV is the approximate relative variation in that prior. Pr Smax values were based on the mean escapement over the period of record.

CU Name	N - SR	N - Age	pr Smax	pr CV
Lower_Skeena	53	28 (1)	141,335	10
Middle_Skeena	53	5264 (42)	103,064	1
Upper_Skeena	14	984 (9)	7,677	1

Table CO.2. Preliminary benchmarks for Skeena coho salmon Conservation Units (CU) based on all available data from brood years 1954-2008. The 0.1*So and Sgen1 statistics are two alternatives that could be used as the lower benchmark. They are the escapement that is 10% of the unfished equilibrium escapement, and the escapement that will allow the population to recover to the stock size that maximizes catch (Smsy) in one generation, respectively. Smsy and Smax are two alternatives for the upper benchmark, the latter being the escapement that maximizes recruitment. Prod is equivalent to e^{α}, which is the initial slope of the stock recruitment curve (maximum recruits/spawner). Uopt is the exploitation rate which maximizes catch (i.e., the exploitation rate at Smsy) and Umax is the exploitation rate that will lead to extirpation of the CU. Benchmark statistics are based on the CU-specific stock-recruit parameter values from the HBM (mean), as well as the lower and upper 95% credible intervals (LCL and UCL, respectively).

Stat	Mean	LCL	UCL
Lower_Skeena			
0.1*So	42,209	28,751	70,954
Sgen1	86,739	57,477	151,226
Smsy	173,479	114,955	302,452
Smax	339,572	192,306	684,758
Prod	3.75	2.60	5.10
Uopt	0.53	0.42	0.63
Umax	0.73	0.62	0.80
Middle_Skeena			
0.1*So	24,951	19,283	34,566
Sgen1	49,736	37,718	70,604
Smsy	99,472	75,436	141,208
Smax	174,266	120,011	272,448
Prod	4.34	3.20	5.70
Uopt	0.58	0.49	0.66
Umax	0.77	0.69	0.82
Upper_Skeena			
0.1*So	1,297	995	1,890
Sgen1	790	244	2,229
Smsy	4,665	3,276	7,460
Smax	6,740	3,985	13,309
Prod	8.18	3.60	15.20
Uopt	0.72	0.53	0.84
Umax	0.87	0.73	0.93

Table CO.3. Status of Skeena coho salmon CUs based on comparing the average escapement between 2006 and 2010 relative to Sgen1 (lower) and Smsy (upper) benchmarks (benchmarks computed from all available brood year 1954-2008 data). The probabilities associated with each abundance status level were determined from the posterior distributions of Sgen1 and Smsy predicted from the HBM. Also shown is the average total exploitation rate (ER) between 2006 and 2010 relative to the average optimal exploitation rate (Uopt) and the probability that the 2006-2010 average has exceeded the optimal exploitation rate (Prob. OverExp.). Also shown are the ratios of the current average escapement to the unfished equilibrium (Avg. Esc/So) and the current exploitation rate relative to the optimal rate (Avg. ER/Uopt).

	Abundance Status				**Exploitation Rate Status**				
CU	**Avg. Esc. ('06-10)**	**Red (<Sgen1)**	**Amber (<Smsy)**	**Green (>=Smsy)**	**Avg. ER ('06-10)**	**Avg. Uopt**	**Prob. OverExp.**	**Avg.Esc /So**	**Avg. ER /Uopt**
Lower_Skeena	91,450	0.25	0.75	0.00	0.34	0.53	0.00	0.22	0.63
Middle_Skeena	225,257	0.00	0.00	1.00	0.34	0.58	0.00	0.90	0.58
Upper_Skeena	12,344	0.00	0.00	1.00	0.34	0.72	0.00	0.95	0.47

Table CM.1. List of Skeena chum salmon Conservation Units (CUs) and available data for stock-recruit analysis. N-SR denotes the number of stock-recruit data points for CUs with escapement and recruitment data (across 1954-2008 brood years). N-Age denotes the total number of age samples, with values in parentheses denoting the number of years where age data are available. pr Smax is the mean of the lognormal prior (pr) for the escapement that maximizes recruitment, and pr CV is the approximate relative variation in that prior. Pr Smax values were based on the mean escapement over the period of record.

CU Name	N-SR	N-Age	pr Smax	pr CV
Skeena_Estuary	17		1,118	1
Lower_Skeena	45	7 (2)	20,378	10
Middle_Skeena	35	421 (6)	2,544	1

Table CM.2. Preliminary benchmarks for Skeena chum salmon Conservation Units (CU) based on all available data from brood years 1954-2008. The 0.1*So and Sgen1 statistics are two alternatives that could be used as the lower benchmark. They are the escapement that is 10% of the unfished equilibrium escapement, and the escapement that will allow the population to recover to the stock size that maximizes catch (Smsy) in one generation, respectively. Smsy and Smax are two alternatives for the upper benchmark, the latter being the escapement that maximizes recruitment. Prod is equivalent to e^{α}, which is the initial slope of the stock recruitment curve (maximum recruits/spawner). Uopt is the exploitation rate which maximizes catch (i.e., the exploitation rate at Smsy) and Umax is the exploitation rate that will lead to extirpation of the CU. Benchmark statistics are based on the CU-specific stock-recruit parameter values from the HBM (mean), as well as the lower and upper 95% credible intervals (LCL and UCL, respectively).

Stat	Mean	LCL	UCL
Skeena_Estuary			
0.1*So	249	86	529
Sgen1	681	313	1,463
Smsy	1,121	412	2,384
Smax	4,124	1,939	10,099
Prod	2.01	1.20	3.30
Uopt	0.30	0.09	0.50
Umax	0.49	0.17	0.70
Lower_Skeena			
0.1*So	4,701	2,957	6,628
Sgen1	9,671	4,775	14,661
Smsy	20,238	12,950	28,883
Smax	52,331	27,755	78,280
Prod	2.87	1.90	4.10
Uopt	0.44	0.30	0.57
Umax	0.65	0.48	0.76
Middle_Skeena			
0.1*So	396	229	586
Sgen1	799	457	1,349
Smsy	1,706	1,056	2,515
Smax	4,381	2,771	7,719
Prod	2.70	1.60	4.30
Uopt	0.41	0.21	0.58
Umax	0.62	0.36	0.77

Table CM.3. Status of Skeena chum salmon CUs based on comparing the average escapement between 2006 and 2010 relative to Sgen1 (lower) and Smsy (upper) benchmarks (benchmarks computed from all available brood year 1954-2008 data). The probabilities associated with each abundance status level were determined from the posterior distributions of Sgen1 and Smsy predicted from the HBM. Also shown is the average total exploitation rate (ER) between 2006 and 2010 relative to the average optimal exploitation rate (Uopt) and the probability that the 2006-2010 average has exceeded the optimal exploitation rate (Prob. OverExp.). Also shown are the ratios of the current average escapement to the unfished equilibrium (Avg. Esc/So) and the current exploitation rate relative to the optimal rate (Avg. ER/Uopt).

	Abundance Status				Exploitation Rate Status				
CU	Avg. Esc. ('06-10)	Red (<Sgen1)	Amber (<Smsy)	Green (>=Smsy)	Avg. ER ('06-10)	Avg. Uopt	Prob. OverExp.	Avg.Esc /So	Avg. ER /Uopt
Skeena_Estuary	378	0.93	0.05	0.02	0.11	0.30	0.05	0.15	0.38
Lower_Skeena	5,373	0.93	0.07	0.00	0.12	0.44	0.00	0.11	0.28
Middle_Skeena	1,342	0.03	0.84	0.13	0.14	0.41	0.01	0.34	0.34

Table PK.1. List of Skeena pink salmon Conservation Units (CUs) and available data for stock-recruit analysis. N-SR denotes the number of stock-recruit data points for CUs with escapement and recruitment data (across 1954-2008 brood years). pr Smax is the mean of the lognormal prior (pr) for the escapement that maximizes recruitment, and pr CV is the approximate relative variation in that prior. Pr Smax values were based on the mean escapement over the period of record.

CU Name	N - SR	pr Smax	pr CV
Nass-Skeena_Estuary_Even	28	1668922	1
Middle-Upper_Skeena_Even	28	587859	1
Nass-Skeena_Estuary_Odd	27	209256	1
Lower_Skeena_Odd	27	1367598	1
Middle_Upper_Skeena_Odd	27	1090011	1

Table PK.2. Preliminary benchmarks for Skeena pink salmon Conservation Units (CU) based on all available data from brood years 1954-2008. The 0.1*So and Sgen1 statistics are two alternatives that could be used as the lower benchmark. They are the escapement that is 10% of the unfished equilibrium escapement, and the escapement that will allow the population to recover to the stock size that maximizes catch (Smsy) in one generation, respectively. Smsy and Smax are two alternatives for the upper benchmark, the latter being the escapement that maximizes recruitment. Prod is equivalent to e^{α}, which is the initial slope of the stock recruitment curve (maximum recruits/spawner). Uopt is the exploitation rate which maximizes catch (i.e., the exploitation rate at Smsy) and Umax is the exploitation rate that will lead to extirpation of the CU. Benchmark statistics are based on the CU-specific stock-recruit parameter values from the HBM (mean), as well as the lower and upper 95% credible intervals (LCL and UCL, respectively).

Stat	Mean	LCL	UCL		Stat	Mean	LCL	UCL
Nass-Skeena_Estuary_Even					Lower_Skeena_Odd			
0.1*So	274,642	202,296	399,453		0.1*So	353,309	232,791	643,136
Sgen1	561,925	411,664	842,347		Sgen1	704,814	450,358	1,317,330
Smsy	1,123,851	823,328	1,684,695		Smsy	1,415,953	900,747	2,646,517
Smax	2,208,271	1,375,290	4,080,583		Smax	2,565,312	1,376,354	5,619,635
Prod	3.80	2.20	6.00		Prod	4.37	2.70	6.75
Uopt	0.53	0.36	0.67		Uopt	0.57	0.43	0.70
Umax	0.73	0.55	0.83		Umax	0.76	0.63	0.85
Middle-Upper_Skeena_Even					Middle_Upper_Skeena_Odd			
0.1*So	144,476	89,226	267,408		0.1*So	326,488	191,977	672,989
Sgen1	299,776	184,715	559,923		Sgen1	666,329	381,395	1,393,493
Smsy	599,552	369,431	1,119,846		Smsy	1,332,657	762,790	2,786,986
Smax	1,241,292	659,609	2,663,984		Smax	2,569,519	1,218,910	6,250,000
Prod	3.52	2.15	5.60		Prod	3.94	2.50	6.10
Uopt	0.50	0.34	0.65		Uopt	0.54	0.40	0.68
Umax	0.71	0.54	0.82		Umax	0.74	0.60	0.84
Nass-Skeena_Estuary_Odd								
0.1*So	75,865	37,511	173,714					
Sgen1	164,042	81,762	378,580					
Smsy	328,083	163,524	757,160					
Smax	818,041	354,220	2,081,368					
Prod	2.71	1.90	4.00					
Uopt	0.42	0.28	0.56					
Umax	0.62	0.46	0.75					

Table PK.3. Status of Skeena pink salmon CUs based on comparing the average escapement between 2006 and 2010 relative to Sgen1 (lower) and Smsy (upper) benchmarks (benchmarks computed from all available brood year 1954-2008 data). The probabilities associated with each abundance status level were determined from the posterior distributions of Sgen1 and Smsy predicted from the HBM. Also shown is the average total exploitation rate (ER) between 2006 and 2010 relative to the average optimal exploitation rate (Uopt) and the probability that the 2006-2010 average has exceeded the optimal exploitation rate (Prob. OverExp.). Also shown are the ratios of the current average escapement to the unfished equilibrium (Avg. Esc/So) and the current exploitation rate relative to the optimal rate (Avg. ER/Uopt).

	Abundance Status				**Exploitation Rate Status**				
CU	**Avg. Esc. ('06-10)**	**Red (<Sgen1)**	**Amber (<Smsy)**	**Green (>=Smsy)**	**Avg. ER ('06-10)**	**Avg. Uopt**	**Prob. OverExp.**	**Avg.Esc /So**	**Avg. ER /Uopt**
Nass-Skeena_Estuary_Even	724,059	0.08	0.92	0.00	0.11	0.53	0.00	0.26	0.21
Middle-Upper_Skeena_Even	162,369	1.00	0.00	0.00	0.20	0.50	0.00	0.11	0.41
Nass-Skeena_Estuary_Odd	451,194	0.01	0.12	0.86	0.27	0.42	0.01	0.59	0.63
Lower_Skeena_Odd	1,620,664	0.01	0.19	0.80	0.27	0.57	0.00	0.46	0.48
Middle_Upper_Skeena_Odd	2,058,957	0.00	0.07	0.92	0.27	0.54	0.00	0.63	0.50

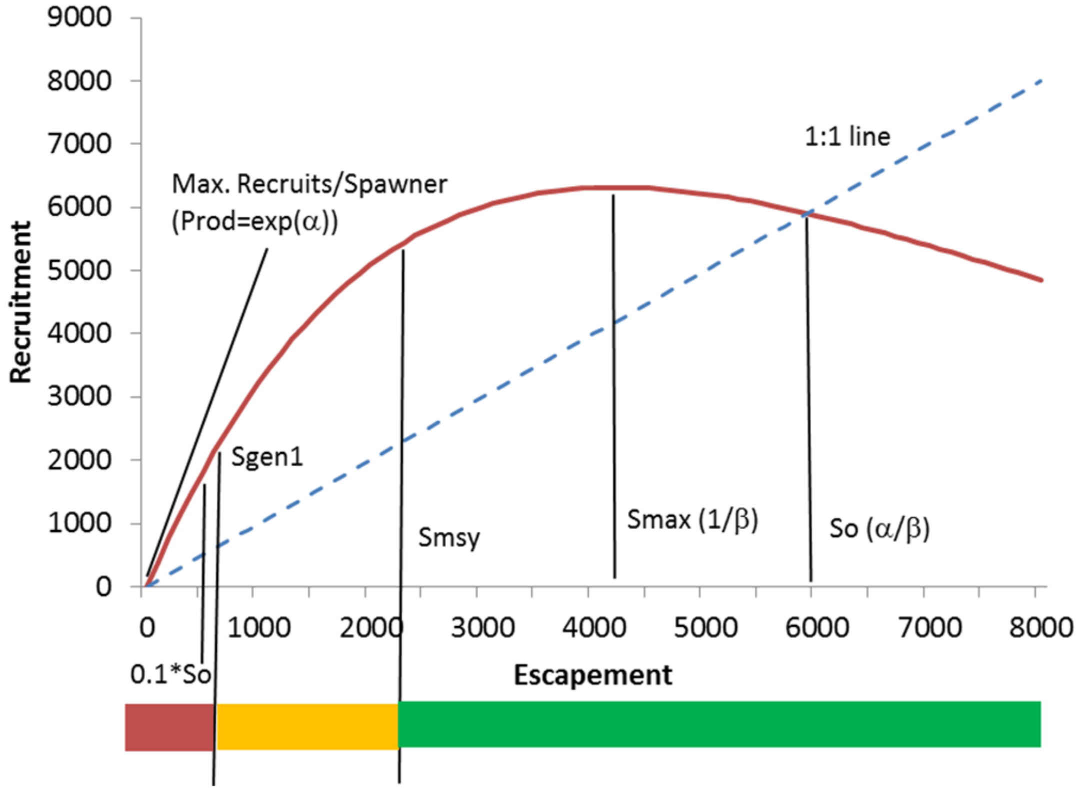

Figure 1. An example of a stock-recruitment relationship showing the abundance-based benchmarks (Sgen1 and 0.1*So) for lower benchmark boundaries, Smsy and Smax for upper benchmark boundaries) used in this study as well as the estimate of maximum recruits/spawner (Prod) that is used to compute the exploitation rate which optimizes yield. Stock productivity is the maximum ratio of recruits (R) to spawners (S) and is the initial slope of the stock-recruitment curve (the Max R/S tangent line). Smsy and Smax are the escapements that maximize catch and recruitment, respectively. So is the equilibrium abundance where escapement equals recruitment. Note that maximum catch occurs at the escapement (Smsy) where the difference between the stock-recruit curve and the 1:1 replacement line is maximized. Sgen1 is the escapement needed to recover to Smsy in one generation respectively. The colored status bar is defined based on escapement relative to Sgen1 and Smsy (red<Sgen1, yellow Sgen1<= and <=Smsy, green > Smsy).

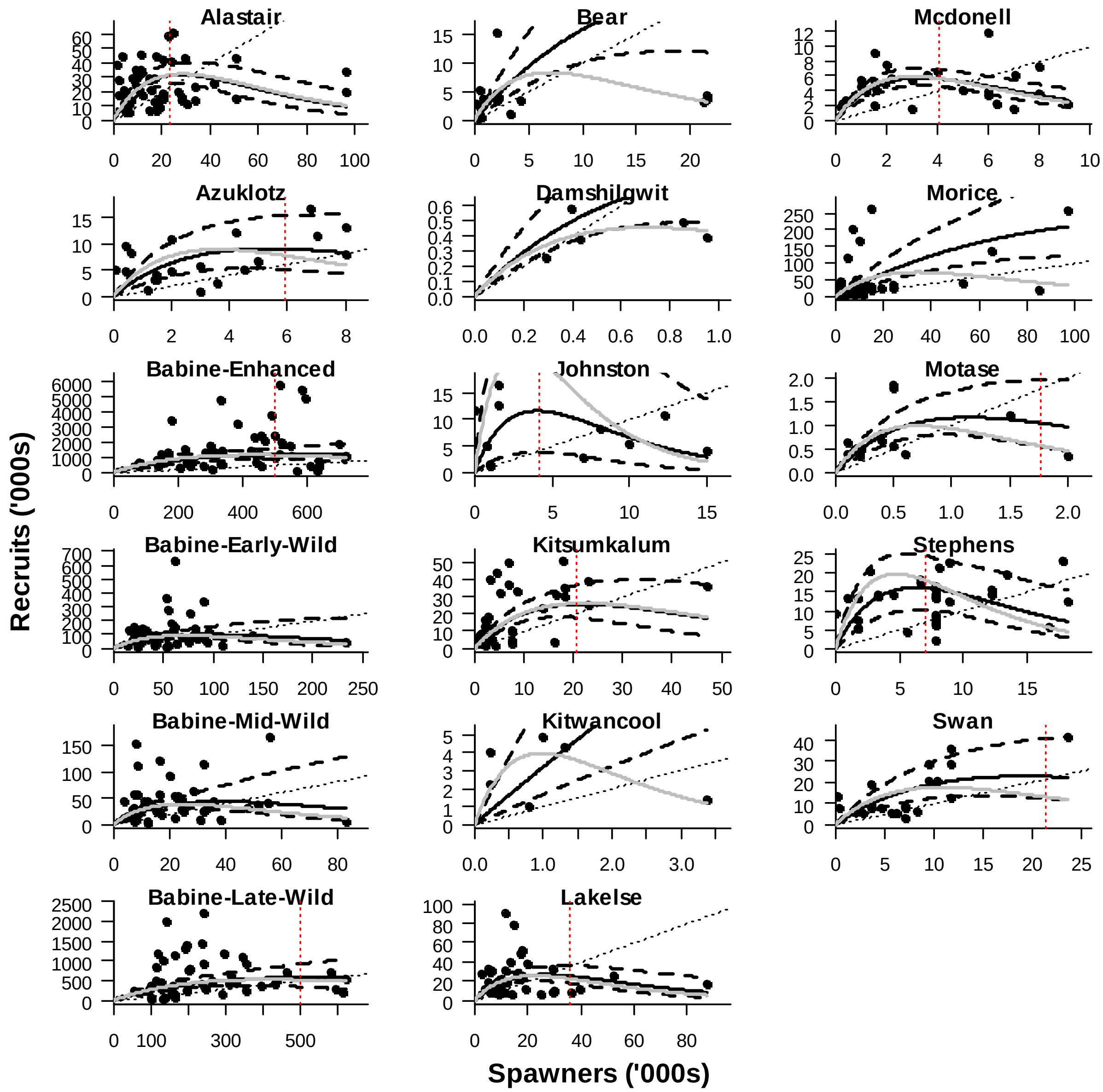

Figure SX.1. Stock-recruit relationships for lake sockeye salmon CUs in the Skeena watershed. The thick black solid and dashed lines denote the expected relationship and 95% confidence limits from the hierarchical Bayesian Model. The solid gray lines show independent estimate of the relationship based on linear regression (and no effect of the prior on Smax). The thin dashed line represents a 1:1 relationship (replacement), and the vertical dashed red line denotes the mean for the prior on the escapement that maximizes recruitment from the PR model (see Table SX.1). This latter line is not visible for some CUs because the PR estimate is greater than the maximum escapement recorded and therefore off the x-axis scale. A CV of 0.3 for the prior on Smax was used to generate these results (except for Babine CUs, where an uninformative prior was used).

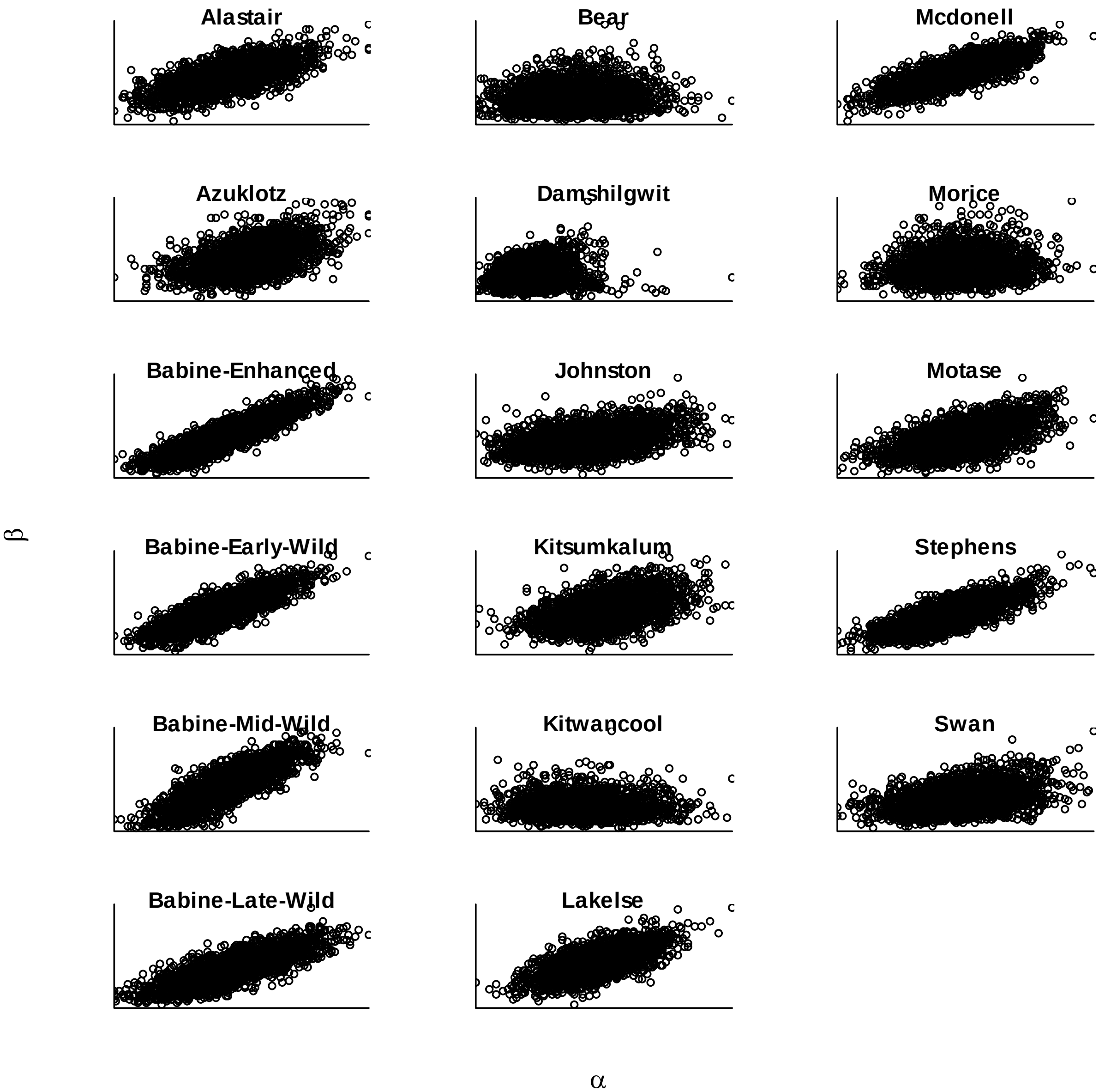

Figure SX.2. Scatter plots showing samples of Ricker α and β parameters for Skeena lake sockeye salmon CUs from posterior distributions generated from the hierarchical Bayesian model.

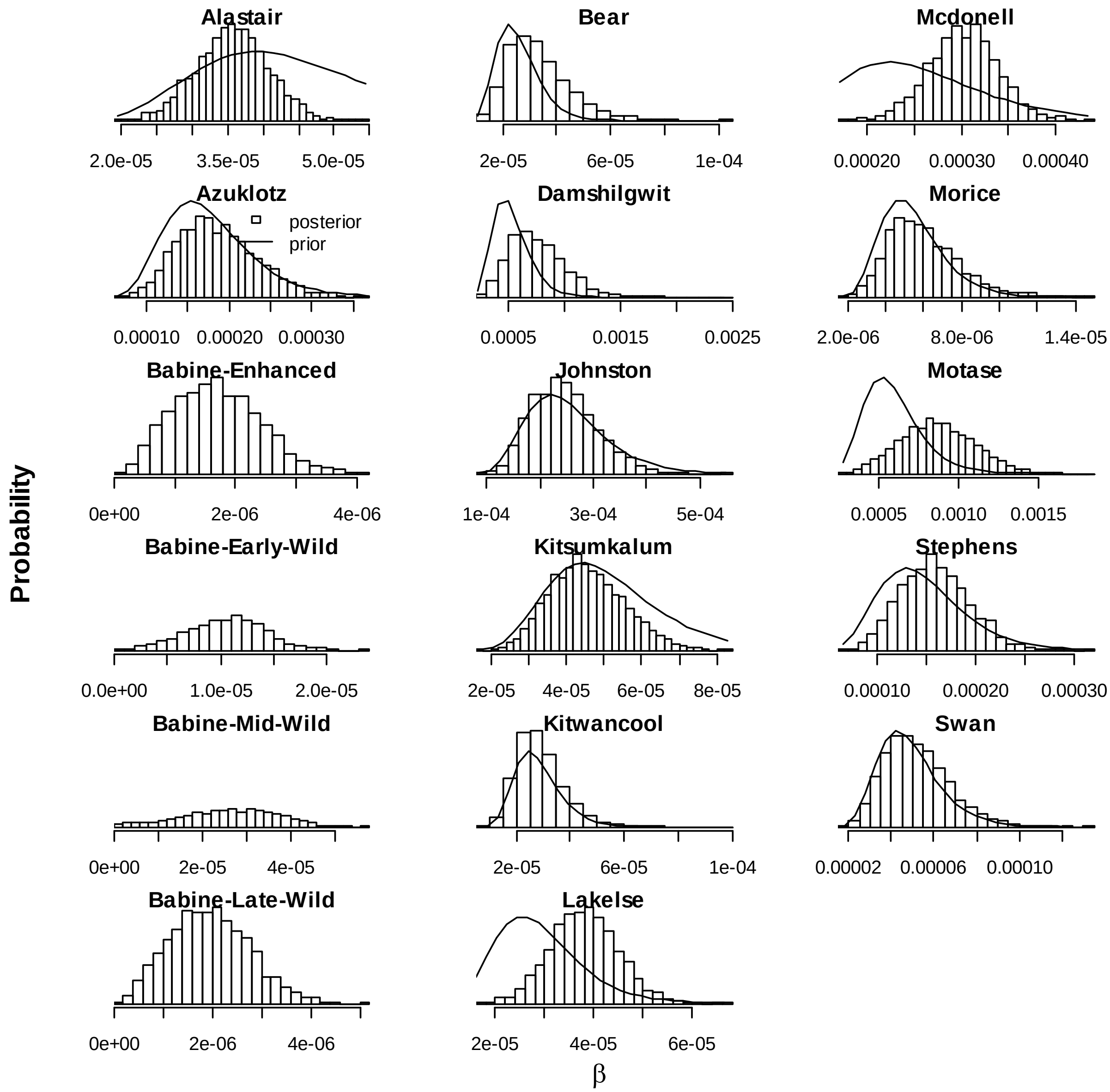

Figure SX.3. Comparison of the posterior distributions of the Ricker β parameter from the hierarchical Bayesian model (bars) with the prior distribution on Smax (converted to β) from the photosynthetic rate model (lines).

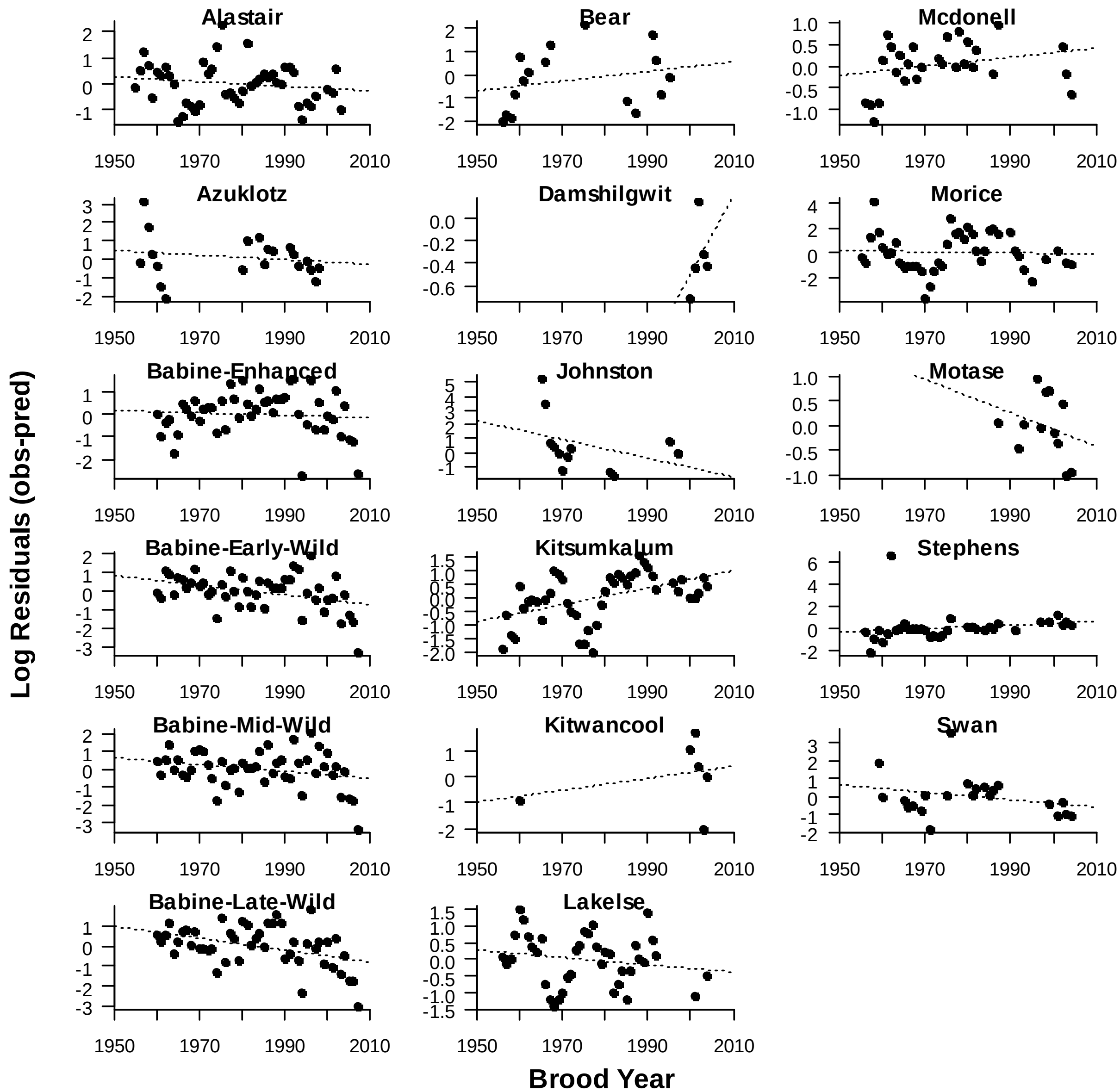

Figure SX.4. Residuals of recruitment from the mean stock-recruit curves from the HBM by brood year for lake sockeye salmon CUs in the Skeena watershed. The dashed line shows the trend in residuals over time. A declining slope indicates that the model is underpredicting recruitment in early years and overpredicting it in later ones, potentially indicative of a declining trend in productivity.

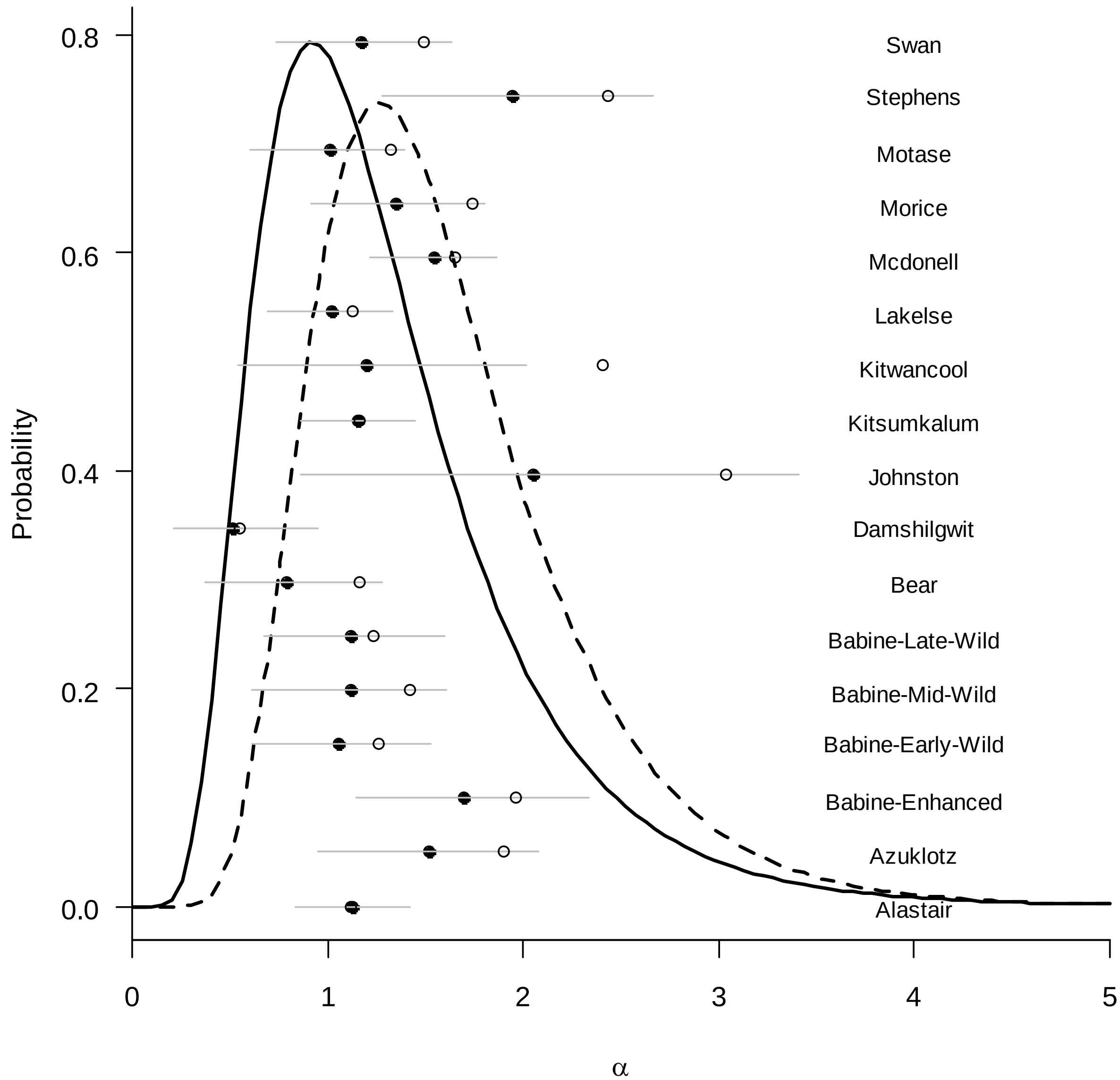

Figure SX.5. CU-specific mean estimates of the Ricker α parameter from the hierarchical Bayesian model (filled circles) and 95% credible intervals (horizontal lines) compared to independent estimates generated by linear regression (open circles) for lake sockeye salmon CUs. Note estimates of α_i from the linear regression method do not include the effects of the prior on Smax. Also shown are the mean hyper-distribution of α from the HBM (thick lognormal-shaped solid line) and a lognormal distribution estimated from linear independent estimates (thick dashed line).

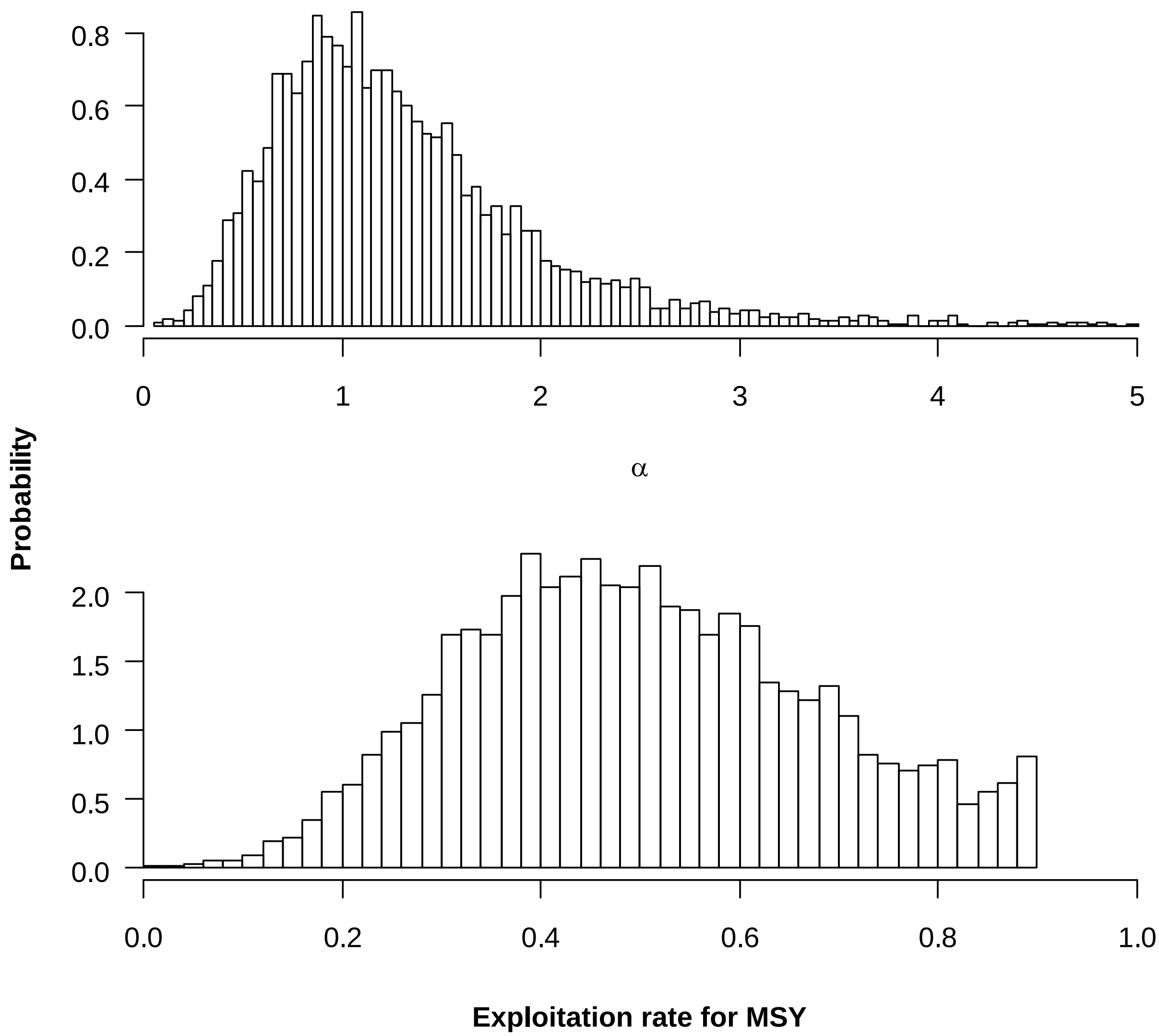

Figure SX.6. The distribution of Ricker α values (top) and associated optimal exploitation rates (bottom) for lake sockeye salmon CUs based on samples of α drawn from α hyper-distributions determined from the posterior distributions of μ_α and σ_α.

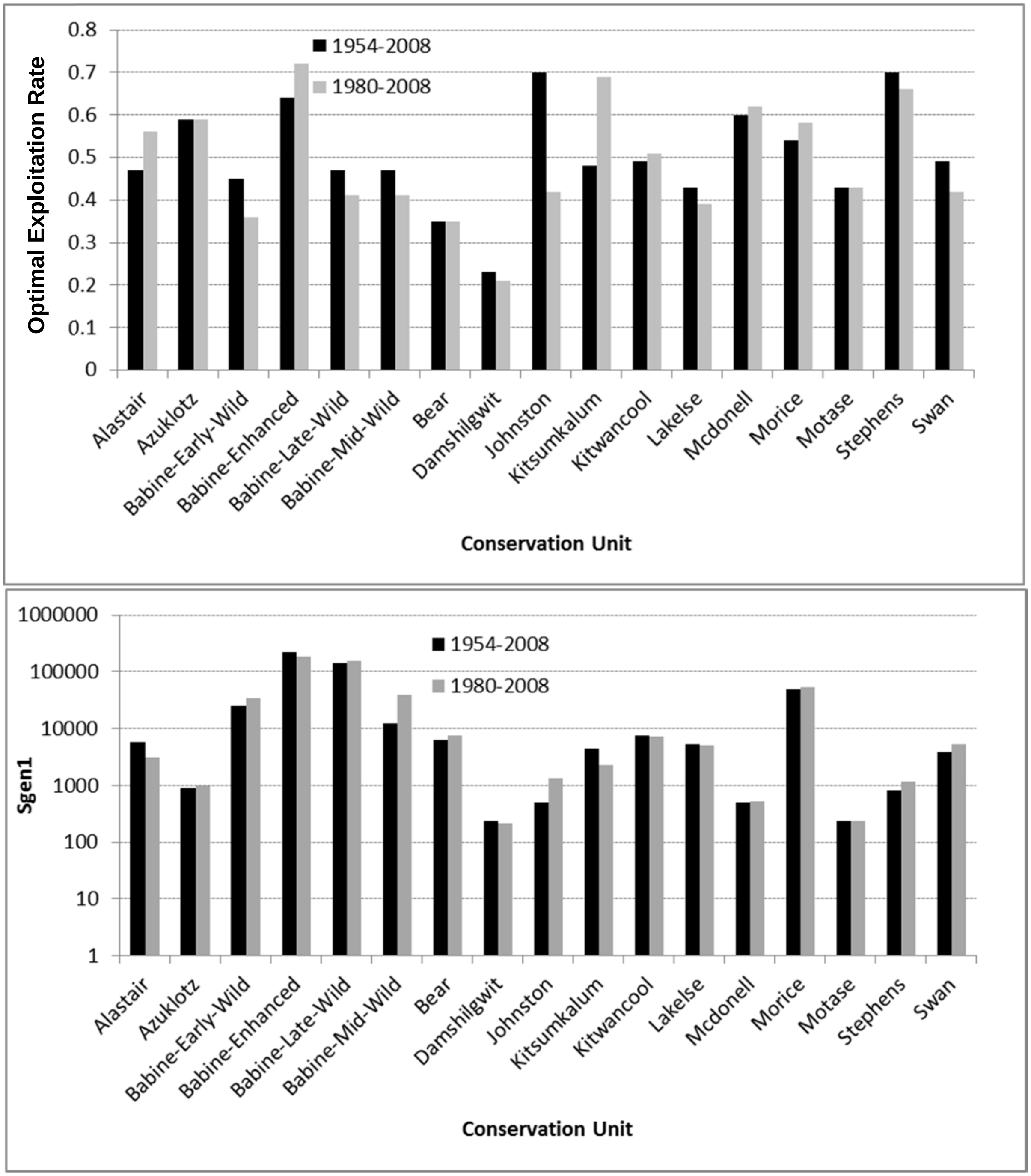

Figure SX.7. Comparison of two benchmarks computed using all available stock-recruitment data (from 1954-2008 brood years) with those computed using a subset of data (from 1980-2008 brood years) where escapement and catch estimates may have been more reliable for lake sockeye salmon CUs. Plots show the exploitation rate which maximizes yield (top, Uopt) and the escapement required to recover to Smsy in one generation (bottom, Sgen1).

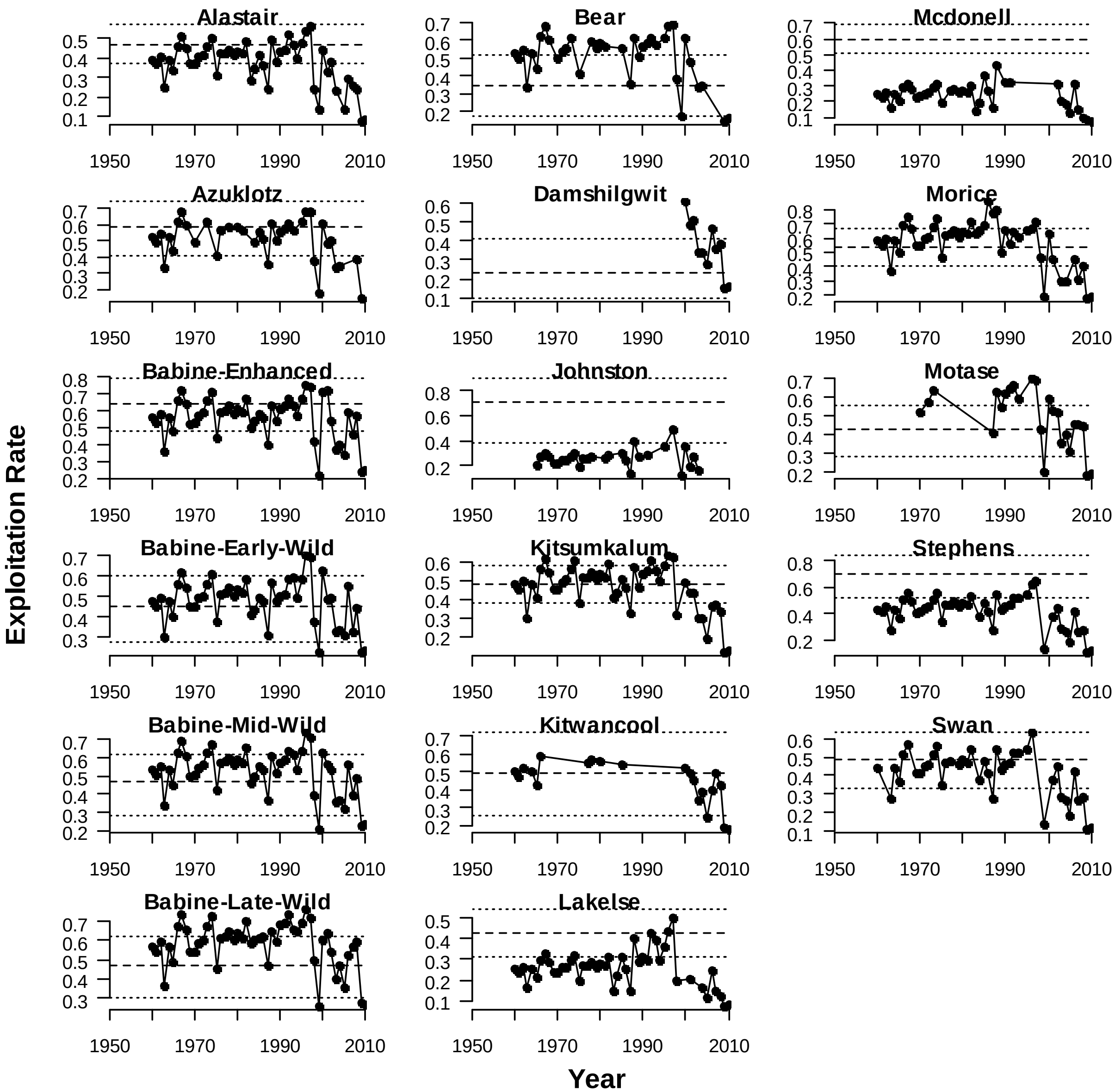

Figure SX.8. The historical exploitation rate for lake sockeye salmon CUs in the Skeena relative to the mean estimate of the optimal exploitation rate (dashed horizontal line) and the 95% credible intervals of that optimal rate (finely dashed horizontal lines).

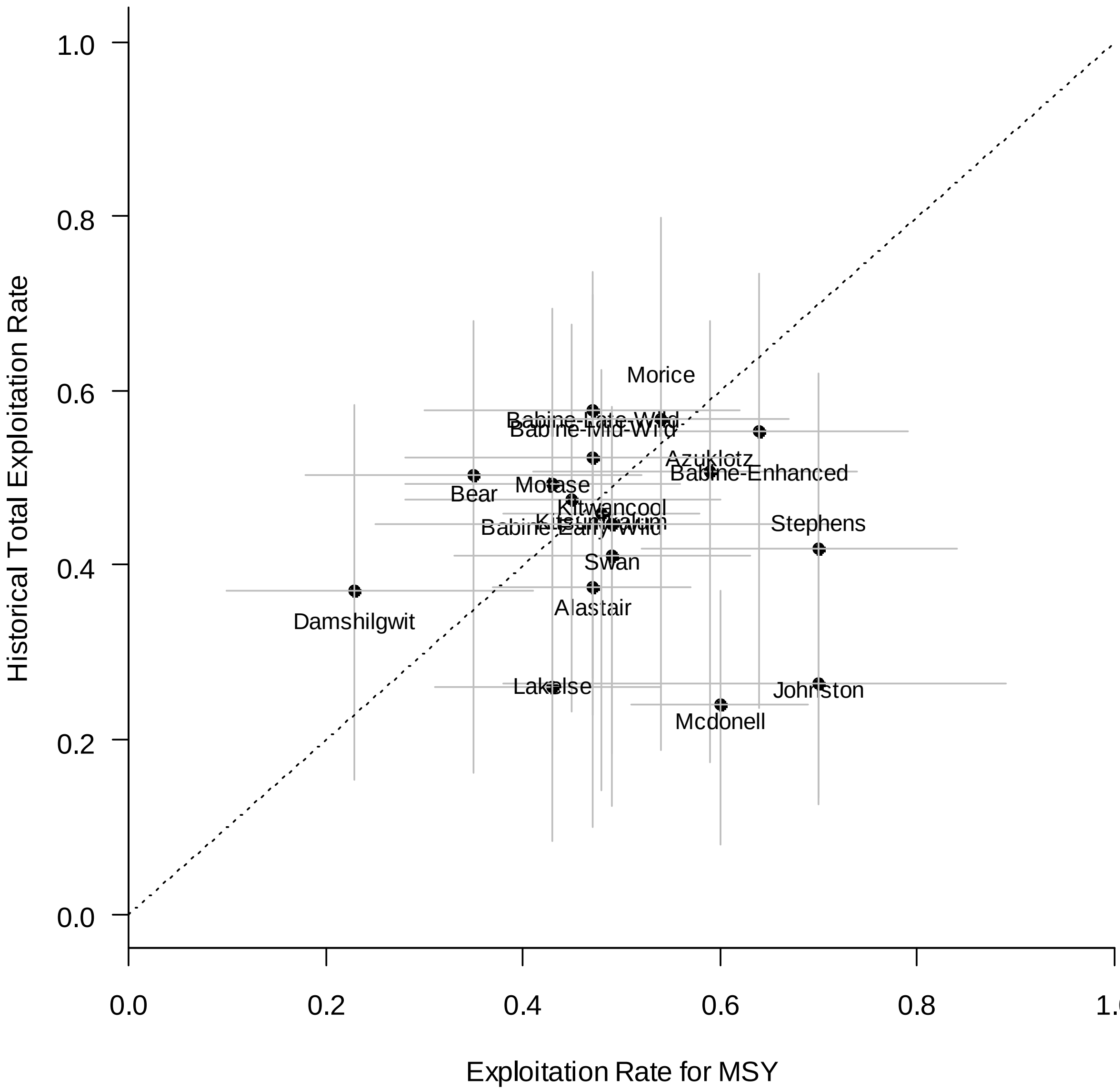

Figure SX.9. Comparison of the historical average (points) and the 95% quantile (vertical gray bars) of the total exploitation rate over the period of record (brood years1954-2008) relative to the estimated optimal rate to produce the maximum sustainable yield estimate from the HBM (Uopt). Points and horizontal lines denote the mean estimate of Uopt and the 95% credible interval. Points below the 1:1 line indicate that the historical average exploitation rate is less than the optimal rate, indicating the CU has been under exploited relative to MSY.

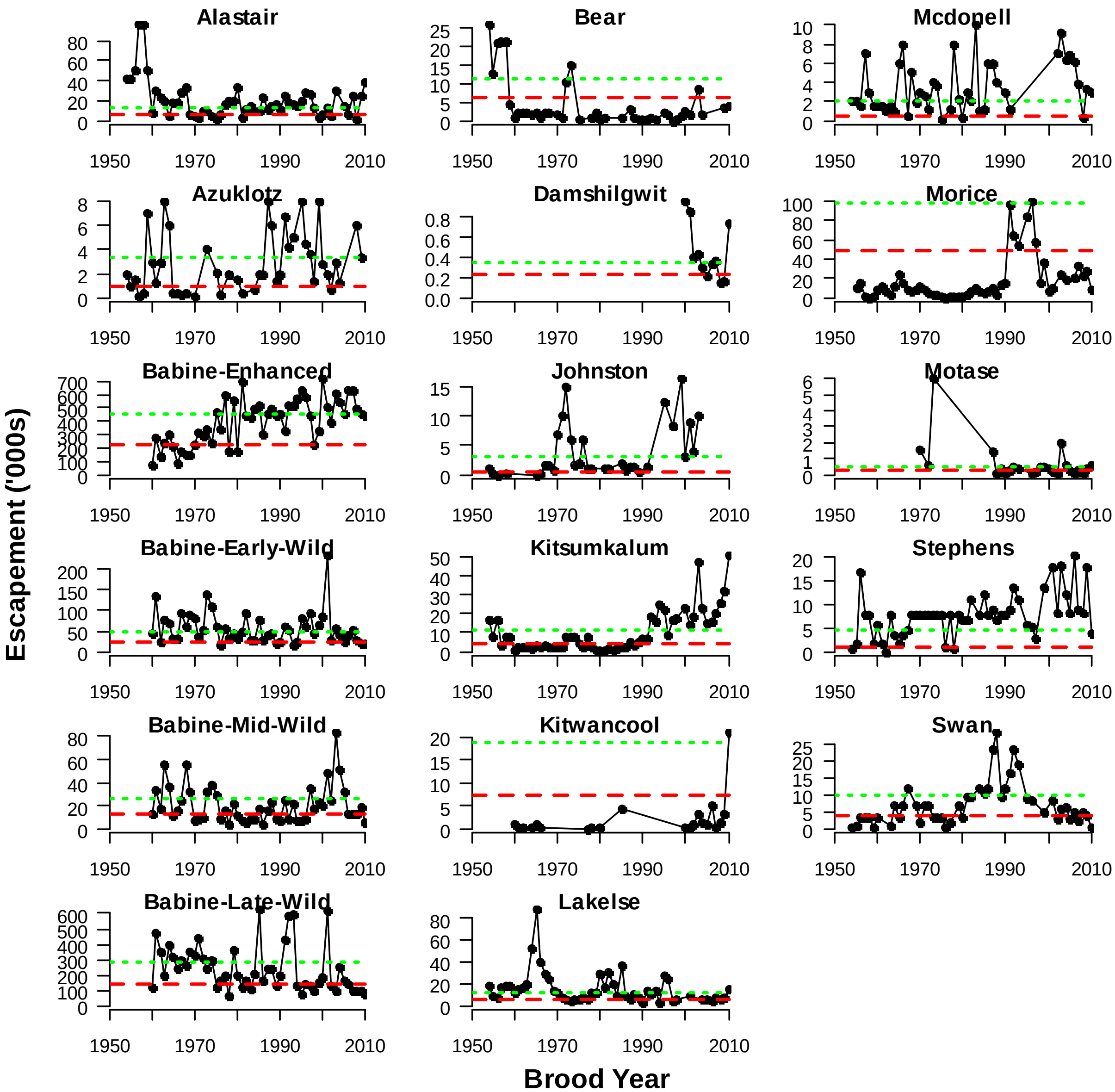

Figure SX.10. Time series of escapement estimates for lake sockeye salmon CU's in the Skeena watershed. These plots show the entire available time series, including a limited number of points which do not have complete recruitment pairs (by brood year) that would be omitted from the stock-recruit analysis. Dashed red lines and dotted green lines denote the estimated lower (Sgen1) and upper (Smsy) benchmarks generated from the hierarchical Bayesian model, respectively.

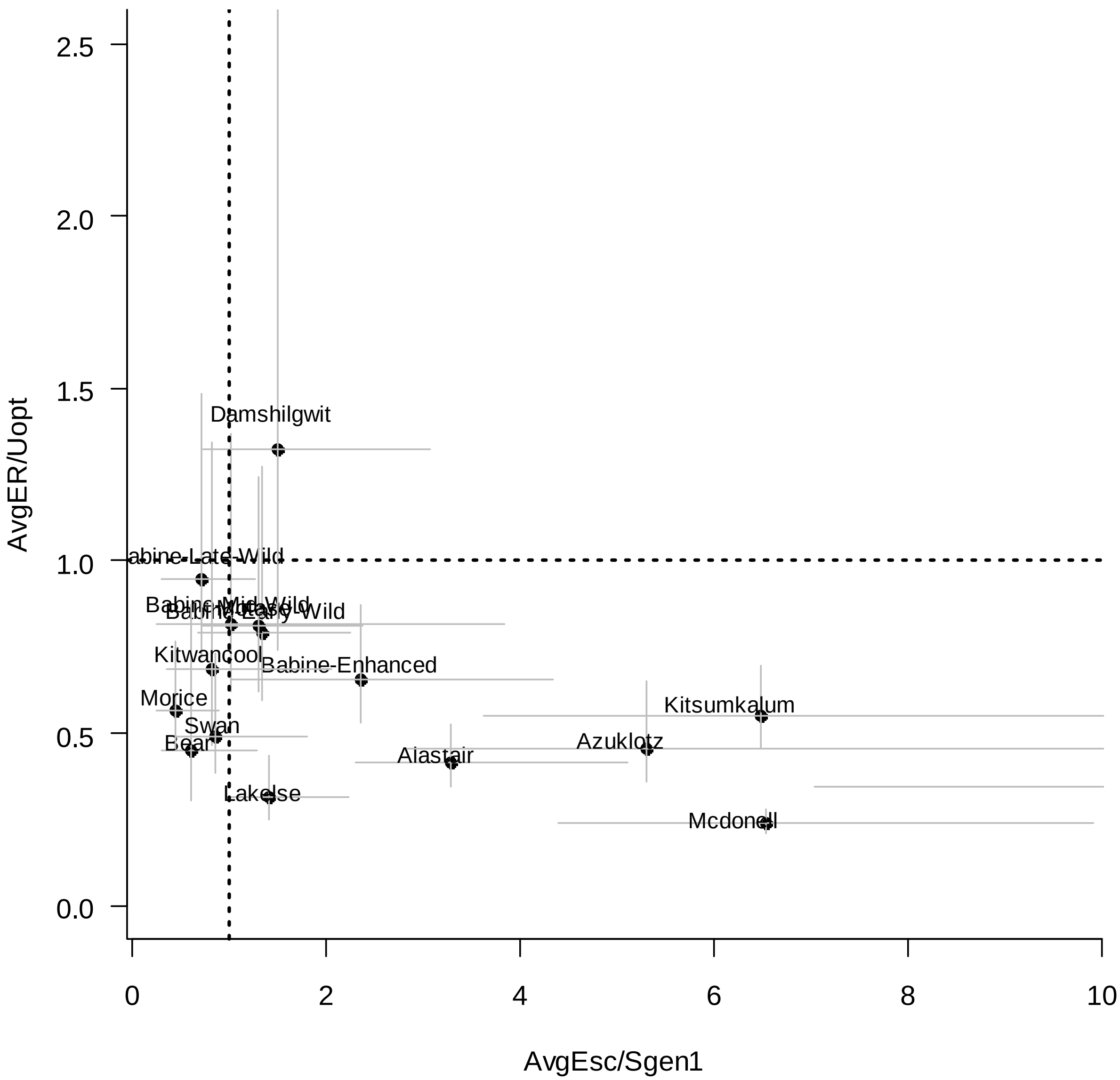

Figure SX.11. Status of lake sockeye salmon CUs in the Skeena based on the average escapement and exploitation rate between 2006 and 2010 data relative to abundance and exploitation benchmarks. The x-axis is the ratio of the average escapement relative to the lower benchmark (Sgen1). CUs with ratios less than one would be in the red status zone. The y-axis is the ratio of the average exploitation rate relative to the rate which maximizes yield (Uopt). CUs with ratios greater than one would be considered overfished. The solid points are the expected ratio and the gray lines represent the 95% credible intervals. The Johnston CU is not shown as there are no escapements or exploitation rate estimates over the 2006-2010 period.

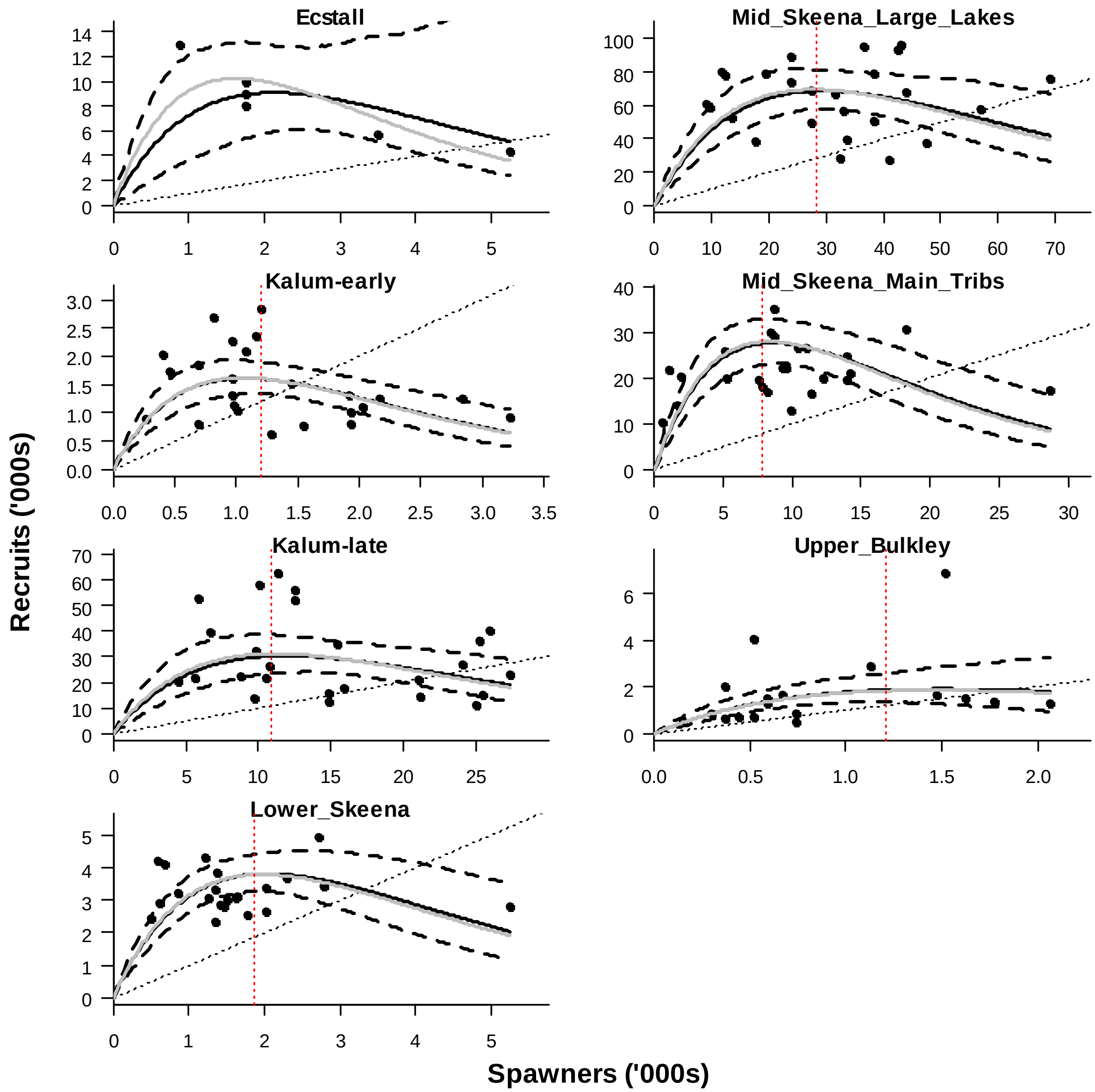

Figure CN.1. Stock-recruit relationships for Chinook salmon CUs in the Skeena watershed. The thick black solid and dashed lines denote the expected relationship and 95% confidence limits from the hierarchical Bayesian model. The solid gray lines show independent estimate of the relationship based on linear regression (and no effect of the prior on Smax). The thin dashed line represents a 1:1 relationship (replacement), and the vertical dashed red line denotes the mean for the prior on the escapement that maximizes recruitment (see Table CN.1). Uninformative priors (CVs of 10 or 1) for Smax was used to generate these results.

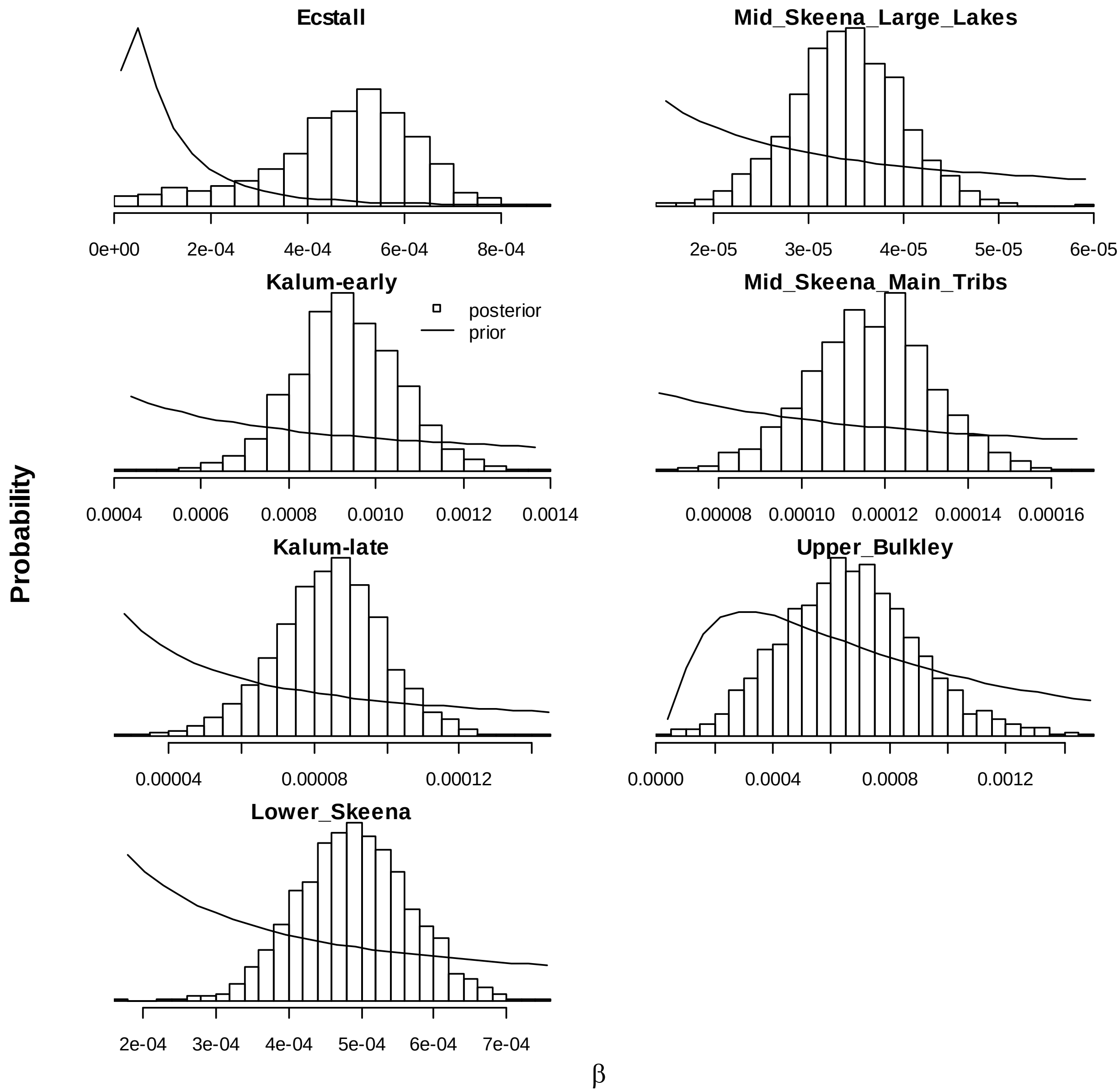

Figure CN.2. Comparison of the posterior distributions of the Ricker β parameter for Chinook salmon CUs from the hierarchical Bayesian model (bars) with the prior distribution on Smax (converted to β, lines).

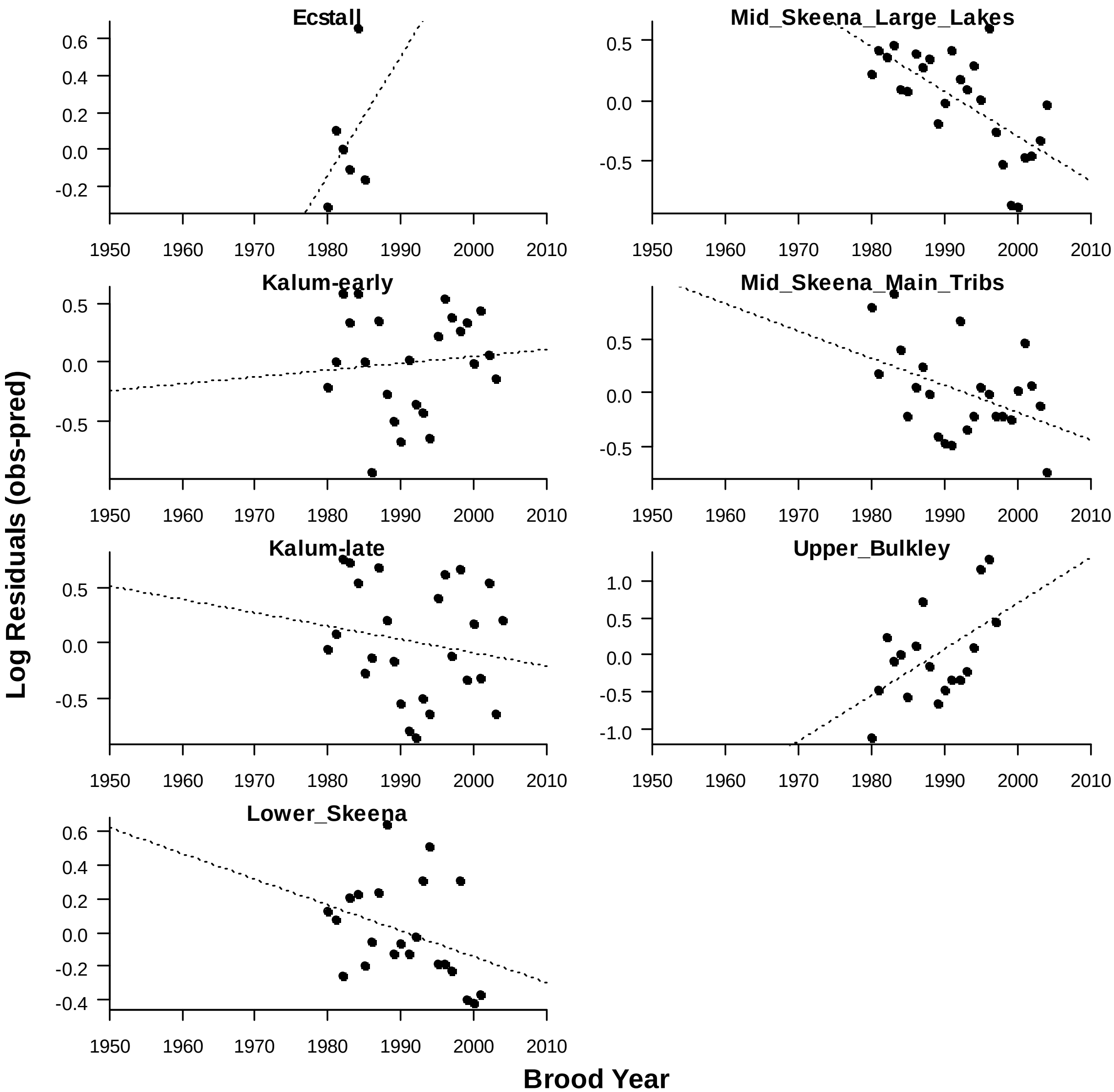

Figure CN.3. Residuals of recruitment from the mean stock-recruit curves from the HBM by brood year for Chinook salmon CUs in the Skeena watershed. The dashed line shows the trend in residuals over time. A declining slope indicates that the model is underpredicting recruitment in early years and overpredicting it in later ones, potentially indicative of a declining trend in productivity.

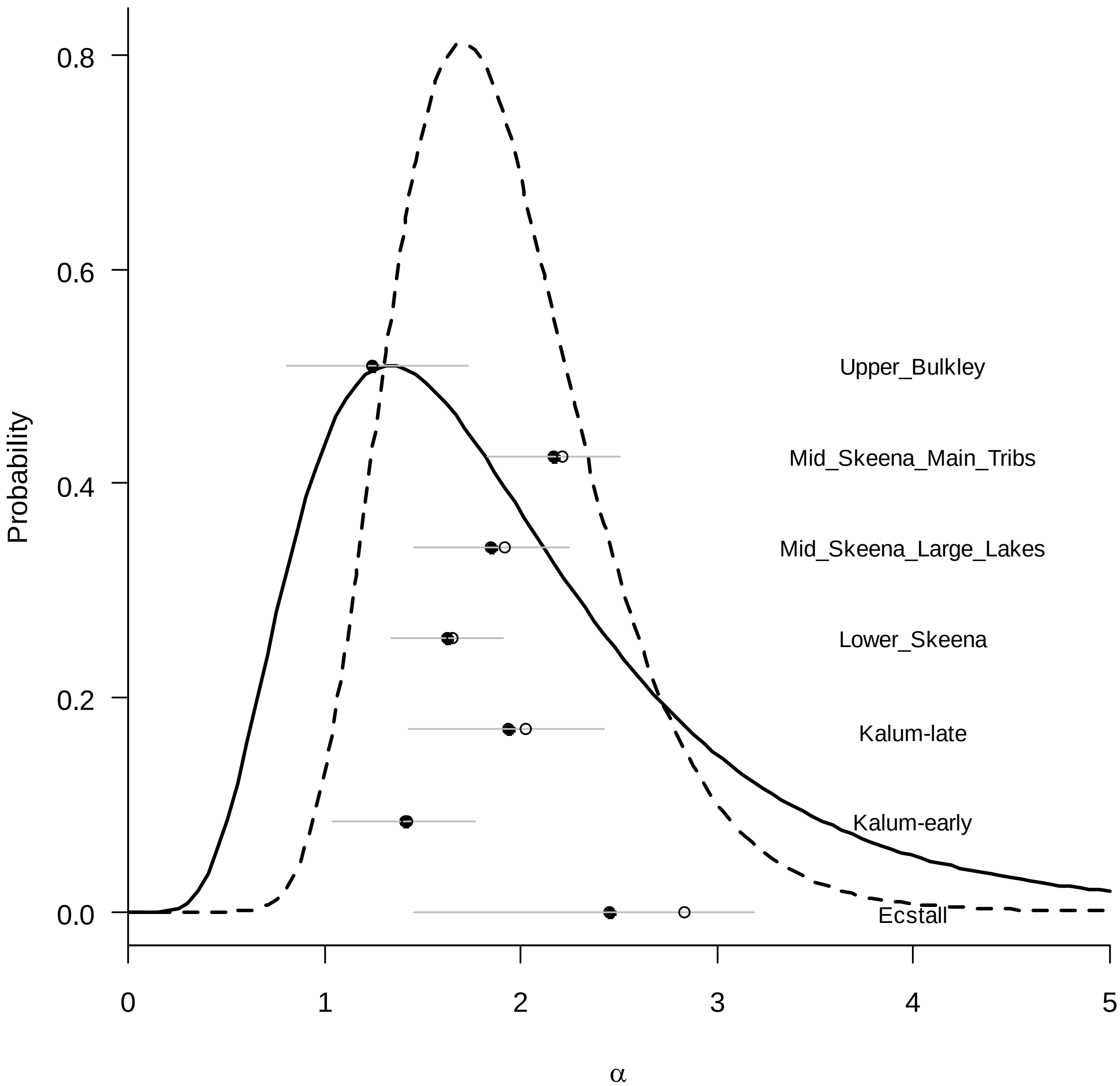

Figure CN.4. CU-specific mean estimates of the Ricker α parameter for Chinook salmon CUs from the hierarchical Bayesian model (filled circles) and 95% credible intervals (horizontal lines) compared to independent estimates generated by linear regression (open circles). Note estimates of α_i from the linear regression method do not include the effects of the prior on Smax. Also shown are the mean hyper-distribution of α from the HBM (thick lognormal-shaped solid line) and a lognormal distribution estimated from linear independent estimates (thick dashed line).

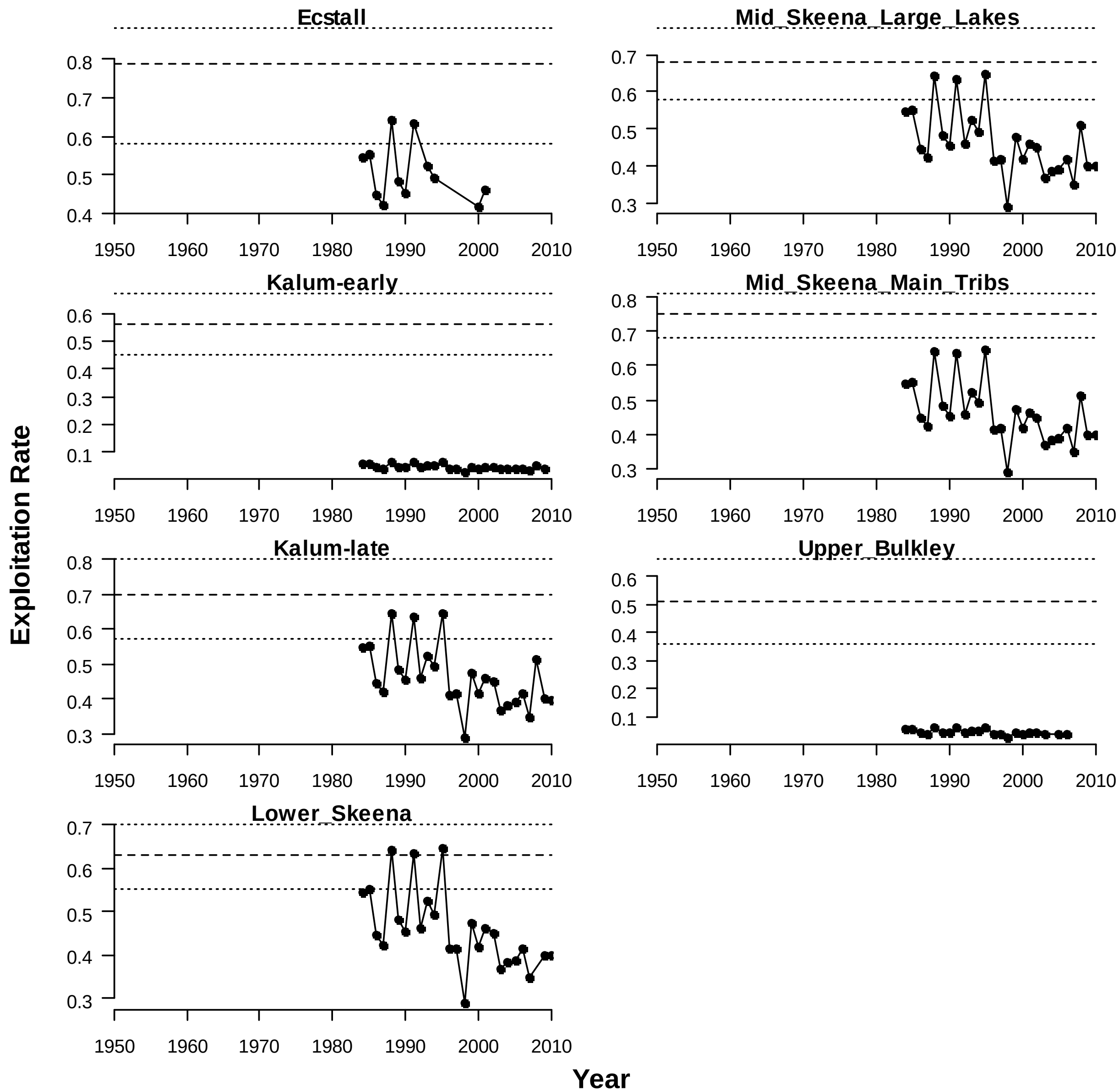

Figure CN.5. The historical exploitation rate for Chinook salmon CUs in the Skeena relative to the mean estimate of the optimal exploitation rate (dashed horizontal line) and the 95% credible intervals of that optimal rate (finely dashed horizontal lines).

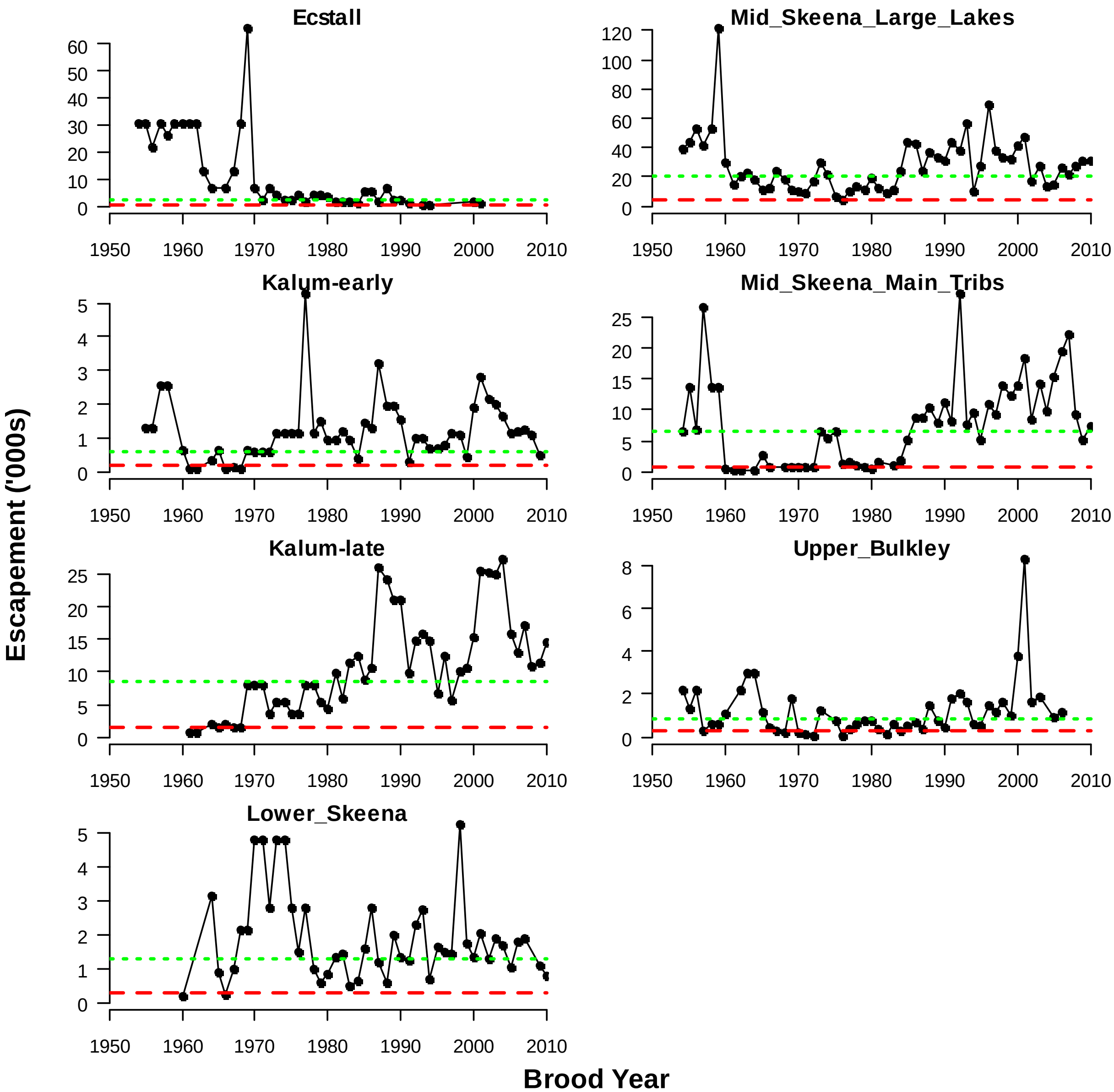

Figure CN.6. Time series of escapement estimates for Chinook salmon CUs in the Skeena watershed. These plots show the entire available time series, including a number of points which do not have complete recruitment pairs (by brood year) that would be omitted from the stock-recruit analysis. Dashed red lines and dotted green lines denote the estimated lower (Sgen1) and upper (Smsy) benchmarks generated from the hierarchical Bayesian model, respectively.

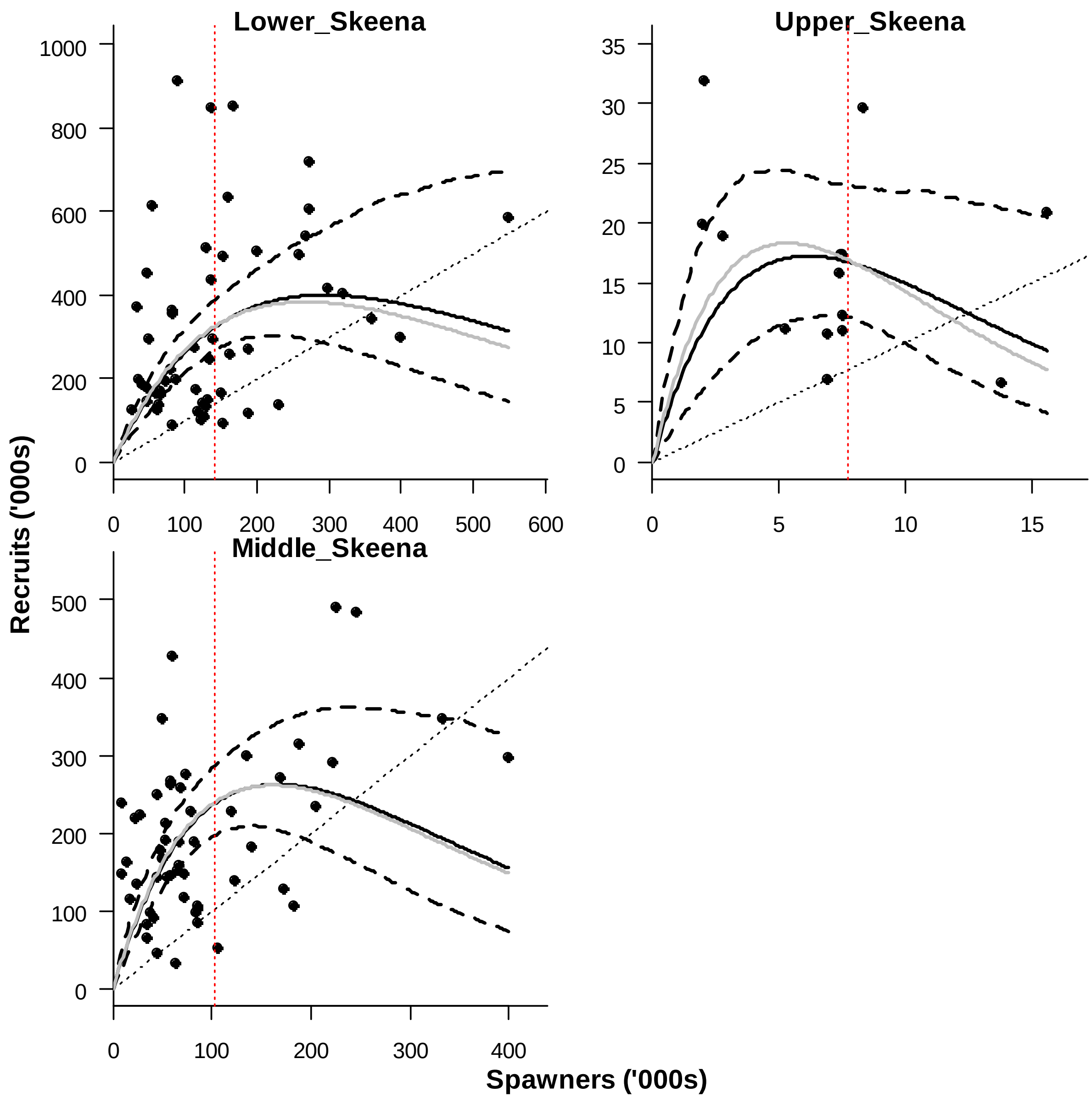

Figure CO.1. Stock-recruit relationships for coho salmon CUs in the Skeena watershed. The thick black solid and dashed lines denote the expected relationship and 95% confidence limits from the hierarchical Bayesian Model. The solid gray lines show independent estimate of the relationship based on linear regression (and no effect of the prior on Smax). The thin dashed line represents a 1:1 relationship (replacement), and the vertical dashed red line denotes the mean for the prior on the escapement that maximizes recruitment (see Table CO.1). Uninformative priors (CVs of 10) for Smax were used to generate these results.

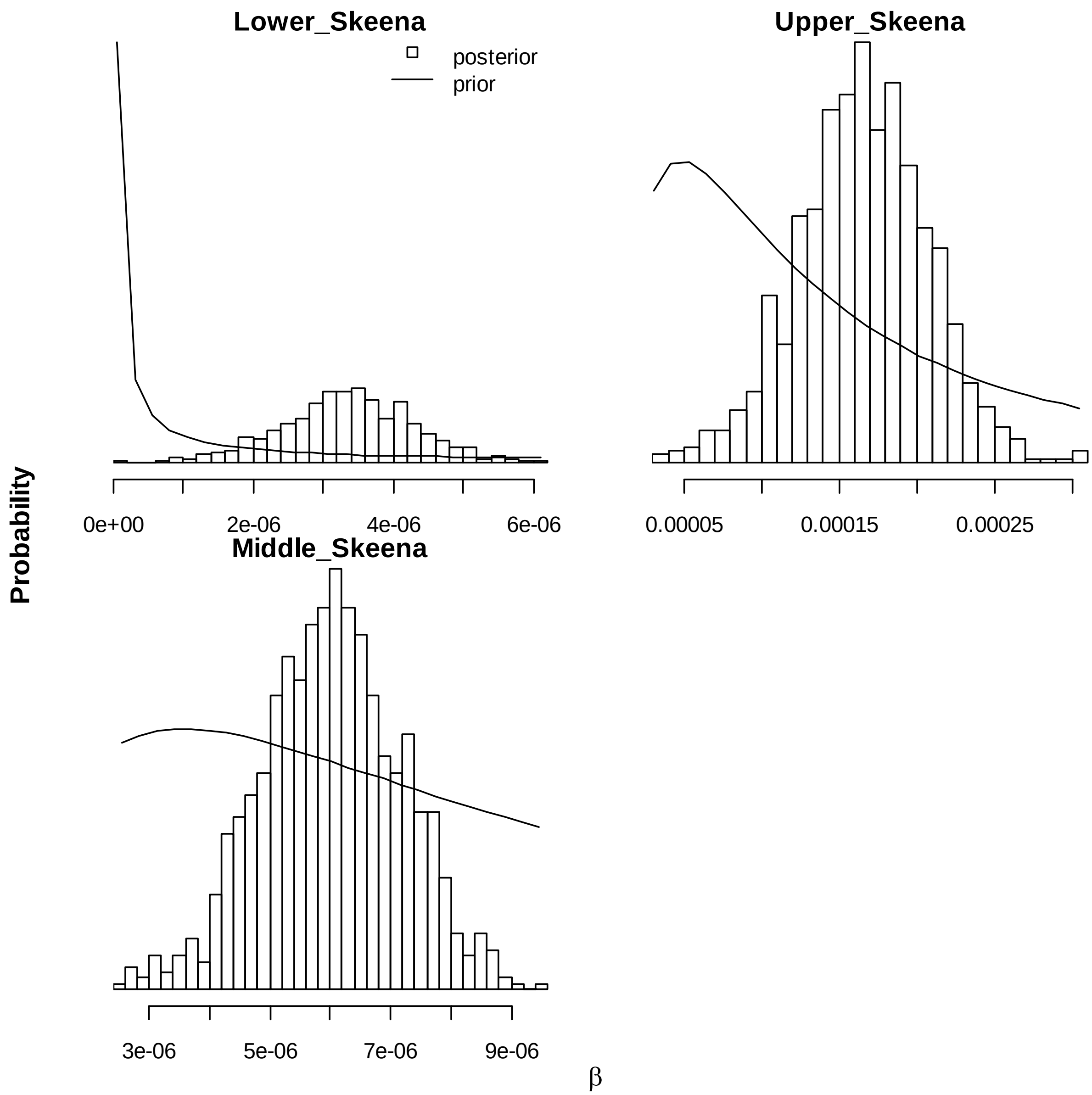

Figure CO.2. Comparison of the posterior distributions of the Ricker β parameter for coho salmon CUs from the hierarchical Bayesian model (bars) with the prior distribution on Smax (converted to β, lines).

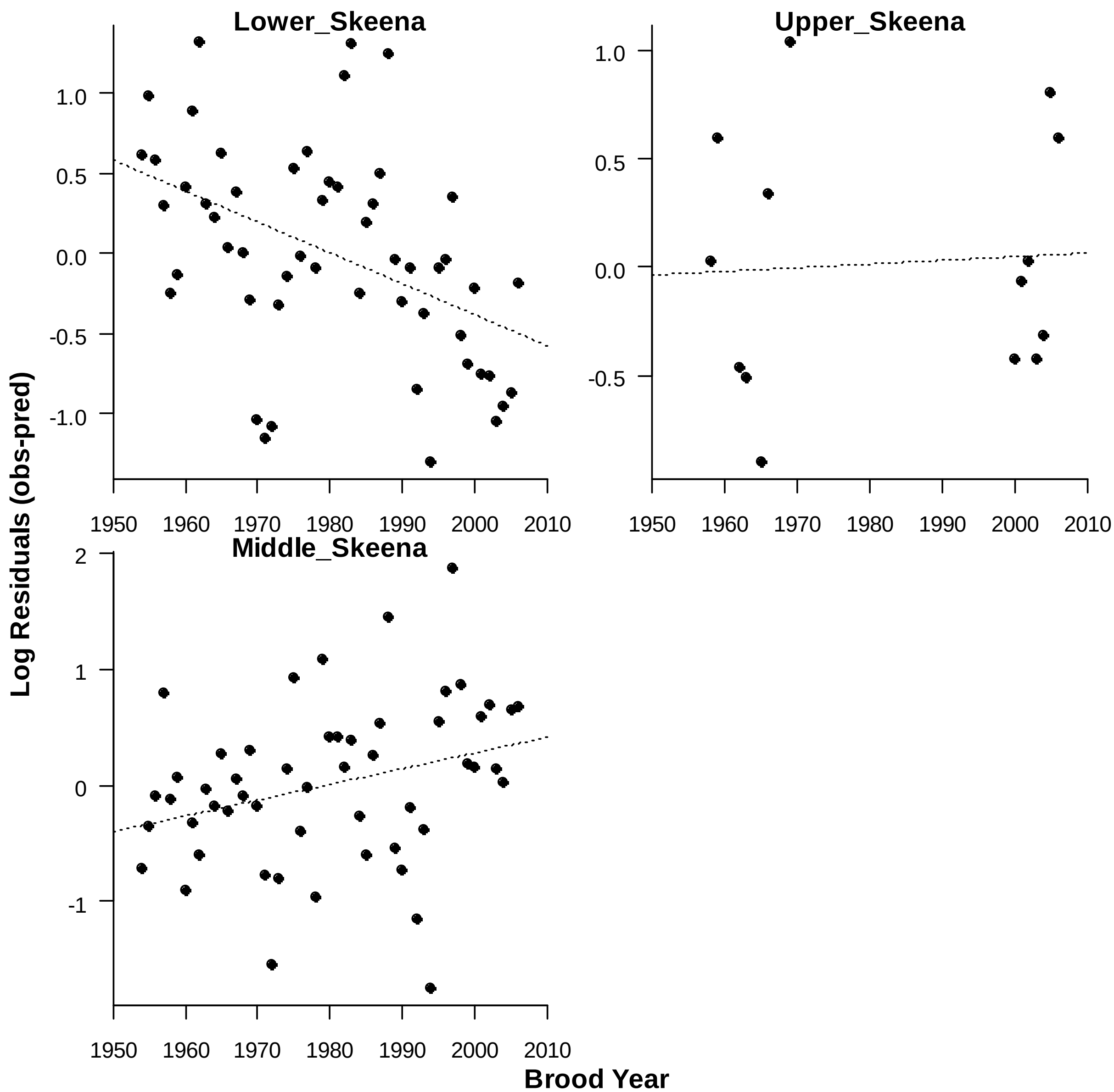

Figure CO.3. Residuals of recruitment from the mean stock-recruit curves from the HBM by brood year for coho salmon CUs in the Skeena watershed. The dashed line shows the trend in residuals over time. A declining slope indicates that the model is underpredicting recruitment in early years and overpredicting it in later ones, potentially indicative of a declining trend in productivity.

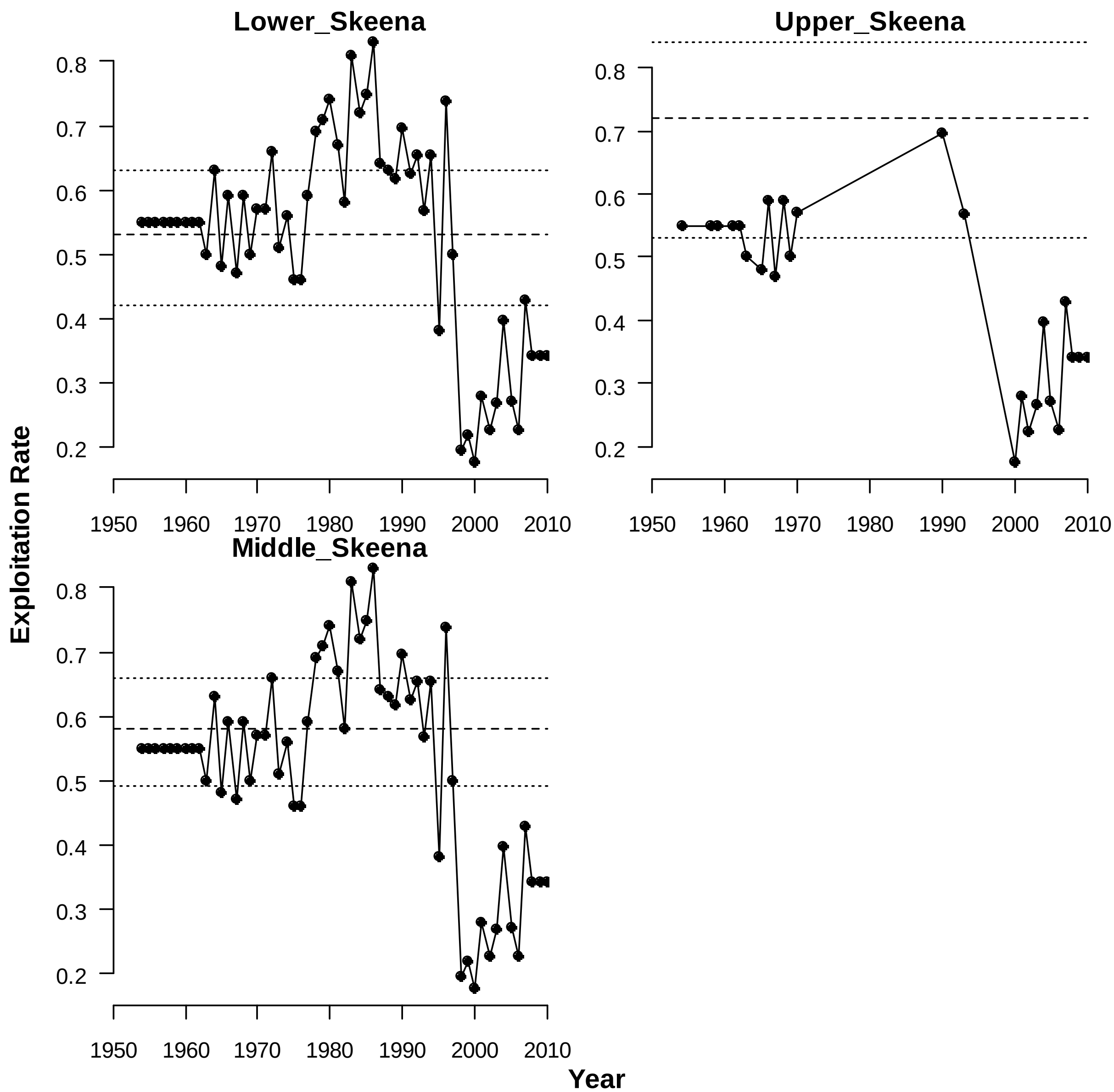

Figure CO.4. The historical exploitation rate for coho salmon CUs in the Skeena relative to the mean estimate of the optimal exploitation rate (dashed horizontal line) and the 95% credible intervals of that optimal rate (finely dashed horizontal lines).

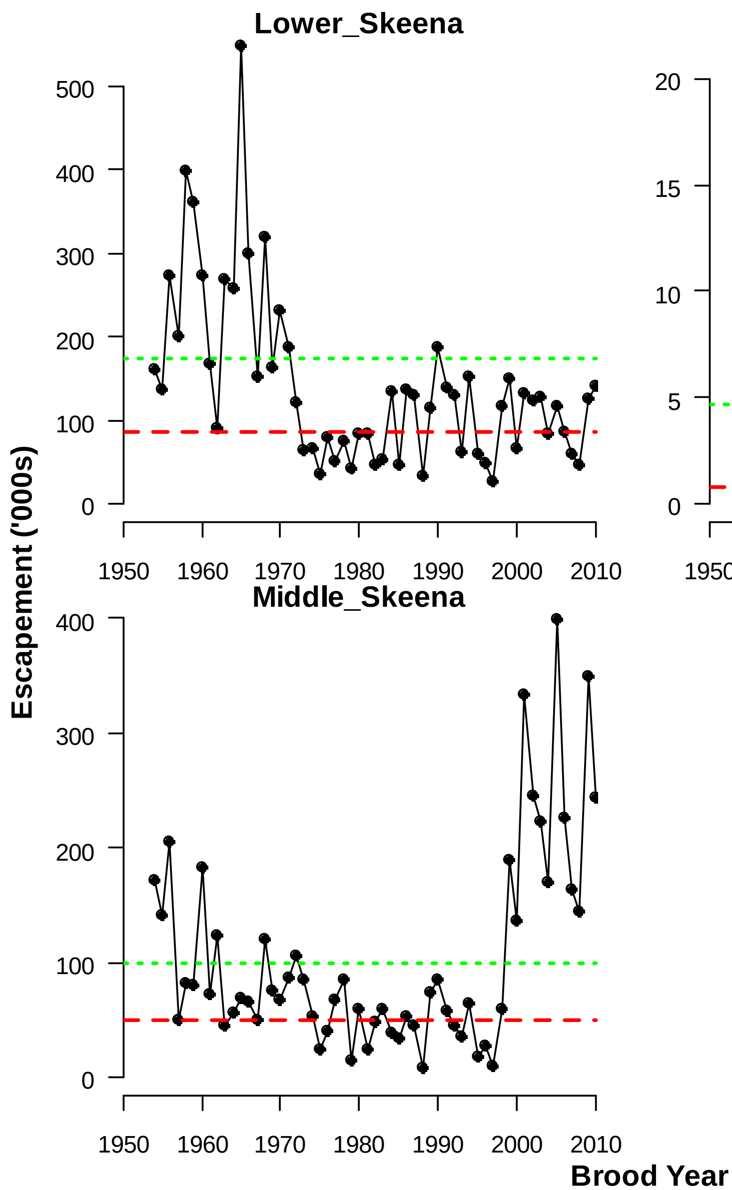

Figure CO.5. Time series of escapement estimates for coho salmon CUs in the Skeena watershed. These plots show the entire available time series, including a limited number of points which do not have complete recruitment pairs (by brood year) that would be omitted from the stock-recruit analysis. Dashed red lines and dotted green lines denote the estimated lower (Sgen1) and upper (Smsy) benchmarks generated from the hierarchical Bayesian model, respectively.

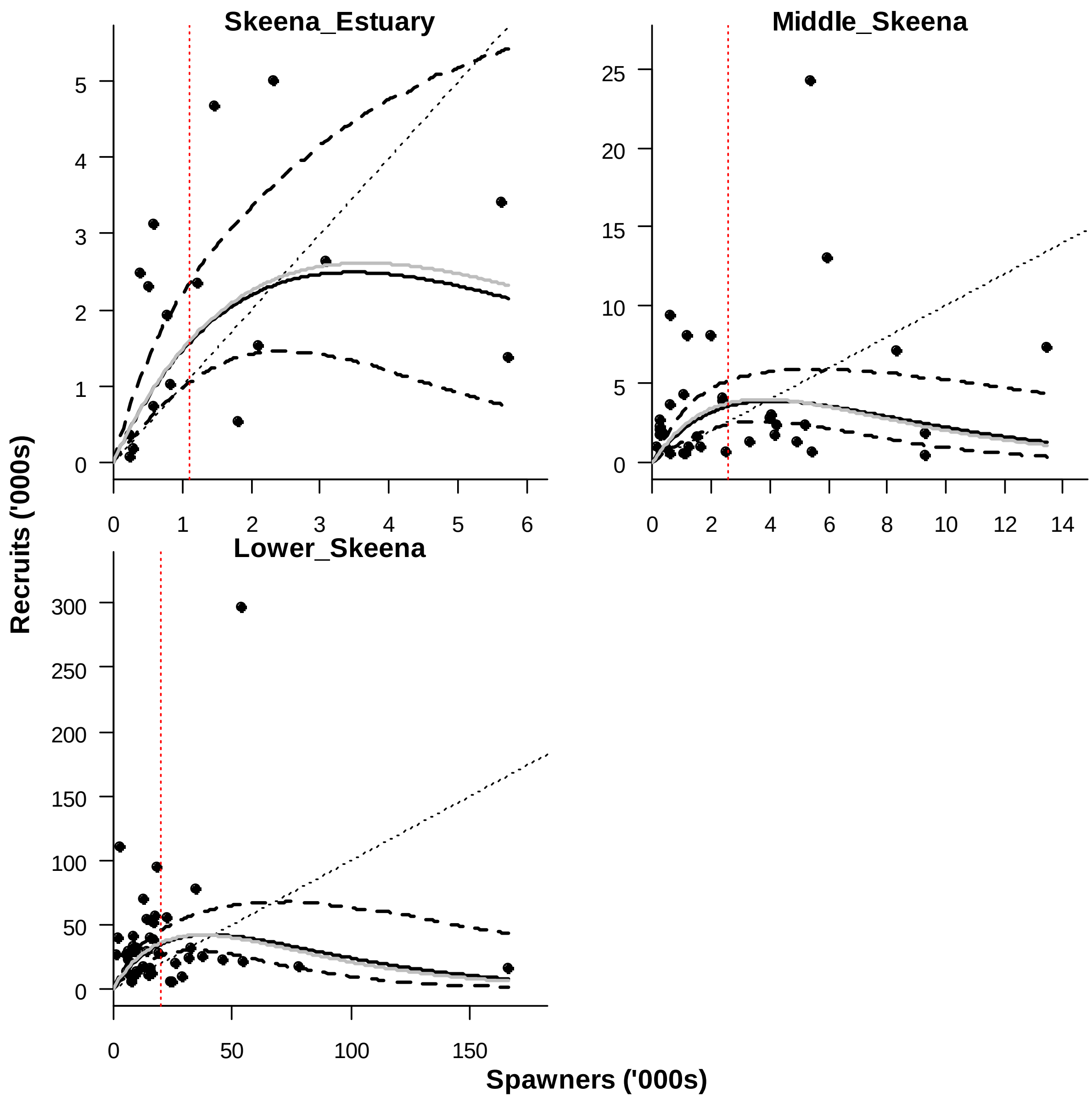

Figure CM.1. Stock-recruit relationships for chum salmon CUs in the Skeena watershed. The thick black solid and dashed lines denote the expected relationship and 95% confidence limits from the hierarchical Bayesian Model. The solid gray lines show independent estimate of the relationship based on linear regression (and no effect of the prior on Smax). The thin dashed line represents a 1:1 relationship (replacement), and the vertical dashed red line denotes the mean for the prior on the escapement that maximizes recruitment (see Table CM.1). Uninformative priors (CVs of 10 or 1) for Smax was used to generate these results.

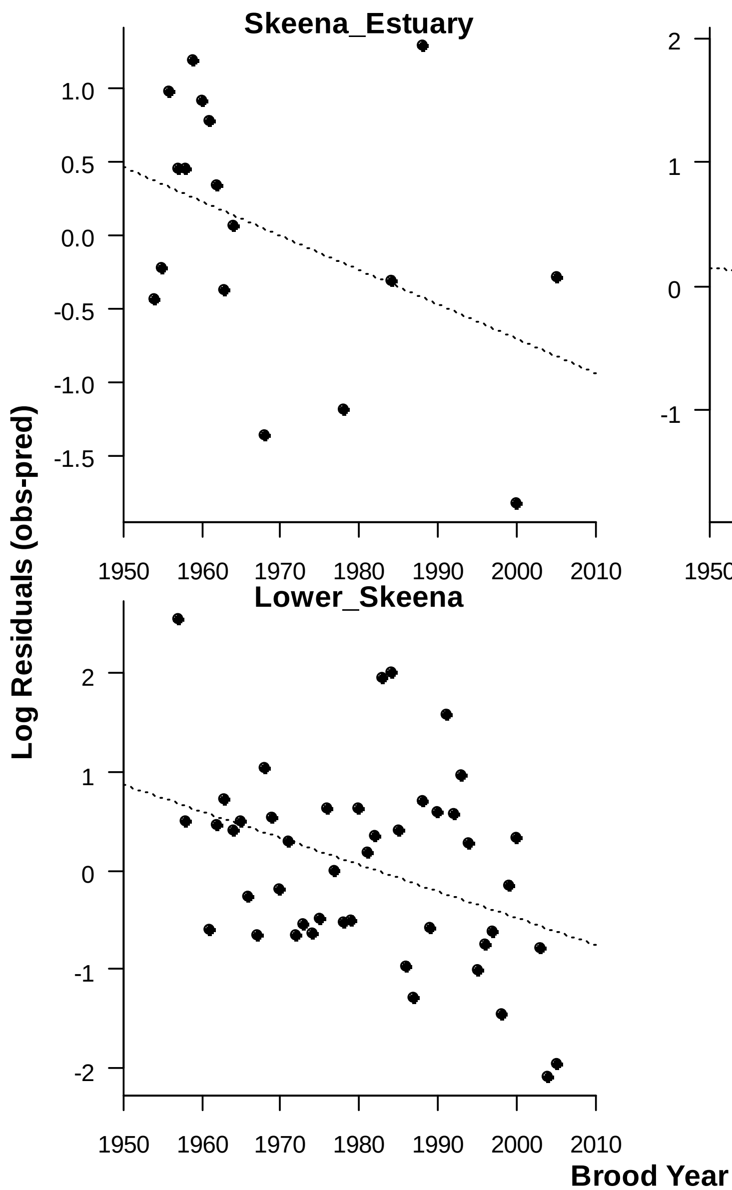

Figure CM.2. Residuals of recruitment from the mean stock-recruit curves from the HBM by brood year for chum salmon CUs in the Skeena watershed. The dashed line shows the trend in residuals over time. A declining slope indicates that the model is underpredicting recruitment in early years and overpredicting it in later ones, potentially indicative of a declining trend in productivity.

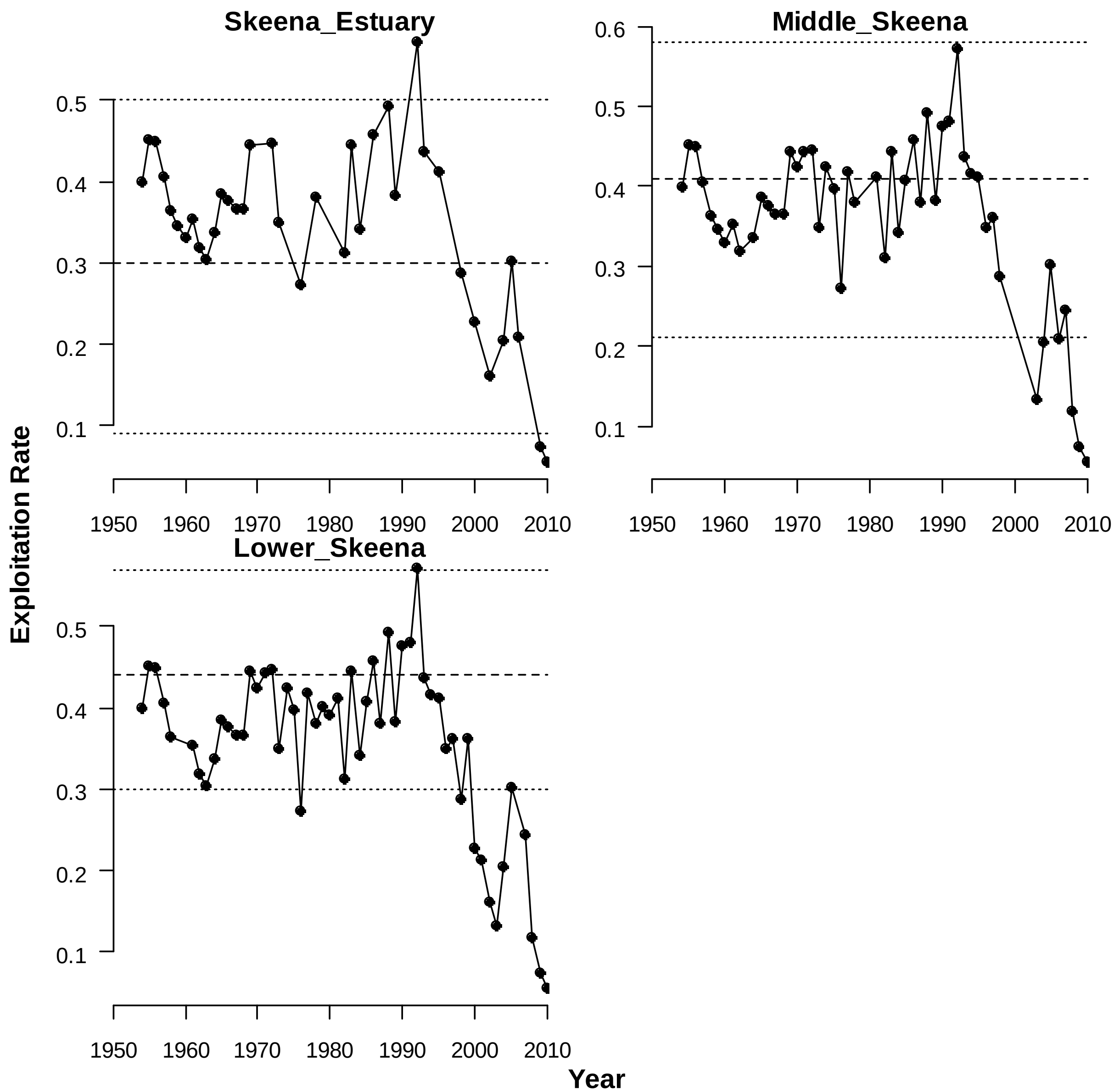

Figure CM.3. The historical exploitation rate for chum salmon CUs in the Skeena relative to the mean estimate of the optimal exploitation rate (dashed horizontal line) and the 95% credible intervals of that optimal rate (finely dashed horizontal lines).

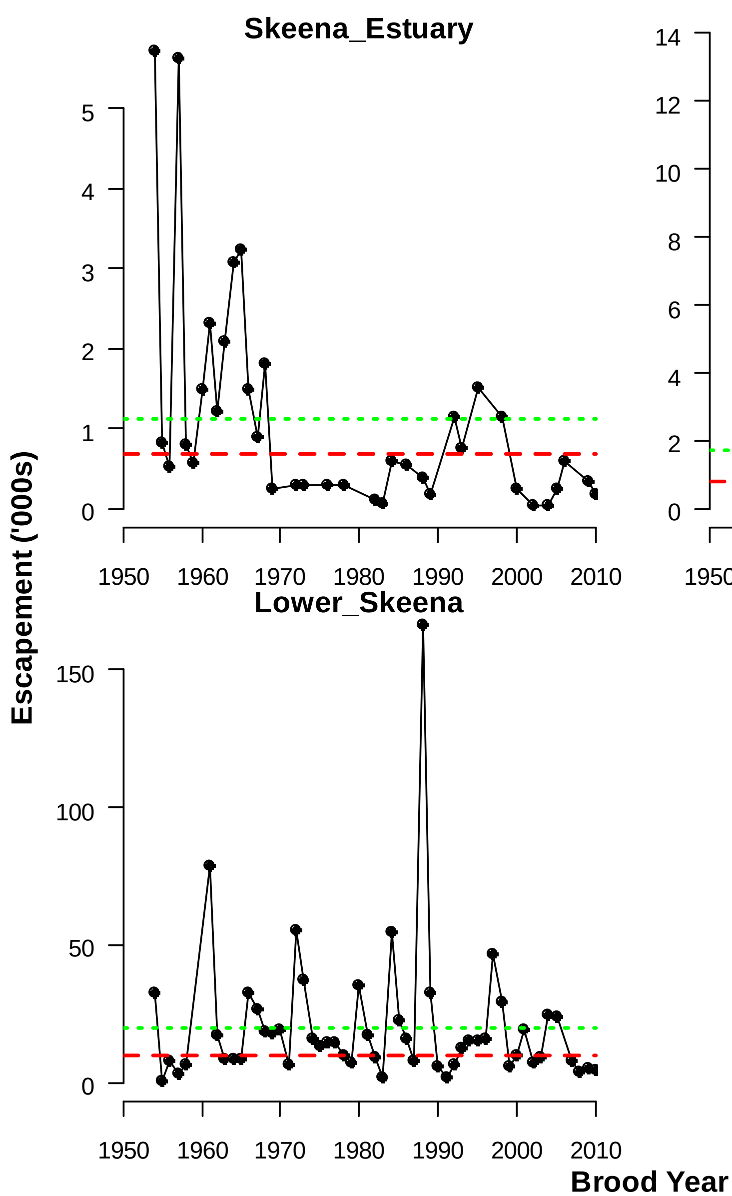

Figure CM.4. Time series of escapement estimates for chum salmon CUs in the Skeena watershed. These plots show the entire available time series, including a limited number of points which do not have complete recruitment pairs (by brood year) that would be omitted from the stock-recruit analysis. Dashed red lines and dotted green lines denote the estimated lower (Sgen1) and upper (Smsy) benchmarks generated from the hierarchical Bayesian model, respectively.

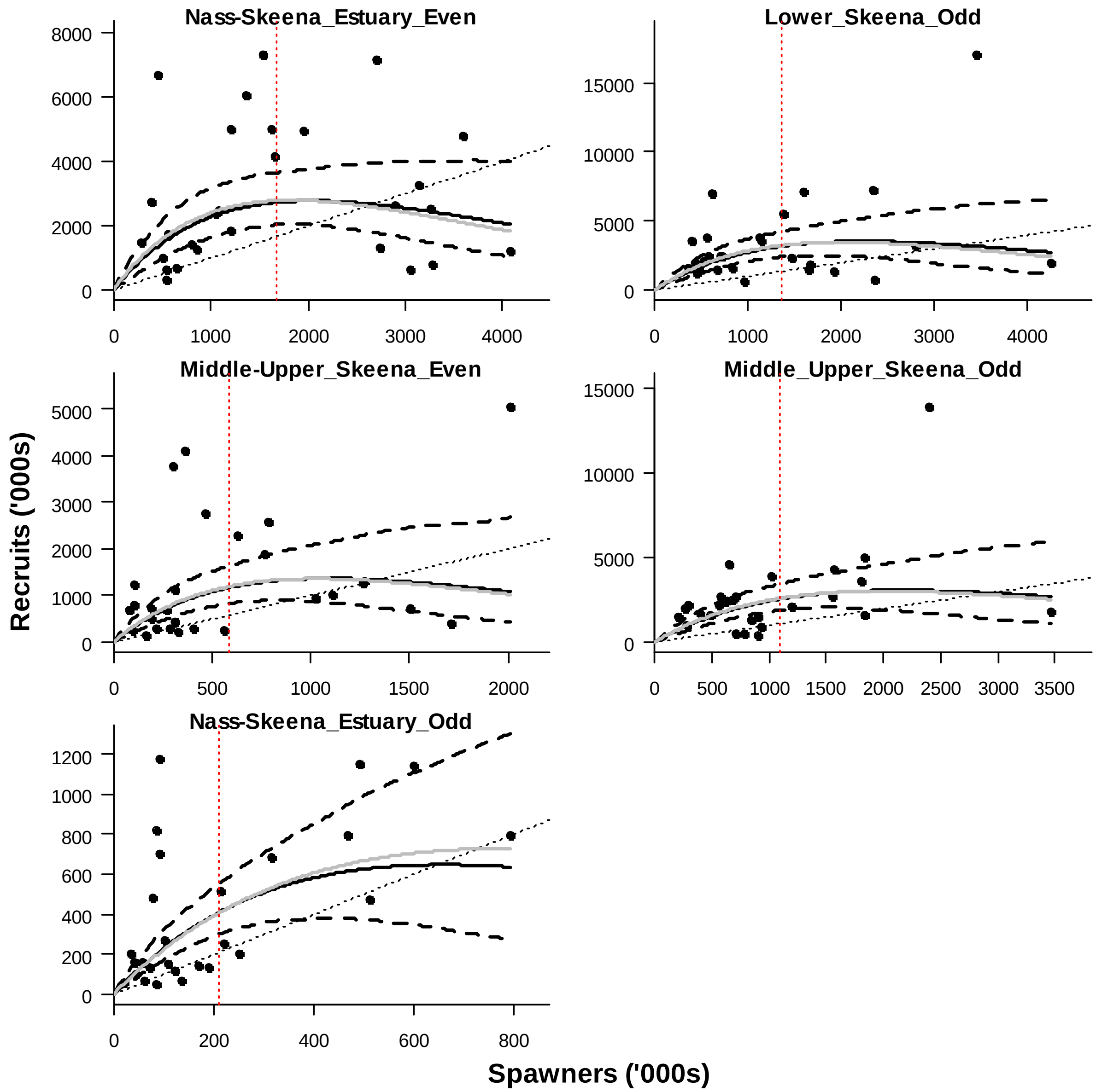

Figure PK.1. Stock-recruit relationships for pink salmon CUs in the Skeena watershed. The thick black solid and dashed lines denote the expected relationship and 95% confidence limits from the hierarchical Bayesian Model. The solid gray lines show independent estimate of the relationship based on linear regression (and no effect of the prior on Smax). The thin dashed line represents a 1:1 relationship (replacement), and the vertical dashed red line denotes the mean for the prior on the escapement that maximizes recruitment (see Table PK.1). Uninformative priors (CVs of 1) for Smax was used to generate these results.

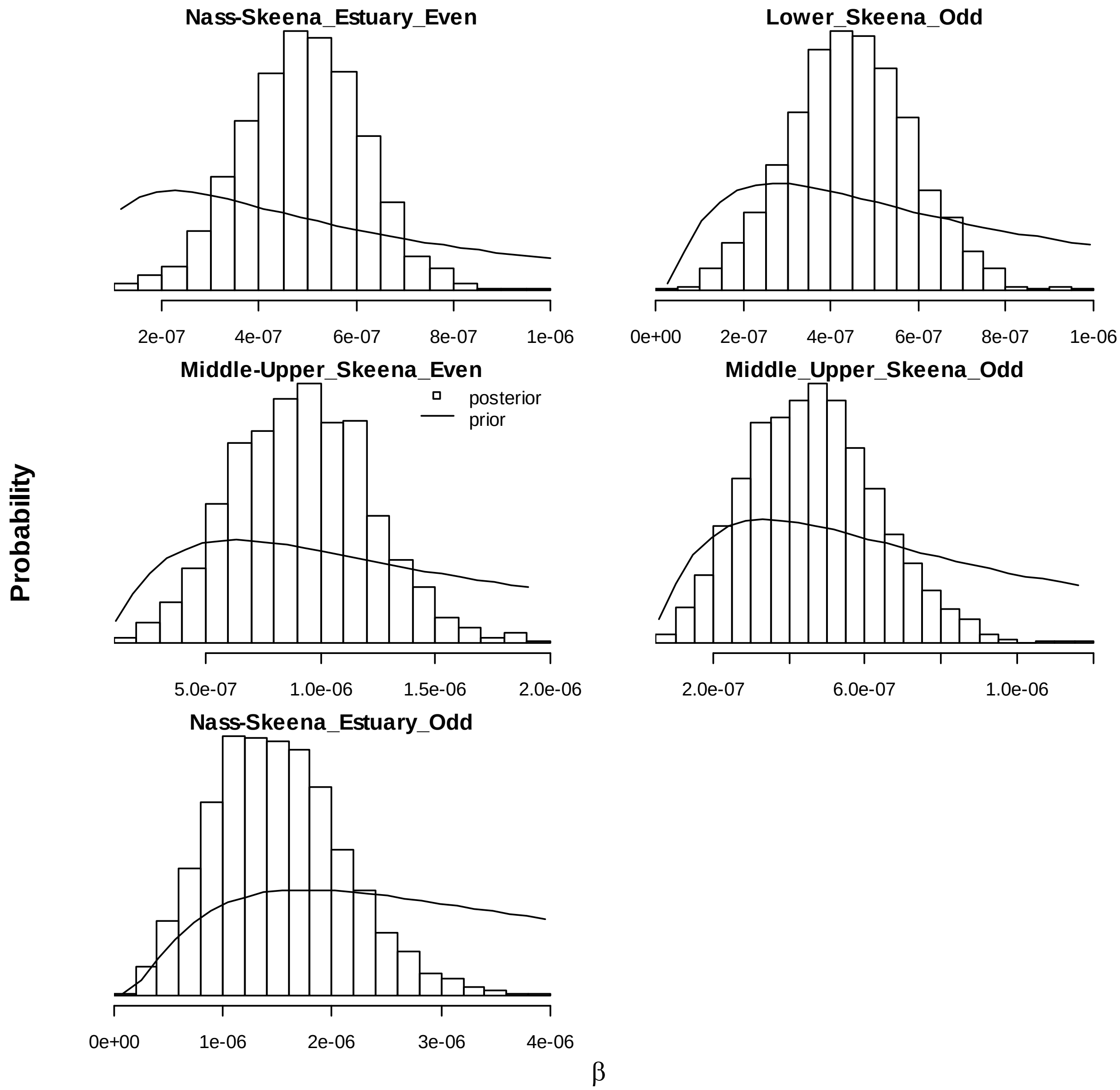

Figure PK.2. Comparison of the posterior distributions of the Ricker β parameter for pink salmon CUs from the hierarchical Bayesian model (bars) with the prior distribution on Smax (converted to β, lines).

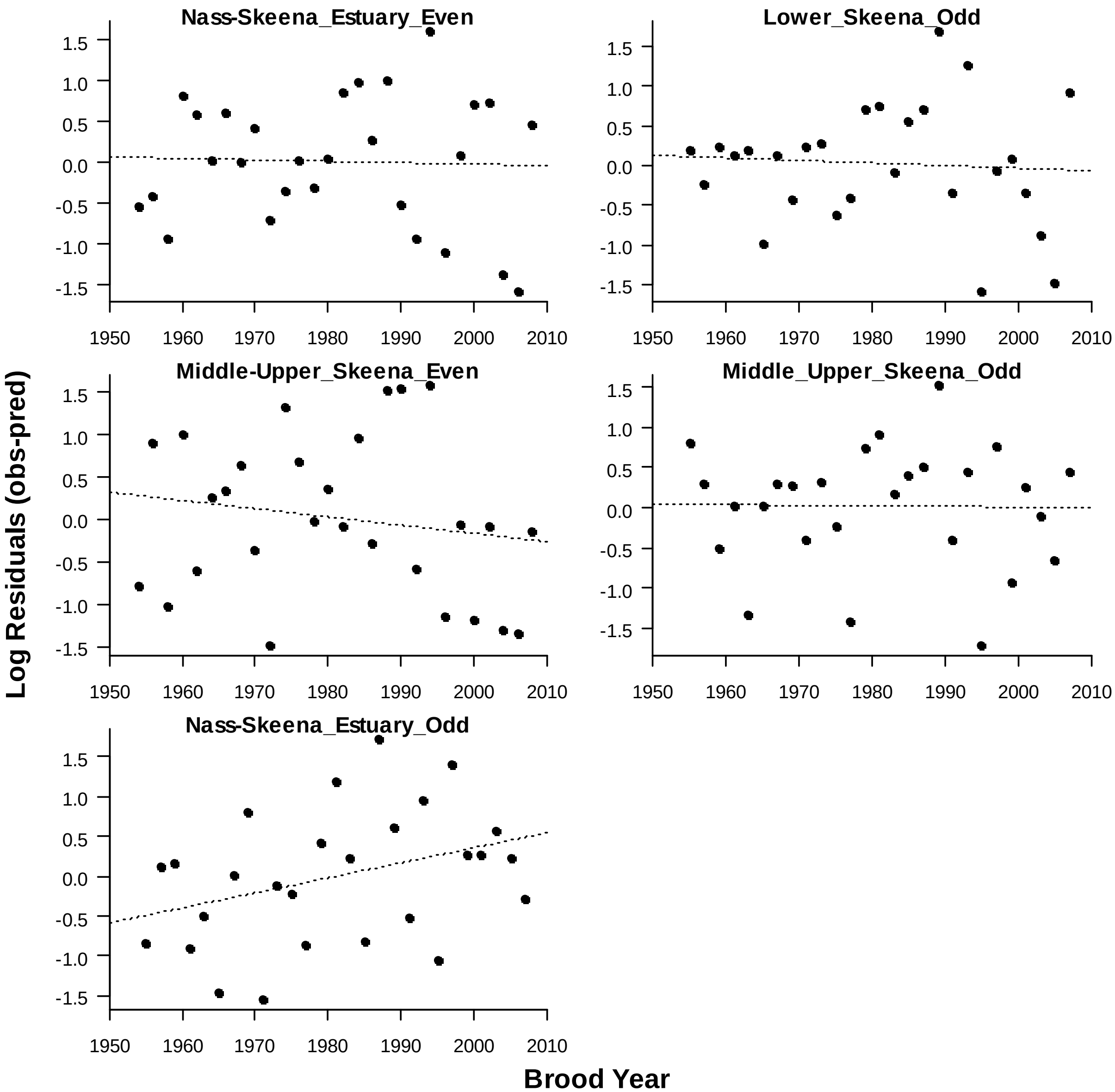

Figure PK.3. Residuals of recruitment from the mean stock-recruit curves from the HBM by brood year for pink salmon CUs in the Skeena watershed. The dashed line shows the trend in residuals over time. A declining slope indicates that the model is underpredicting recruitment in early years and overpredicting it in later ones, potentially indicative of a declining trend in productivity.

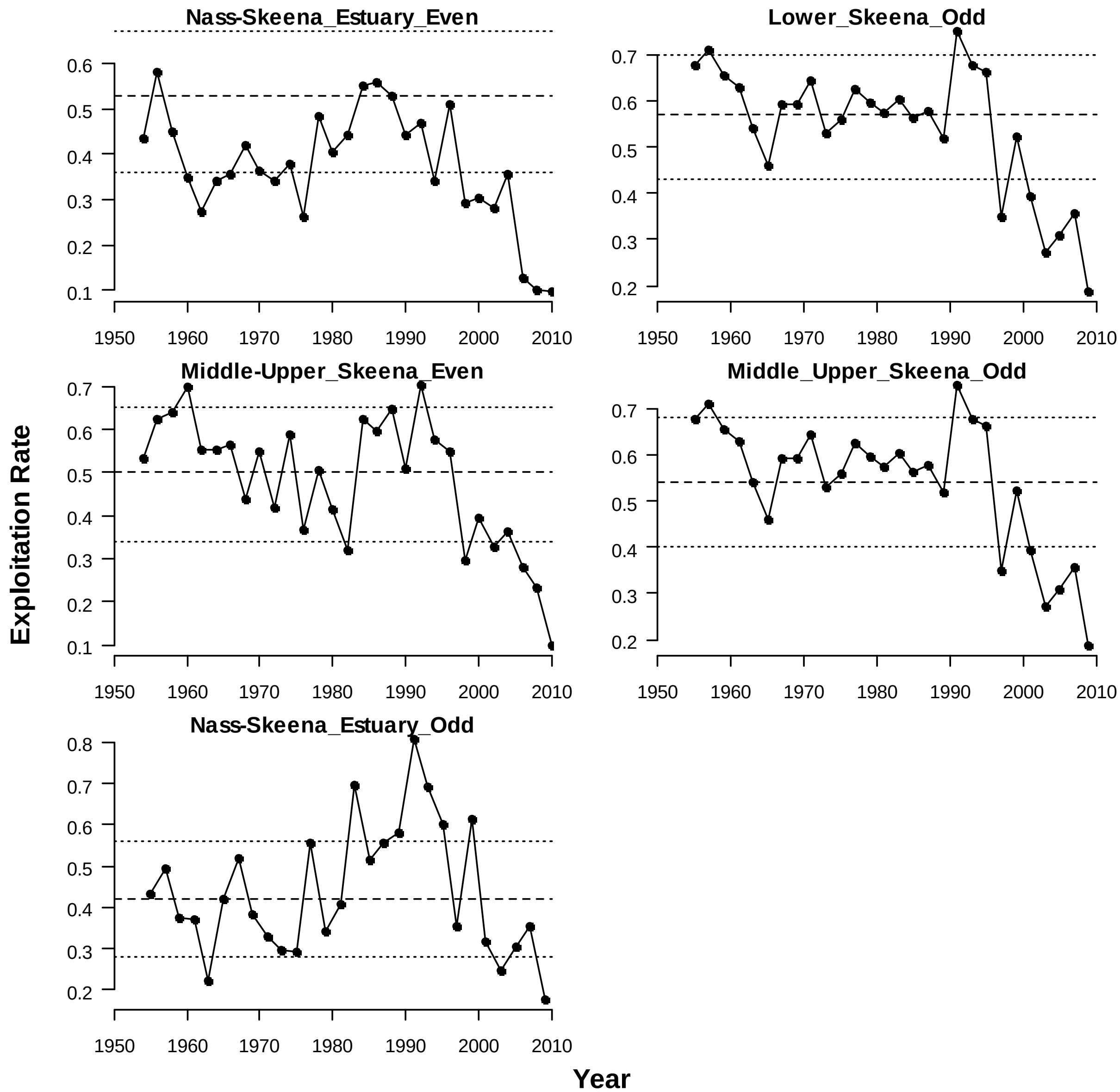

Figure PK.4. The historical exploitation rate for pink salmon CUs in the Skeena relative to the mean estimate of the optimal exploitation rate (dashed horizontal line) and the 95% credible intervals of that optimal rate (finely dashed horizontal lines).

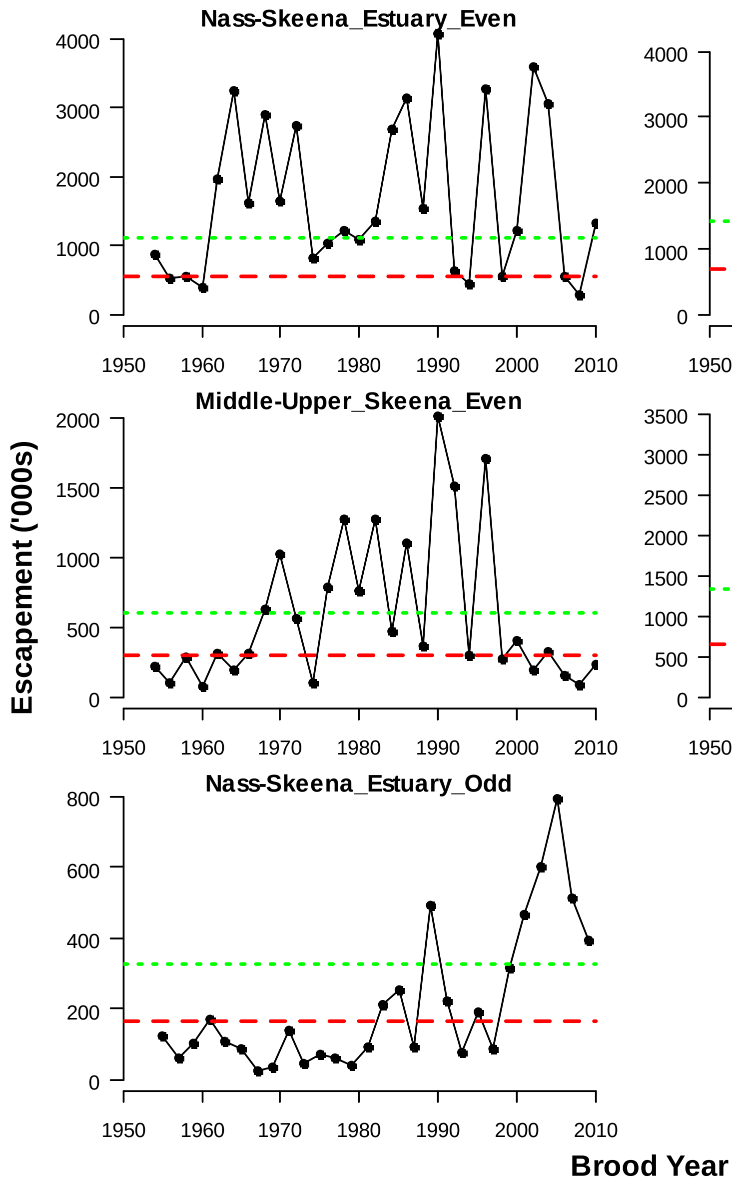

Figure PK.5. Time series of escapement estimates for pink salmon CUs in the Skeena watershed. These plots show the entire available time series, including a limited number of points which do not have complete recruitment pairs (by brood year) that would be omitted from the stock-recruit analysis. Dashed red lines and dotted green lines denote the estimated lower (Sgen1) and upper (Smsy) benchmarks generated from the hierarchical Bayesian model, respectively.

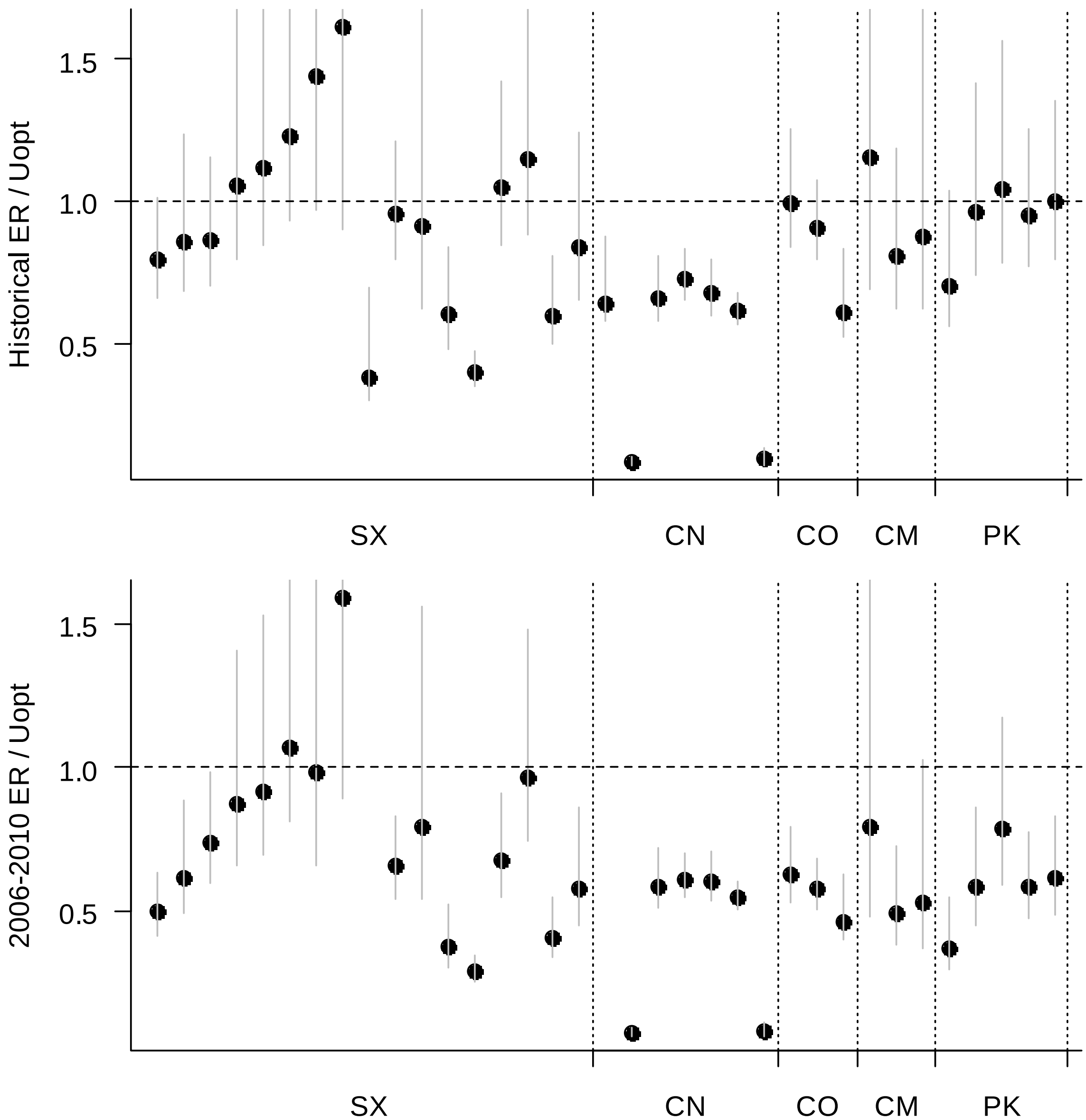

Figure S.1. Ratio of average exploitation rates (ER) computed from all available data over the period of record (1954-2010, top) or more recently (2006-2010, bottom) to the exploitation rates that maximize yield (Uopt) for all CUs. Ratios greater than one (horizontal dashed line) indicate overexploitation. The points represent the expected Uopt estimates from the HBM, and vertical gray lines denote the 95% credible intervals.

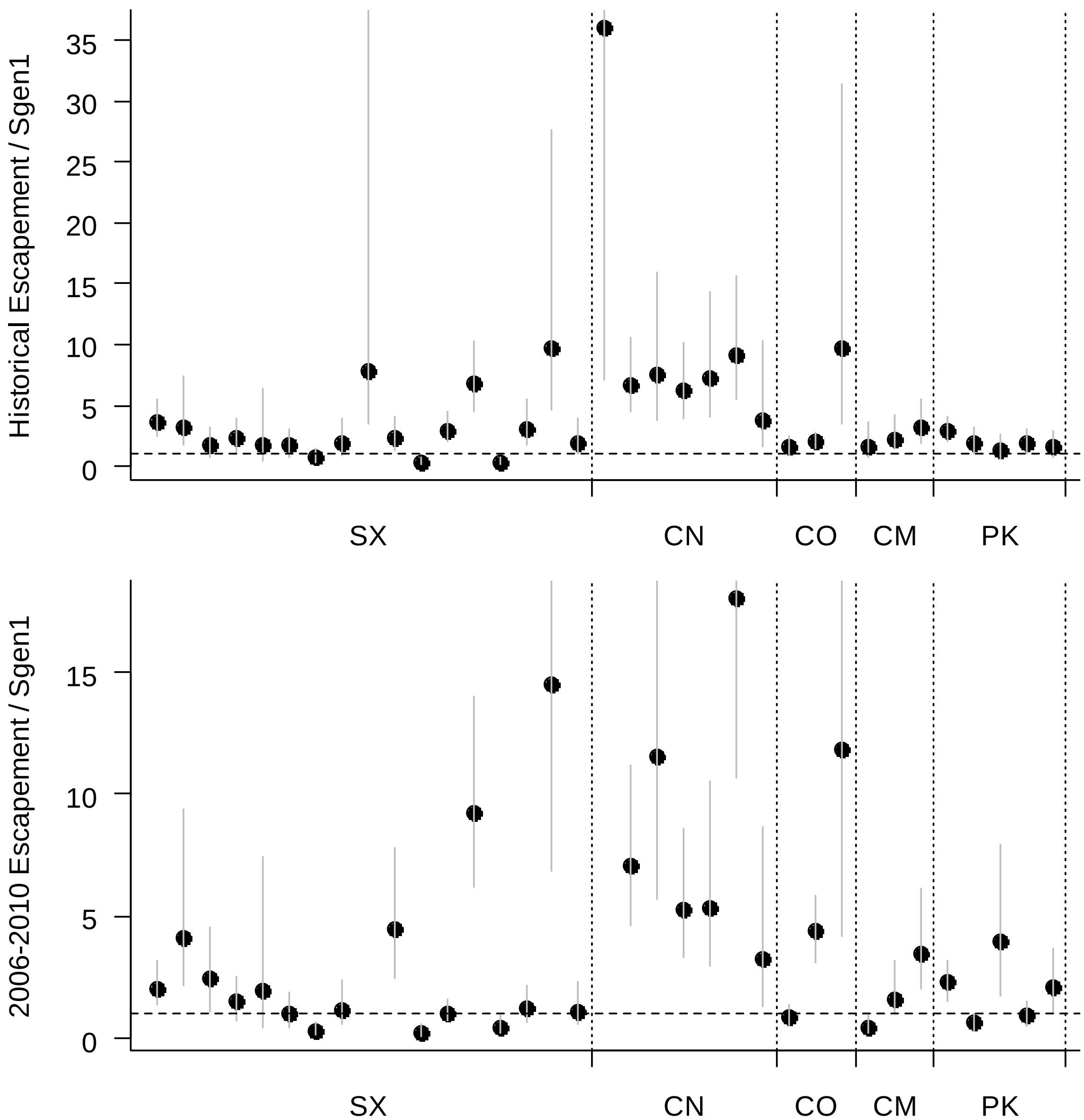

Figure S.2. Ratio of average escapement computed from all available data over the period of record (1954-2010, top) or more recently (2006-2010, bottom) to the escapement that would allow recovery to Smsy in one generation (Sgen1) for all CUs. Ratios less than one (horizontal dashed line) indicate a CU is below the Sgen1 benchmark and potentially in the red conservation zone. The points represent the expected Sgen1 estimates from the HBM, and vertical gray lines denote the 95% credible intervals.

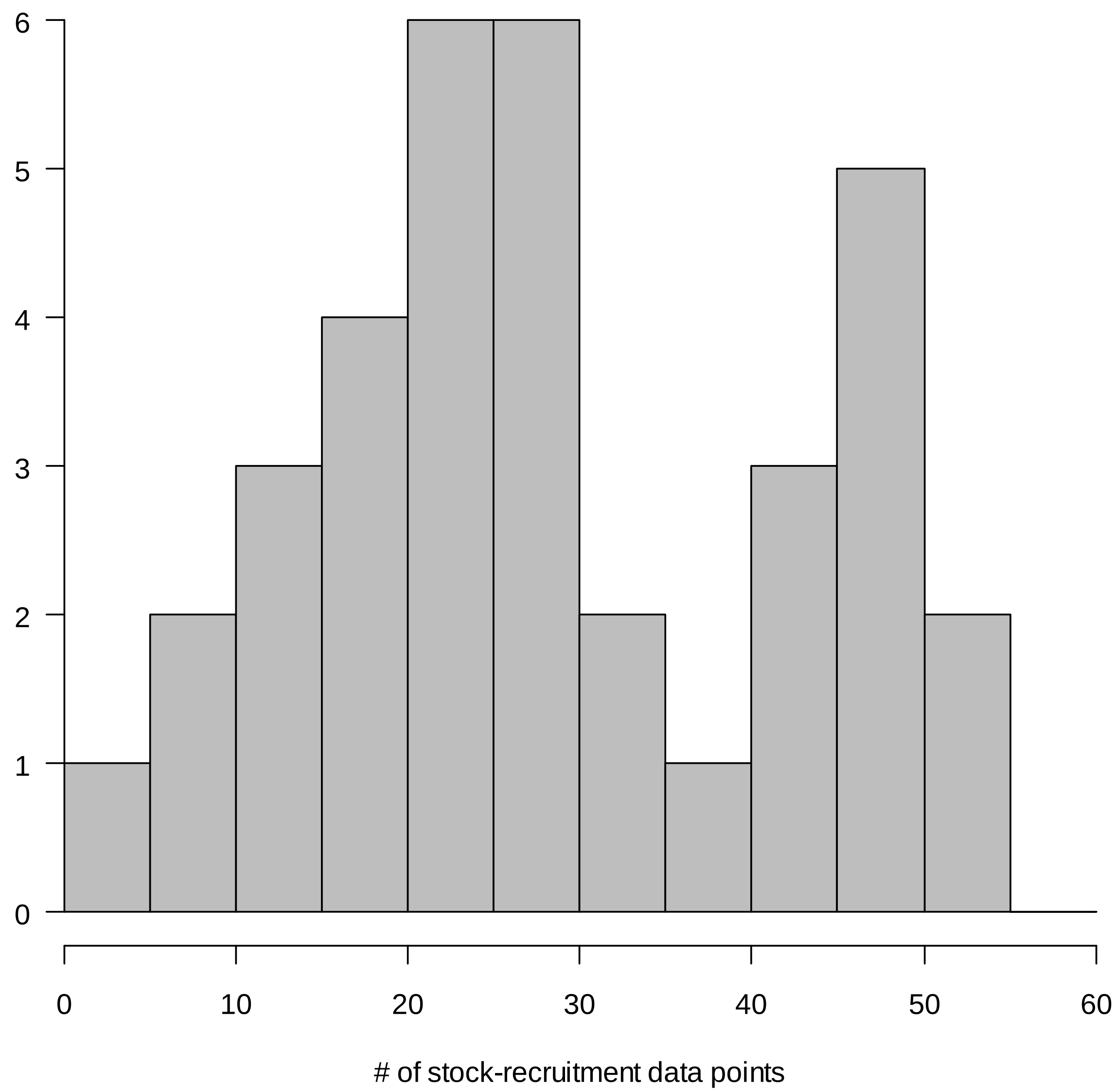

Figure S.3. Distribution of the number of stock-recruitment data points per conservation unit in the Skeena watershed.

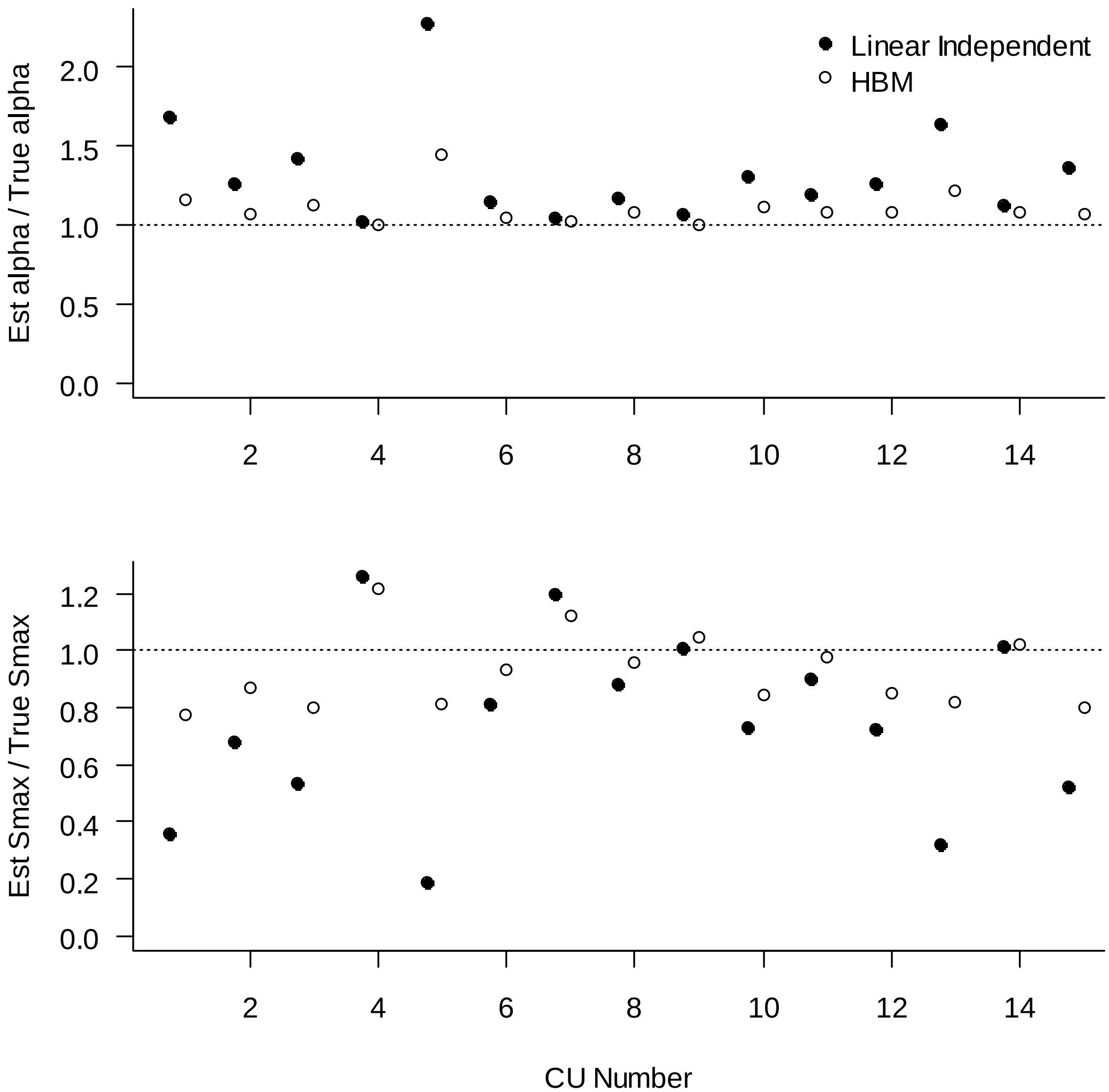

Figure S.4. Results from a simulation comparing bias in estimated α and Smax stock-recruit parameters for 15 CUs based on estimation using linear regression and the assumption that productivity of each CU is completely independent, with estimates from a HBM with a prior on Smax with a CV of 0.3. Bias is computed as the ratio of the estimated parameter to the true simulated value. Simulations assumed that the standard deviations of process and measurement error were both 0.5, the lag-1 autocorrelation in process error was 0.5, and CUs were depleted to 25% of their unfished abundance prior to the 15 yr. simulated periods and fished at a constant exploitation rate of 50%.

Appendix 1: Lookup Table Linking Original 2007 CU Definitions to those Used in Current Analysis

CU index[1]	CU name[2]	Notes on CU name & delineation[3]	Included in current analysis?
sockeye-lake type [SEL]			
L-20-1	Alastair		yes
L-20-4	Ecstall/Lower		
L-20-5	Johnston		yes
L-20-6	Kitsumkalum		yes
L-20-7	Lakelse		yes
L-20-8	Mcdonell	Includes Dennis (L-20-3 in HC2007) & Aldrich (L-20-2 in HC2007)	yes
L-21-2	Babine	Also known as "Babine early" or "Babine early wild"; includes sockeye spawing in non-enhanced tributaries to Babine Lake and in Onerka Lake.	yes
L-21-3	Bulkley	Includes Maxan (L-21-6 in HC2007)	
L-21-5	Kitwancool		yes
L-21-7	Morice	Includes Atna (L-21-1 in HC2007)	yes
L-21-8	Nilkitkwa	Also known as "Babine late" or "Babine late wild".	yes
L-21-9	Stephens		yes
L-21-10	Swan	Includes Club (L-19-4 in HC2007)	yes
L-21-11	Tahlo/Morrison	Also known as "Babine mid" or "Babine mid wild".	yes
L-22-1	Asitika		
L-22-2	Azuklotz		yes
L-22-3	Bear		yes
L-22-4	Damshilgwit		yes
L-22-5	Johanson		
L-22-6	Kluatantan		
L-22-7	Kluayaz		
L-22-8	Motase		yes
L-22-9	Sicintine		
L-22-10	Slamgeesh		
L-22-11	Spawning		
L-22-12	Sustut		
L-21-12	Footsore/Hodder	New CU that was not included in HC2007	
n/a	"Babine enhanced"	Not an official DFO CU, but included as an analysis unit.	yes
	TOTAL: 28		**TOTAL IN CURRENT: 17**

[1]As provided by Holtby (see English et al. 2012)

[2]Names are as provided by Holtby (see English et al. 2012), and match those used in English 2013.

[3]Unless otherwise noted, CU names and delineations match Holtby & Ciruna 2007 (HC2007). For exact streams assigned to each CU please see English et al. 2013 data files.

CU index[1]	CU name[2]	Notes on CU name & delineation[3]	Included in current analysis?
sockeye-river type [SER]			
R18	Skeena River		
R19	Skeena River-high interior		
	TOTAL: 2		**TOTAL IN CURRENT: 0**
Chinook [CK]			
45	Skeena Estuary		
46	Ecstall		yes
48	Lower Skeena	Includes Gitnadoix (47 in HC2007)	yes
49	Kalum-Early		yes
50	Kalum-Late		yes
51	Lakelse		
53	Middle Skeena-large lakes		yes
54	Middle Skeena mainstem tributaries	Includes Middle Skeena (52 in HC2007)	yes
55	Upper Bulkley River		yes
56	Upper Skeena		
80	Zymoetz	New CU that was not included in HC2007	
	TOTAL: 11		**TOTAL IN CURRENT: 7**
chum [CM]			
26	Skeena Estuary		yes
27	Lower Skeena		yes
28	Middle Skeena		yes
N/A	N/A	HC2007 also included a CU "Upper Skeena" (29)	
	TOTAL: 3		**TOTAL IN CURRENT: 3**
coho [CO]			
31	Skeena Estuary		
32	Lower Skeena		yes
33	Middle Skeena		yes
34	Upper Skeena		yes
	TOTAL: 4		**TOTAL IN CURRENT: 3**
odd-year pink [PKO]			
14	Nass-Skeena Estuary		yes
15	Lower Skeena River		yes
16	Middle & Upper Skeena River		yes
	TOTAL: 3		**TOTAL IN CURRENT: 3**
even-year pink [PKE]			
7	Nass-Skeena Estuary		yes
8	Middle-Upper Skeena		yes
	TOTAL: 2		**TOTAL IN CURRENT: 2**