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Summary of Preliminary Benchmark Analysis for Lake Sockeye CUs in the Skeena Watershed

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Introduction

The intent of this memorandum is to describe the results of a preliminary stock-recruit analysis focused on Skeena lake sockeye CUs. This effort is part of a larger project to estimate benchmarks and status for all CUs in the Skeena watershed. Most of the methods and approaches used here will apply to other CUs in the Skeena, so a review of the analytical approach used for one species, where the data are relatively good, is a logical beginning.

Data

There are 31 lake sockeye CU's in the Skeena of which 16 have escapement data (Table 1). The stock-recruit data used here was based on escapement and recruitment estimates prepared by English et al. (2011, LGL) in consultation with S. Cox-Rogers and D. Peacock (DFO). Recruitment associated with each brood year escapement was determined based on estimates of total exploitation rate by return year and the average age compositions across years. In the case of lake sockeye in the Skeena, there is age information for 8 CUs. Age proportions for CUs with age data were mapped to CUs without age data by LGL (K. English) and DFO (Peacock). 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 (see N-SR column in Table 1). Asitka had escapement data but was not included in the stock-recruit analysis because none of the recruitment estimates met the criteria (owing to missing escapement data). Escapement trends for all CUs included in the stock-recruit analysis are show in in Figure 1.

Data on photosynthetic rate (PR) and other information (predators, smolt size) was used as auxiliary information in the stock-recruit analysis (see methods below). Estimates of Smax, the escapement that maximizes recruitment, determined from a PR-based model and other information, were taken from Cox-Rogers et al. (2010). Estimates of Smax from the PR model are shown in Table 1.

Methods

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

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

where, i and t denote indices for CU and brood year, respectively, R is recruitment, S is the brood escapement for that recruitment, α is the log of the initial slope of the stock-recruitment curve (recruitment in the absence of density effects, often termed productivity), 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. 2). Under this form of the Ricker relationship, $1/\beta$ is the spawning size which maximizes recruitment (i.e., Smax).

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

where, t has been omitted here and from subsequent equations for notational simplicity. I term such estimates independent linear values, since they were generated by linear regression and were independently estimated from each other.

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),

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

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), will contribute less information to the hyper distribution for α compared to those CUs with 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. Priors for β_i were assumed to be lognormal, with the mean determined by the PR-based estimate of Smax (Table 1), and a CV set to informative (0.3) or uninformative (3) values.

There are three advantages of the HBM compared to the linear regression method. First, the HBM incorporates prior information on carrying capacity (via PR-based Smax estimates). 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 visa-versa. This leads to considerable uncertainty in derived parameters used as benchmarks, like the escapement or harvest rate 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). In this example, the hyper-distribution is needed to estimate productivity values for the 16 of 31 lake sockeye CUs without stock-recruitment data (Table 1). 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 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. 2). Following recommendations used for Fraser sockeye (Grant et al. 2010), Sgen was used as the lower benchmark, which is the escapement which will allow a population to recover to Smsy in one generation. The upper benchmark was computed as the escapement that maximizes catch (Smsy). Escapements beyond Smsy may produce additional ecosystem benefits. To account for this, I used Smax as an alternative for the upper benchmark. I also compute the harvest rate that would maximize yield for each CU for which stock-recruit data is available, generated from α_i values (Uopt). Finally, random draws of α from the posterior distributions of hyper-parameters (μ_α, σ_α) were used to estimate distributions of α values and optimal harvest rates (Uopt) for lake sockeye CUs within the Skeena without stock-recruit data.

Results

Stock-recruit plots for Skeena lake sockeye CUs show typical 'shotgun' patterns in the data (Fig. 3). Only 10 of 15 CUs had more than 15 data points. Given these characteristics, 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. 3). Stock-recruit curves based on independent and linear estimation (gray lines) were similar to those estimated from the hierarchical Bayesian model (HBM) for CUs where the stock-recruit based-estimates of Smax were consistent with estimates from the PR model (e.g. Asuklotz, Babine, Stephens). However, the PR-based estimate of Smax were much greater for other CUs (e.g. Morice, Tahlo/Morrison), which in turn led to lower estimates of productivity from the HBM relative to the linear independent model.

Estimates of α_i and β_i were confounded in most cases, which is not surprising given the limited information about productivity and density dependence in the stock-recruit data (Fig. 4). Note that the 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. 5), either because the prior and stock-recruit based estimates were consistent, or because of strong confounding between α_i and β_i estimates.

Stock productivity (e^{α}, the initial slope of the stock-recruit curve) is a key management parameter as it determines the harvest rate that maximizes yield. There was considerable uncertainty in α_i estimates from the HBM with the exception of Babine and Kitsumkalum (Fig. 6). 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 (e.g., Kitwancool, Fig. 6). 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 larger mean and showed greater variation (solid and dashed lines in Fig. 6). Thus, the effect of the hierarchical α-exchangeability assumption appears to be quite modest. The expected value for the hyper distribution of α from the HBM was 1.3 (3.7 recruits/spawner) with a CV of 0.46 and there was modest uncertainty in the hyper-distribution (Fig. 7). Based on random draws from hyper-parameters, 95% of α estimates for lake Sockeye within the Skeena watershed were between 0.48 and 3.5 with a median of 1.3 (Fig. 8, top). Optimal harvest rates translated from random draws of α produced a distribution with a mean of 0.54 and a 95% credible interval of 0.22-0.88 (Fig. 8, bottom). The wide range in optimal rates reflects the considerable variation in productivity among CUs estimated by the HBM.

Benchmarks for the 15 lake sockeye CUs with stock-recruitment data are presented in Table 2. These estimates were determined based on posterior distributions of α_i and β_i and reflect the uncertainty in these estimates. The ratio of Sgen to Smsy ranged averaged 0.36 and the ratio of Smsy to Smax averaged of 0.53. Optimal harvest rates ranged from 0.38 to 0.74 across CUs with an average of 0.55. Bear, Lakelse, and Johnston had the lowest productivities and optimal harvest rates of all CUs. There was very large uncertainty in optimal harvest rates within CUs due to uncertainty in α_i, with an average relative error (2 * difference in 95% credible interval / mean) across CUs of 1.22.

Status for the 15 lake sockeye CUs with stock-recruitment data was determined by comparing the average escapement over the last 5 years of available data with estimates of Sgen (lower) and Smsy (upper) benchmarks (Table 3). Probabilities of being in red (below Sgen), amber (Sgen-Smsy), and green (>=Smsy) status zones for each CU reflect the uncertainty in Sgen and Smsy values generated from the posterior distributions of α_i and β_i from HBM. Five of 15 CUs had moderate or high probabilities of being in the "red" status zone (Bear, Kitwancool, Morice, Motase, Swan) with the remaining having higher probabilities in amber (Azukoltz, Babine, Lakelse, Tahlo/Morrison) or green (Alastair, Damshilgwit, Johnston, Kitsumakalum, Mcdonell, Stephens) zones. In the last 5 years of available data, all CUs appear to be under exploited relative to the optimal rate to produce MSY. Bear and Kitsumkalum CUs had the highest probabilities of being over exploited, but the probabilities were well below 0.5. Time trends in abundance and exploitation rate relative to the benchmarks are shown in figures 1 and 9, respectively. With the exception of the Bear CU, the historical average exploitation rate has been less than the estimated optimal rate (Fig. 10). Although most if not all CUs have been under exploited, Bear, Kitwancool, Morice, Swan, and Motase are likely in the red abundance zone (Fig. 11).

The strength of the prior on Smax could have important effects on benchmark and status assessments since it effects estimation of productivity and density dependent parameters in the Ricker model. The HBM was rerun with the default informative prior with a CV of 0.3 for all CUs changed to an uninformative value of 3. Surprisingly, there was little effect of the prior on the expected estimates of α_i; eight of 15 CUs showed a small increase in expected values under an uninformative prior while seven showed a very small decrease (Fig. 12). Uncertainty in CU-specific Ricker parameters increased under the uninformative prior (note increased vertical with of credible interval relative to horizontal width). The hyper-distributions generated under both prior information scenarios were similar (Fig. 13). This occurred because effects of the Smax prior were limited for the more informative CUs that had the greatest influence on the hyper distribution for α.

The majority of CUs had only one or two years of age data (Table 1), so all the recruitment estimates used in this analysis were computed assuming that age composition does not vary among years. However, one would expect substantial variation in age composition due solely to variation in the strength of some brood years, let alone density dependent effects on age-at-return. For example, a strong brood in 2000 would result in a higher than average return of age 3 fish in 2003, age 4 fish in 2004, and age 5 fish in 2005. Using an across-year average age composition to compute recruitments would lead to a reduction in the extent of variation in recruitment among brood years, which could affect stock-recruitment parameter estimates. To evaluate this effect, we compared benchmarks for the Babine and Nass sockeye CUs estimated using recruitments generated by year-specific and average age composition estimates. This analysis could only be done for these two CUs as they were the only ones with sufficient age information (e.g. see Table 1). Differences in benchmarks were substantial in the case of Babine sockeye where productivity decreased and Smax increased based on year-specific age compositions relative to values generated using the average age composition (Table 4). This resulted in a 55% increase in Sgen and a 12% decrease in Uopt under year-specific age composition. The effect was particularly strong for the lower confidence limit for Uopt (0.51 vs. 0.36). However, differences in benchmarks for the Nass comparison were small.

Conclusions

Assuming the posterior distribution of Ricker stock-recruit parameters generated for the 15 lake sockeye CUs in the Skeena are unbiased, this analysis leads to the following three conclusions:

1. Approximately 1/3rd of the CUs are likely currently below the lower benchmark and in the ‘red’ status zone;

2. There is very little evidence to suggest that any lake sockeye CU from the Skeena has been overfished to even a moderate extent, and the most recent exploitation rates are approximately one-half of the rates which would maximize yield. That said, any harvest of stocks in the red zone reduces the rate at which they can potentially recover;

3. There is very wide variation in productivity among CUs, indicating wide variation in exploitation rates that optimize yield. If these CUs are fished under a common exploitation rate, considerable losses in yield will be required to protect weaker stocks.

There were modest differences in benchmarks based on year-specific age composition compared to across year-averaged values for the Babine CU, but not for Nass. The different response of these CUs was likely driven by the extent of differences in brood strength among years, and perhaps other factors (exploitation history, contrast in stock-recruit data). Simulation modelling would be needed to understand the causes and magnitude of biases that can result from using average age composition estimates. Such an exercise could help determine the potential extent of the problem in the case of Skeena CUs, although there are other biases (errors-in-variables, time series) that also need to be considered. Thus, the analysis would be complex and well beyond the scope of the Skeena benchmark project.

The hierarchical Bayesian model provides a defensible means to estimate the distribution of productivities for the 16 of 31 lake sockeye CUs in the Skeena that do not have stock-recruitment data. The hyper-distribution of productivity can be used to define optimal harvest rates for these CUs and could also be used to drive a management strategy evaluation model (similar to Cox-Rogers et al. 2010 as proposed by Walters and Hawkshaw, UBC). If PR-based methods are used to estimate Smax, it would be possible to combine them with the α hyper-distribution to generate abundance-based benchmarks such as Sgen and Smsy. However, considering there is no historical data to compare to these benchmarks, and the likelihood of collecting reliable information on escapement for these CUs in the future is probably low, there does not appear to be a strong rationale to produce them. Furthermore, the lower and upper benchmarks used here and in other analyses (e.g., Grant et al. 2010) are quite arbitrary and fraught with uncertainties about the ecological benefits of higher escapements and the population risks associated with low escapements. Focusing a future management strategy evaluation on fixed exploitation rate strategies, or variable exploitation rates based on the abundance of weak stocks with escapement data, seems like the most logical way to proceed.

This analysis should be considered preliminary until reviewed by DFO (Cox-Rogers, Peacock) and outside experts (Riddell). The analysis for the Babine CU could be expanded to consider the early-, middle-, and late-timed wild components separately (pending data and suggestions on stock structure to be provided by Cox-Rogers.). The stock-recruit analysis could be repeated based on updated values of the CVs on Smax for individual CUs, as the confidence in the PR-based estimates among CUs is variable (see Cox-Rogers et al. 2010). That said, it is unlikely that varying the CVs in Smax among CUs will have a large effect considering the relatively small difference associated with the 10-fold change in the CV on Smax explored in this analysis.

References

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.

English, K.K., Mochizuki, T., and D. Robichaud. 2011. 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.

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.

Table 1. List of Skeena lake sockeye Conservation Units (CUs). N-SR denotes the number of stock-recruit data points for CUs with escapement and recruitment data. N-Age denotes the total number of age samples, with values in parentheses denoting the number of years where age data are available. PR-based Smax values are estimates of the spawning stock size that produces maximum recruitment based on the photosynthetic rate model and other factors (from Cox-Rogers et al. 2010). These estimates are used as priors on β_i in the stock-recruit analysis.

CU Name	N - SR	N - Age	PR-based Smax
Alastair	21	151 (2)	23,437
Aldrich			
Asitika			
Atna			
Azuklotz	13		5,933
Babine	23	17,489 (32)	1,808,245
Bear	6	46 (1)	40,532
Bulkley			
Damshilgwit	3	67 (1)	423
Dennis			
Ecstall/Lower			
Footsore			
Johanson			
Johnston	4		4,125
Kitsumkalum	19		20,531
Kitwancool	3	299 (4)	36,984
Kluatantan			
Kluayaz			
Lakelse	14	194 (1)	35,916
Maxan			
Mcdonell	6		4,072
Morice	15	98 (1)	191,362
Motase	10		1,764
Nilkitkwa			
Sicintine			
Slamgeesh			
Spawning			
Stephens	12		7,069
Sustut			
Swan	10	100 (1)	21,432
Tahlo/Morrison	18		44,587

Table 2. Preliminary benchmarks for Skeena lake sockeye Conservation Units (CU). Sgen is used as the lower benchmark, and is the escapement that will allow the population to recover to the stock size that maximizes catch (Smsy) in one generation. Smsy and Smax are 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 harvest rate which maximizes catch (i.e., the harvest rate at Smsy). Benchmark statistics are based on the CU-specific tock-recruit parameter values from the HBM (mean), as well as the lower and upper 95% credible intervals (LCL and UCL, respectively).

CU	Benchmark	Mean	LCL	UCL		CU	Benchmark	Mean	LCL	UCL
Alastair	Sgen	3,279	1,738	5,700		Lakelse	Sgen	4,955	2,576	8,254
	Smsy	8,704	6,754	11,843			Smsy	10,479	6,635	17,447
	Smax	18,176	11,614	29,833			Smax	26,489	14,703	44,276
	Prod	3.35	2.30	5.00			Prod	2.65	1.70	4.10
	Uopt	0.49	0.36	0.63			Uopt	0.41	0.25	0.57
Azuklotz	Sgen	954	382	1,716		Mcdonell	Sgen	874	155	12,994
	Smsy	3,665	2,392	5,664			Smsy	3,003	2,100	4,280
	Smax	6,050	3,634	9,932			Smax	4,138	2,648	6,549
	Prod	5.14	2.90	8.80			Prod	8.79	4.10	16.70
	Uopt	0.62	0.46	0.76			Uopt	0.74	0.56	0.85
Babine	Sgen	320,890	158,398	571,466		Morice	Sgen	31,074	14,929	55,472
	Smsy	1,092,050	785,469	1,537,725			Smsy	90,029	40,495	169,725
	Smax	1,959,986	1,201,476	3,112,575			Smax	179,749	95,233	306,141
	Prod	4.21	3.00	5.90			Prod	3.59	2.00	6.60
	Uopt	0.57	0.47	0.67			Uopt	0.50	0.32	0.69
Bear	Sgen	7,771	3,739	14,200		Motase	Sgen	301	161	506
	Smsy	17,735	6,563	36,479			Smsy	701	427	1,148
	Smax	41,933	22,414	75,305			Smax	1,606	920	2,661
	Prod	2.93	1.50	6.50			Prod	2.89	2.10	4.20
	Uopt	0.42	0.20	0.69			Uopt	0.44	0.33	0.57
Damshilgwit	Sgen	81	31	129		Stephens	Sgen	1,371	578	2,207
	Smsy	227	144	316			Smsy	5,762	4,582	7,607
	Smax	456	293	684			Smax	8,707	6,153	12,968
	Prod	3.95	1.90	8.60			Prod	6.24	4.00	9.60
	Uopt	0.51	0.28	0.75			Uopt	0.67	0.56	0.77
Johnston	Sgen	907	461	1,439		Swan	Sgen	4,480	2,197	7,774
	Smsy	1,829	1,006	2,965			Smsy	11,912	7,236	19,206
	Smax	4,935	2,786	7,849			Smax	24,817	14,147	41,719
	Prod	2.54	1.60	4.70			Prod	3.31	2.20	5.00
	Uopt	0.38	0.21	0.61			Uopt	0.49	0.35	0.63
Kitsumkalum	Sgen	2,646	611	35,899		Tahlo/Morrison	Sgen	6,397	2,699	12,644
	Smsy	8,473	5,709	14,169			Smsy	20,097	10,767	35,783
	Smax	11,715	7,341	20,555			Smax	37,775	18,997	71,280
	Prod	7.90	5.70	10.40			Prod	3.90	2.50	5.80
	Uopt	0.73	0.66	0.79			Uopt	0.54	0.40	0.66
Kitwancool	Sgen	9,052	1,477	10,366						
	Smsy	27,164	11,472	49,820						
	Smax	38,802	19,462	64,600						
	Prod	8.48	2.60	19.00						
	Uopt	0.70	0.41	0.86						

Table 3. Status of Skeena lake sockeye CUs based on comparing the average escapement over the last 5 years of available data relative to Sgen (lower) and Smsy (upper) benchmarks. The probabilities associated with each abundance status level were determined from the posterior distributions of Sgen and Smsy predicted from the HBM. Also shown is the average total exploitation rate (ER) over the last 5 years of available data relative to the average optimal harvest rate (Uopt) and the probability that the recent average has exceeded the optimal exploitation rate.

		Abundance Status					**Exploitation Rate Status**		
CU		**Avg. Esc. Last 5 Yrs**	**Red (<Sgen)**	**Amber (<Smsy)**	**Green (>=Smsy)**		**Avg. ER Last 5 Yrs**	**Avg. Uopt**	**Prob. OverExp.**
Alastair		13,613	0.00	0.01	0.99		0.12	0.49	0.00
Azuklotz		1,920	0.01	0.99	0.00		0.47	0.62	0.03
Babine		966,536	0.00	0.71	0.29		0.41	0.57	0.00
Bear		2,836	1.00	0.00	0.00		0.37	0.42	0.35
Damshilgwit		271	0.00	0.12	0.88		0.32	0.51	0.04
Johnston		4,877	0.00	0.00	1.00		0.30	0.38	0.20
Kitsumkalum		12,046	0.04	0.07	0.89		0.38	0.73	0.00
Kitwancool		3,535	0.59	0.41	0.00		0.38	0.70	0.02
Lakelse		5,590	0.30	0.70	0.00		0.11	0.41	0.00
Mcdonell		4,683	0.03	0.01	0.96		0.38	0.74	0.00
Morice		20,571	0.86	0.14	0.00		0.21	0.5	0.00
Motase		282	0.52	0.48	0.00		0.32	0.44	0.02
Stephens		11,147	0.01	0.00	0.99		0.25	0.67	0.00
Swan		3,836	0.63	0.37	0.00		0.25	0.49	0.00
Tahlo/Morrison		18,964	0.00	0.50	0.50		0.32	0.54	0.00

Table 4. Benchmarks for Skeena and Nass sockeye CUs where recruitment estimates were computed using the average age composition across years compared with those computed using year-specific age composition. Parameters were estimated from a Bayesian model without prior information on β_i and where α_i estimates were assumed to be completely independent. See Table 2 for definitions of Sgen, Smsy, Smax, Prod, and Uopt.

	Average Age Composition			**Year-Specific Age Composition**		
Babine						
	Mean	**LCL**	**UCL**	**Mean**	**LCL**	**UCL**
Sgen	240,879	141,036	392,949	375,605	131,093	1,151,051
Smsy	898,155	708,519	1,199,148	1,001,734	604,099	2,241,124
Smax	1,539,444	1,083,354	2,270,786	2,090,271	974,564	6,003,034
Prod	4.51	3.50	5.90	3.69	2.30	5.70
Uopt	0.59	0.51	0.67	0.52	0.36	0.66
Nass						
	Mean	**LCL**	**UCL**	**Mean**	**LCL**	**UCL**
Sgen	67,558	13,185	989,525	66,706	12,906	982,925
Smsy	229,575	162,762	355,000	221,080	156,573	352,835
Smax	316,629	198,528	552,986	306,962	194,396	559,613
Prod	8.51	5.00	13.40	8.44	4.90	13.70
Uopt	0.74	0.62	0.83	0.74	0.62	0.83

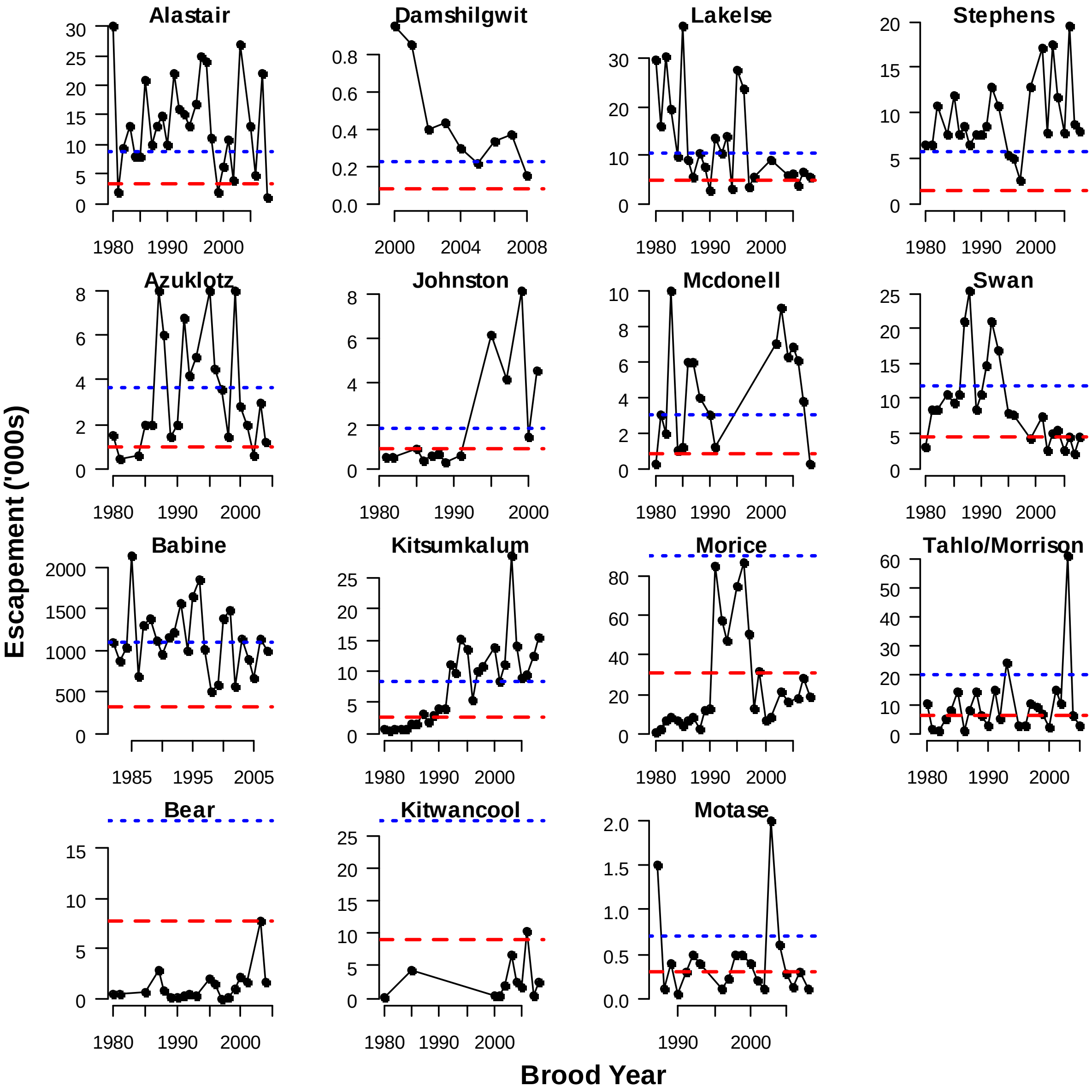

Figure 1. Tim series of escapement estimates for 15 lake Sockeye CU's in the Skeena watershed. These plots show the entire available time series, including a limited number of points which do not have complete recruitment pairs (by brood year) that would be omitted from the stock-recruit analysis. Dashed red lines and dotted blue lines denote the estimated lower (Sgen) and upper (Smsy) benchmarks generated from the hierarchical Bayesian model, respectively.

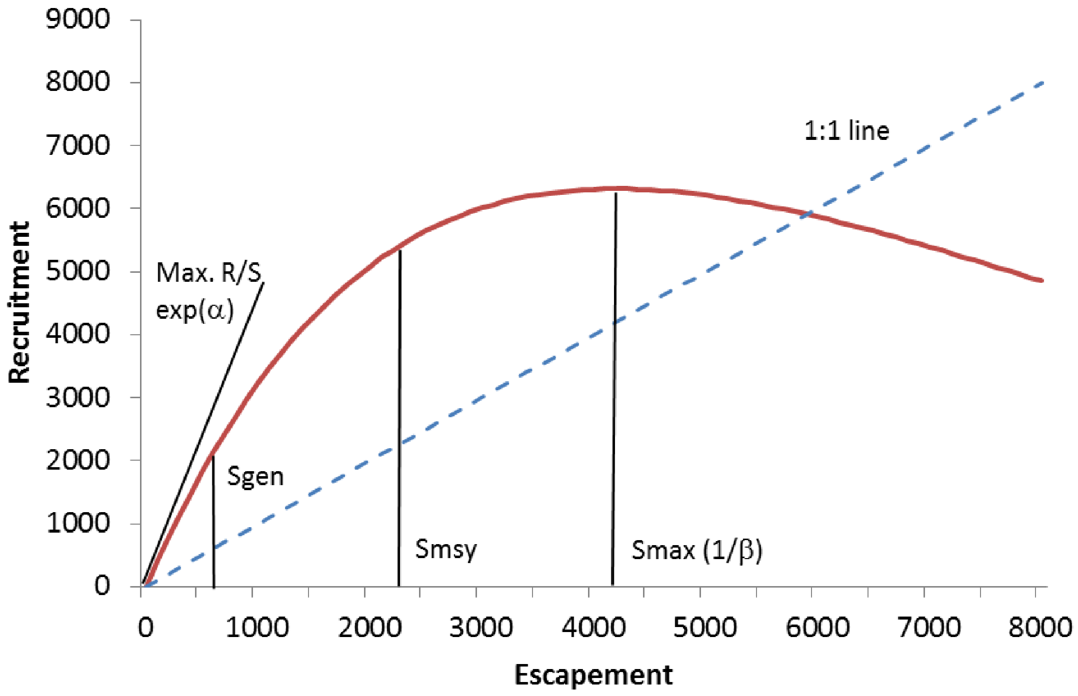

Figure 2. An example of a stock-recruitment relationship showing the 3 abundance-based benchmarks used in this study as well as the estimate of maximum recruits/spawner that is used to compute the exploitation rate which optimizes yield.

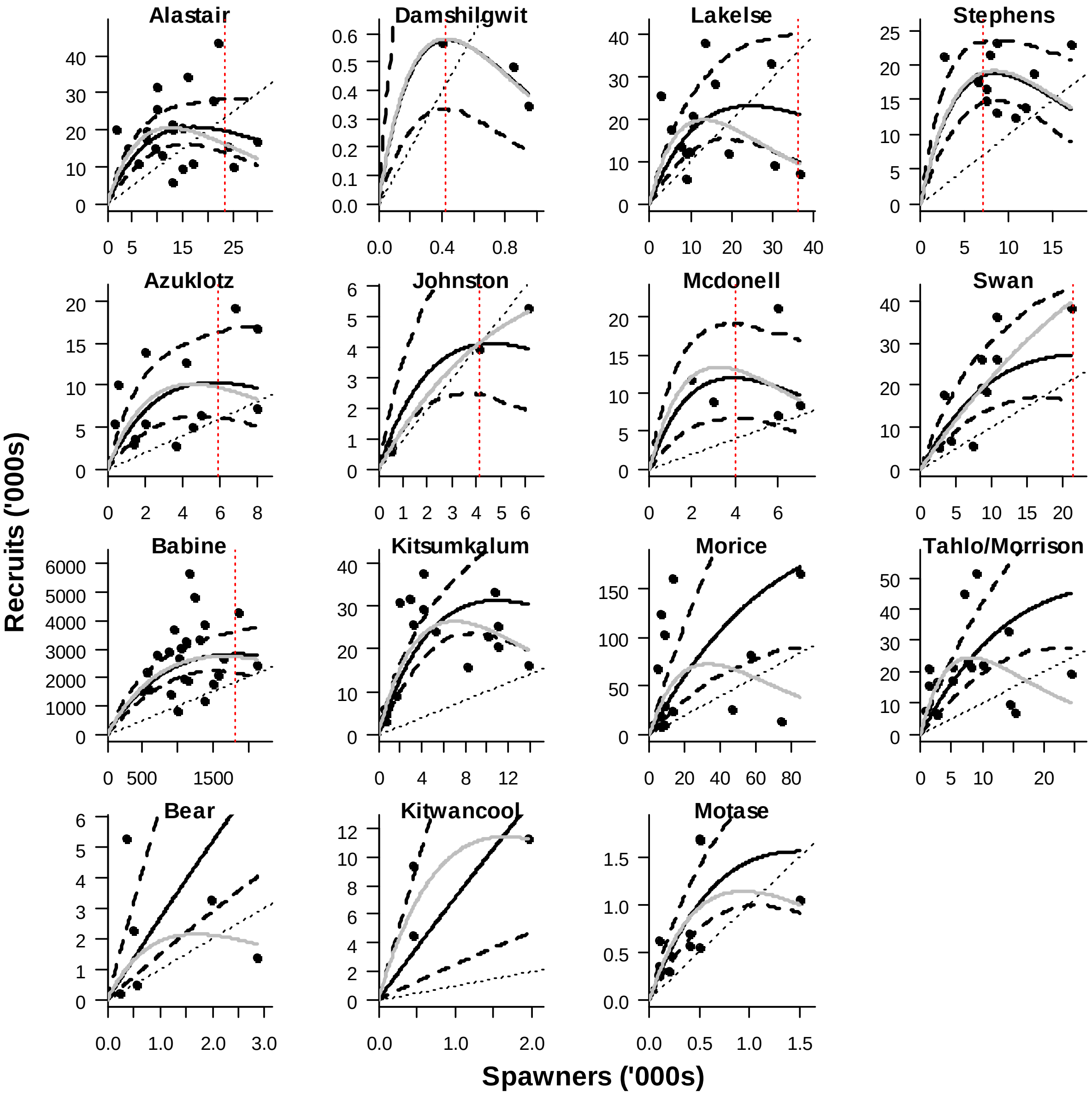

Figure 3. Stock-recruit relationships for lake sockeye CUs in the Skeena watershed. The thick black solid and dashed lines denote the expected relationship and 95% confidence limits from the hierarchical Bayesian Model. The solid gray lines show independent estimate of the relationship based on linear 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 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.

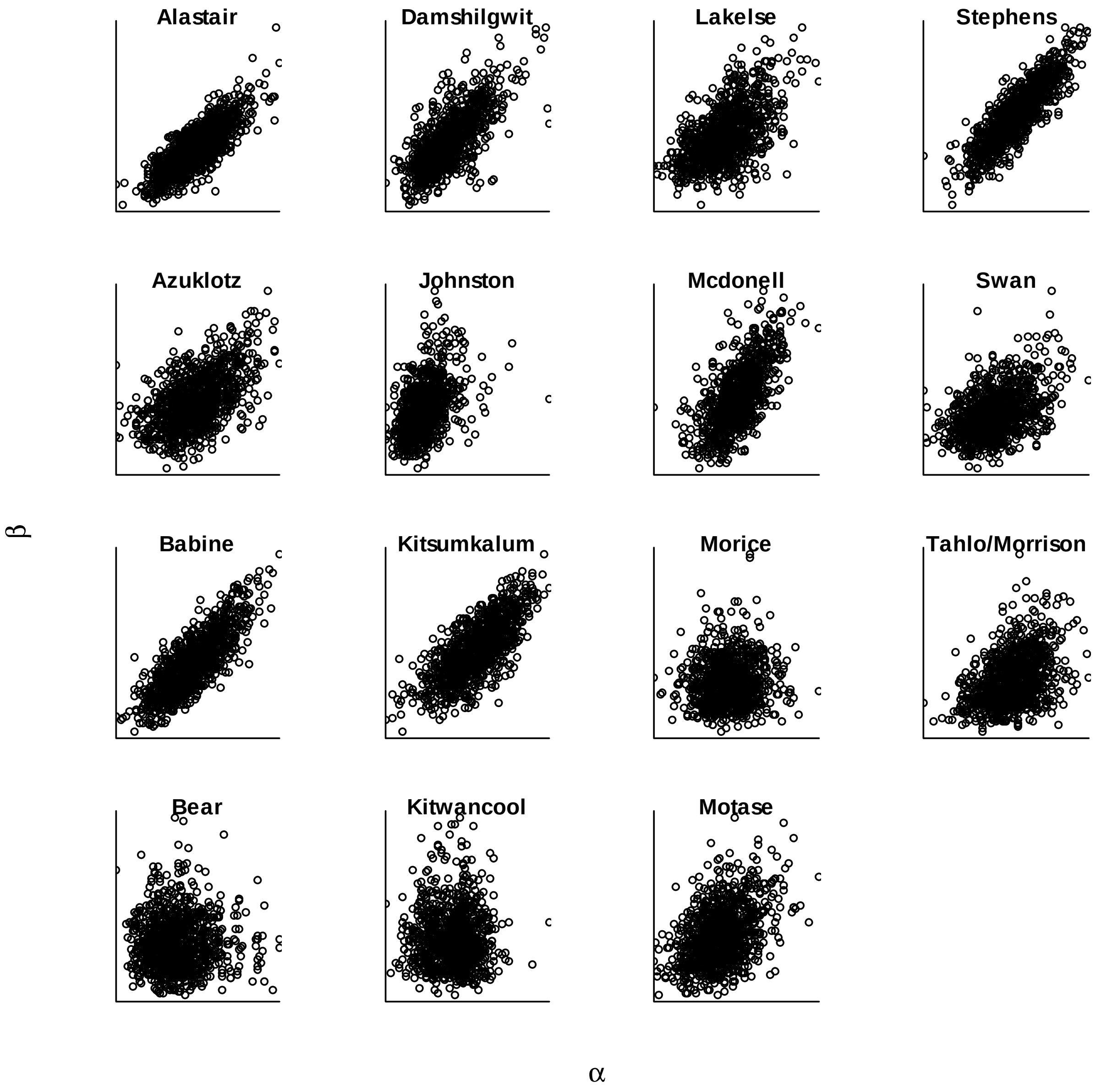

Figure 4. Scatter plots showing samples of Ricker α and β parameters for Skeena lake sockeye CUs from posterior distributions generated from the hierarchical Bayesian model. A CV of 0.3 for the prior on Smax was used to generate these results.

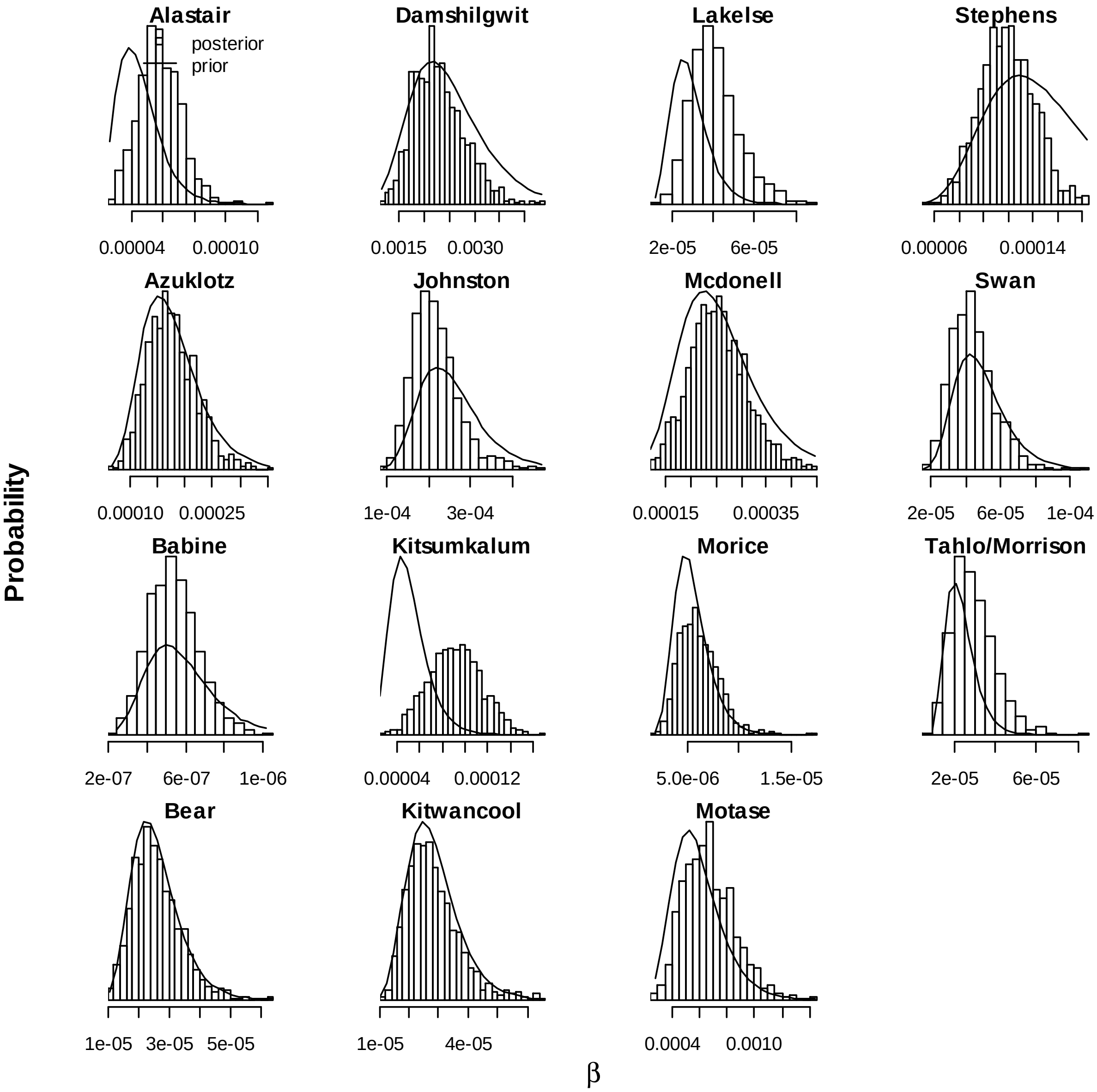

Figure 5. Comparison of the posterior distributions of the Ricker β parameter from the hierarchical Bayesian model (bars) with the prior distribution on Smax (converted to β) from the photosynthetic rate model (lines). A CV of 0.3 for the prior on Smax was used to generate these results.

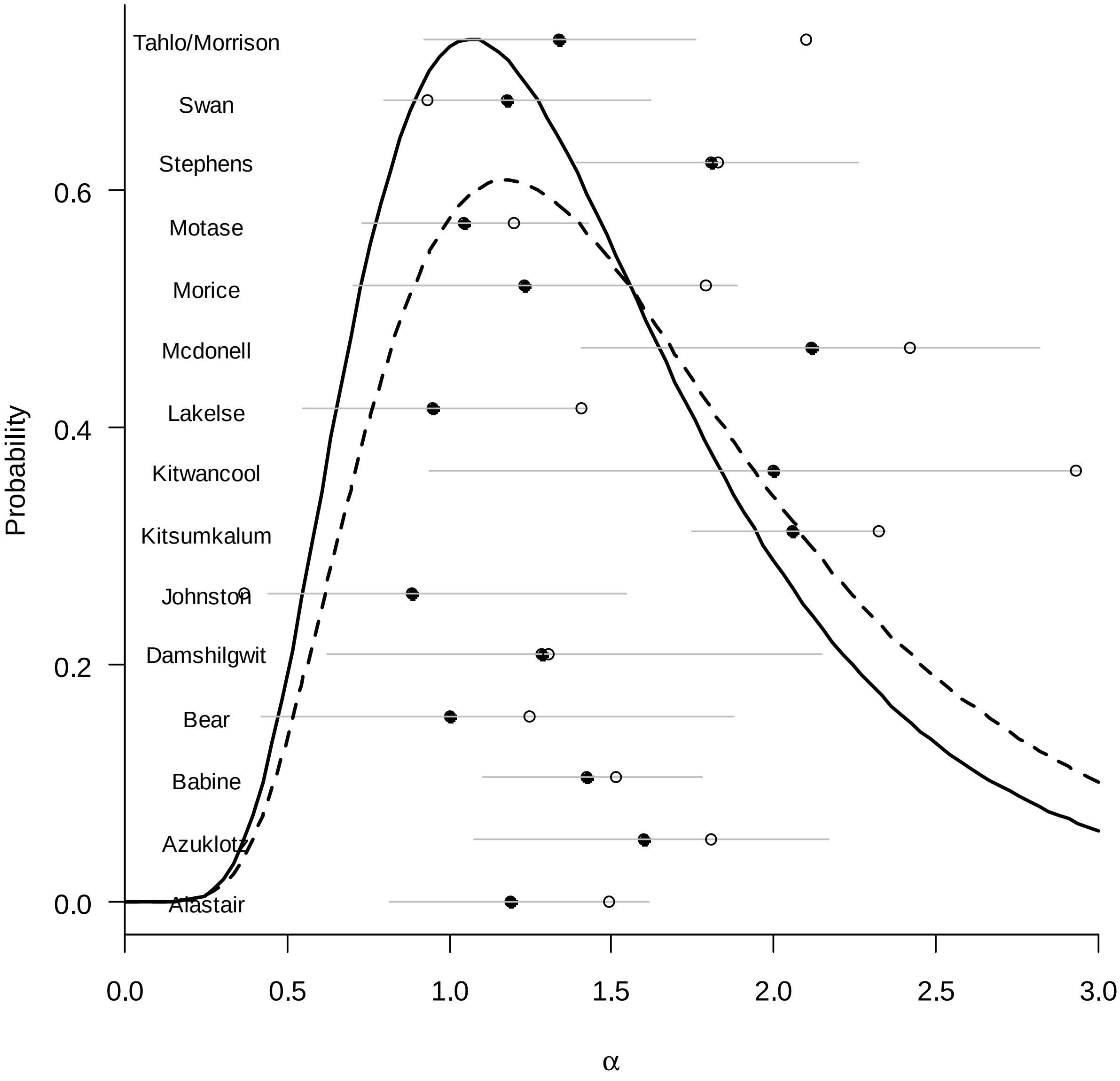

Figure 6. CU-specific mean estimates of the Ricker α parameter from the hierarchical Bayesian model (filled circles) and 95% credible intervals (horizontal lines) compared to independent estimates generated by linear regression (open circles). Note estimates of α_i from the linear regression method do 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).

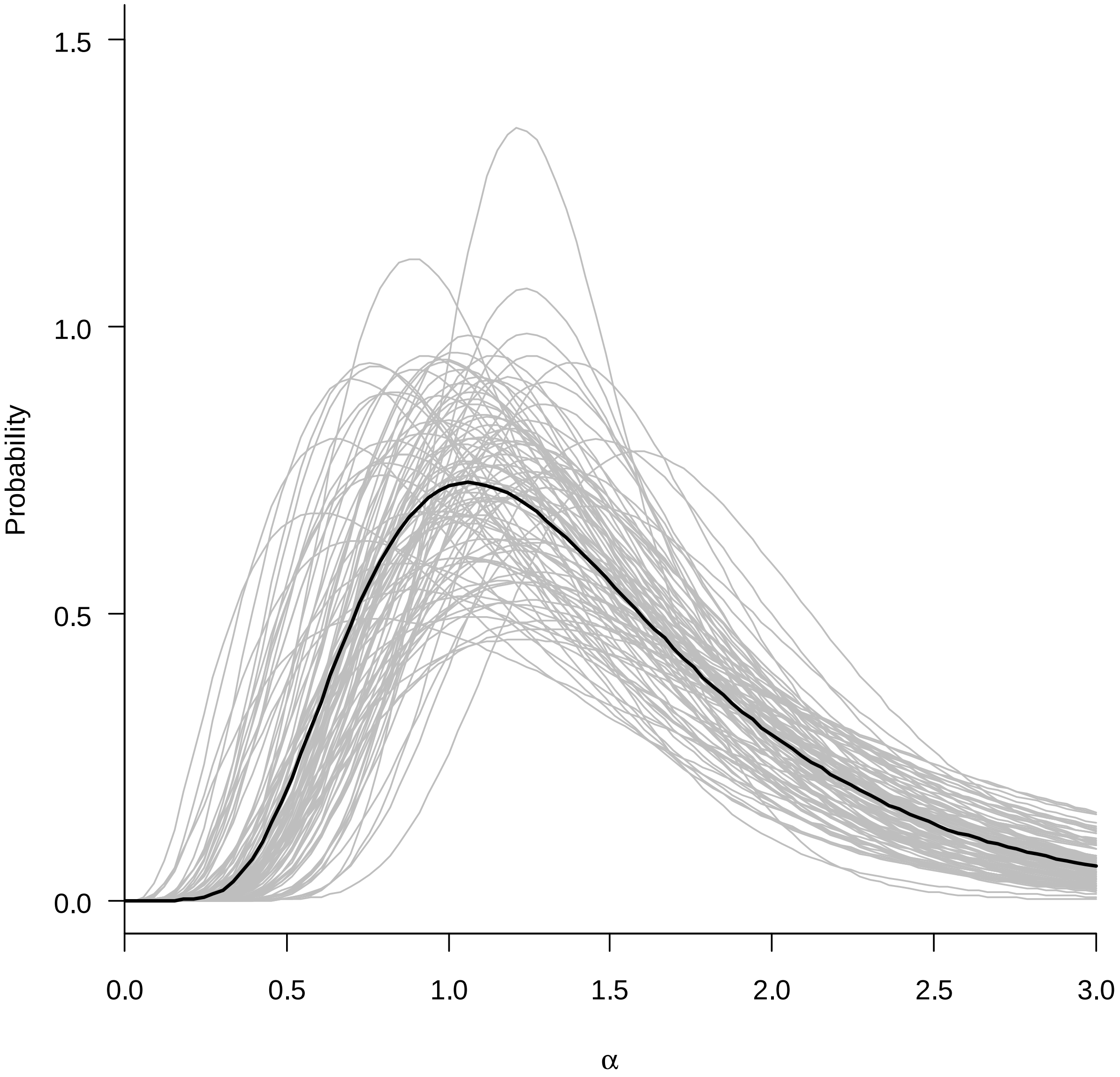

Figure 7. The mean hyper distribution of α from the HBM (solid thick line) compared to 100 random draws the μ_α and σ_α hyper parameters (gray lines). This shows the uncertainty in the α hyper distribution (bottom).

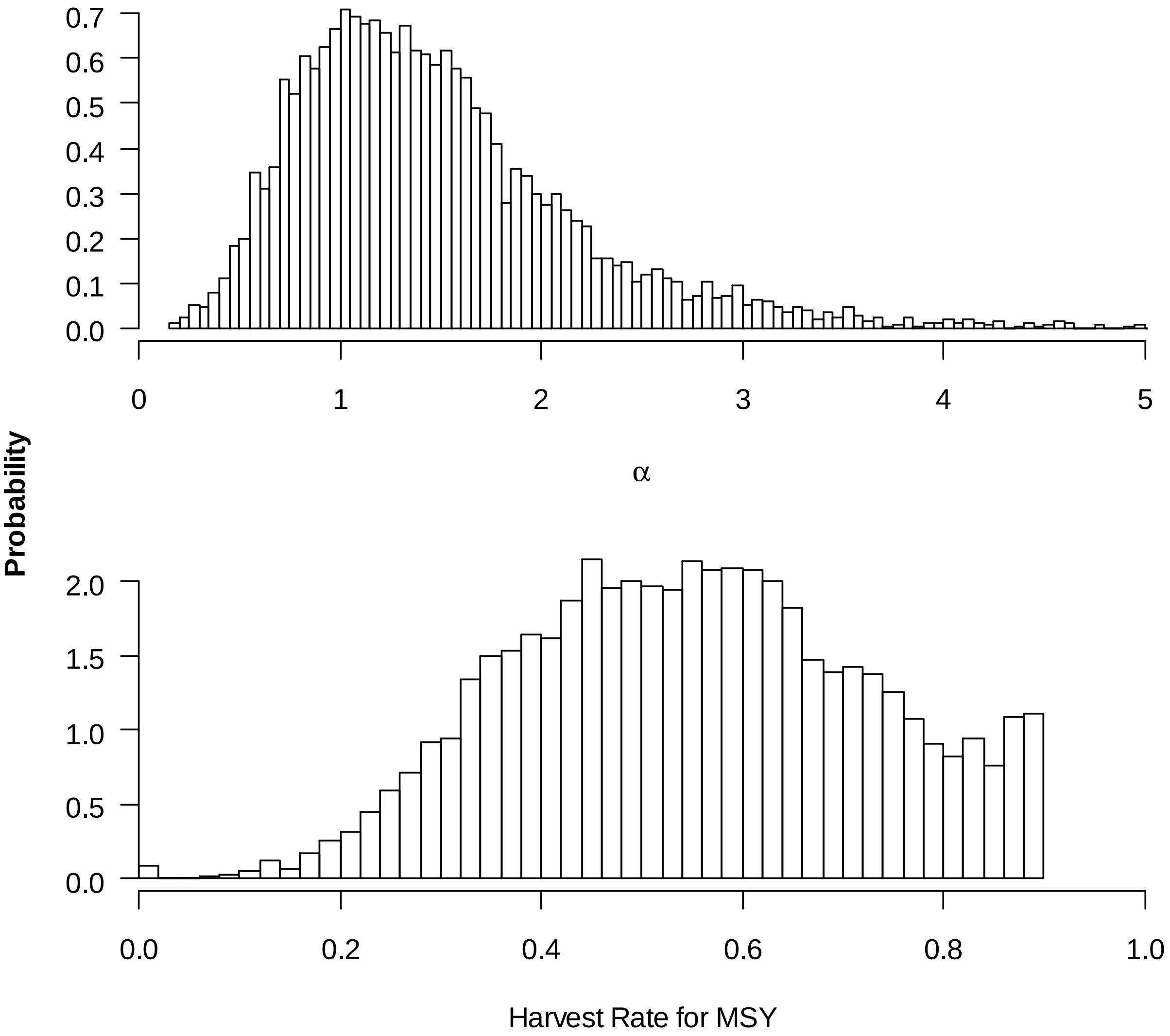

Figure 8. The distribution of Ricker α values (top) and associated optimal harvest rates (bottom) based on samples of α drawn from α hyper distributions determined from the posterior distributions of μ_α and σ_α.

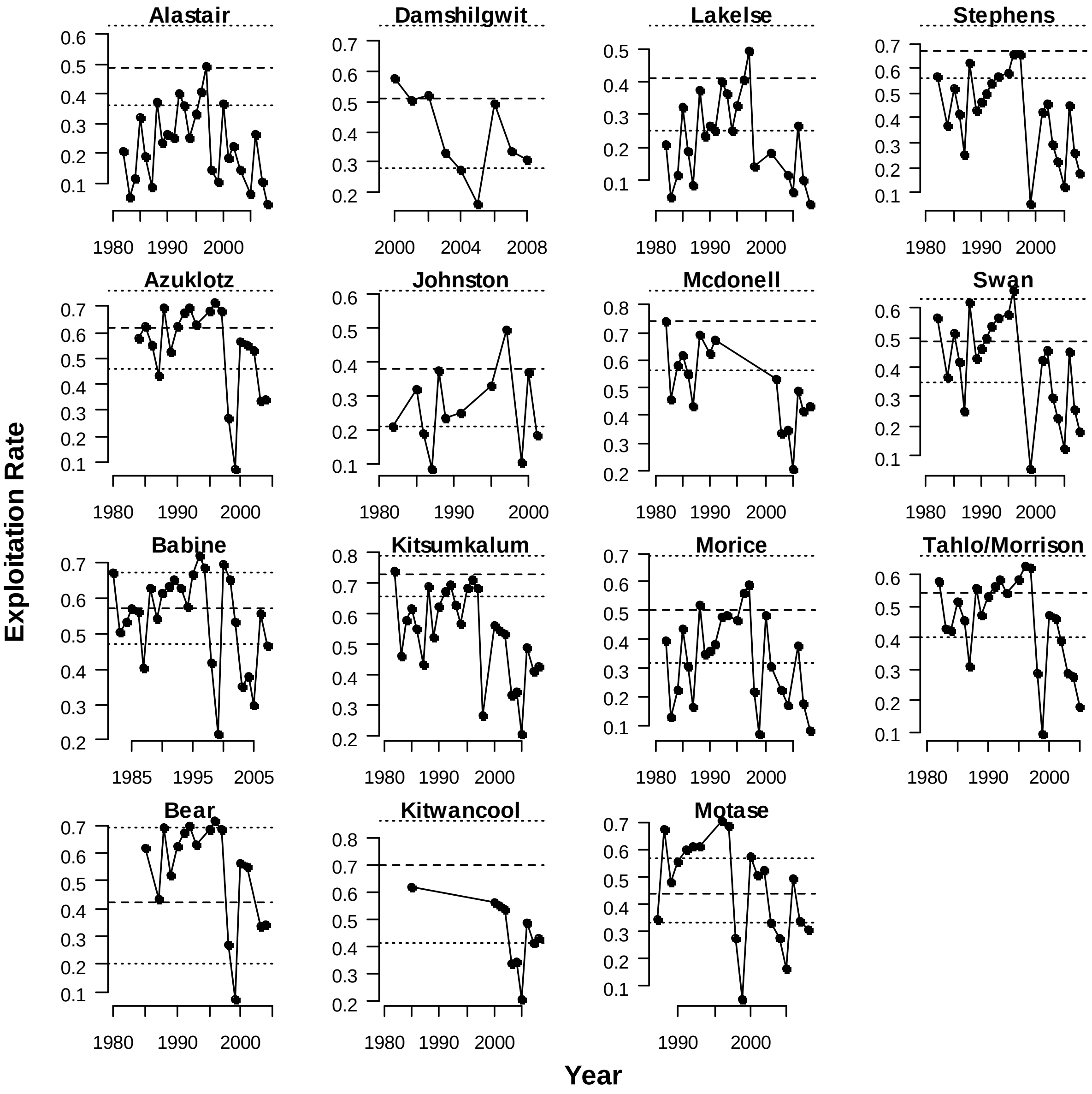

Figure 9. The historical exploitation rate for lake sockeye CUs in the Skeena relative to the mean estimate of the optimal exploitation rate (dashed horizontal line) and the 95% credible intervals of that optimal rate (finely dashed horizontal lines).

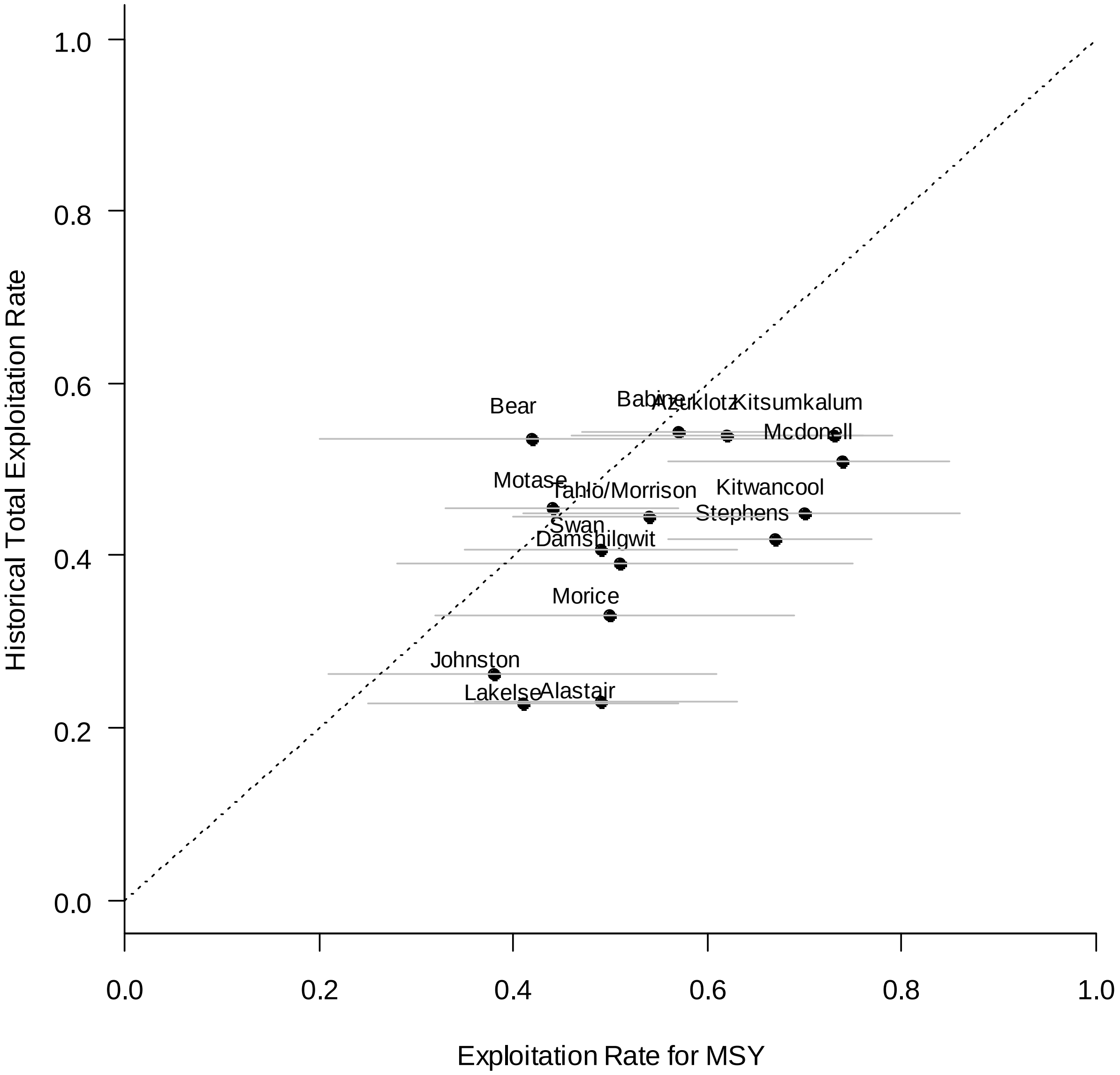

Figure 10. Comparison of the historic average total exploitation rate over the period of record (historical) relative to the estimated optimal rate to produce the maximum sustainable yield estimate from the HBM (Uopt). Points and horizontal lines denote the mean estimate of Uopt and the 95% credible 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.

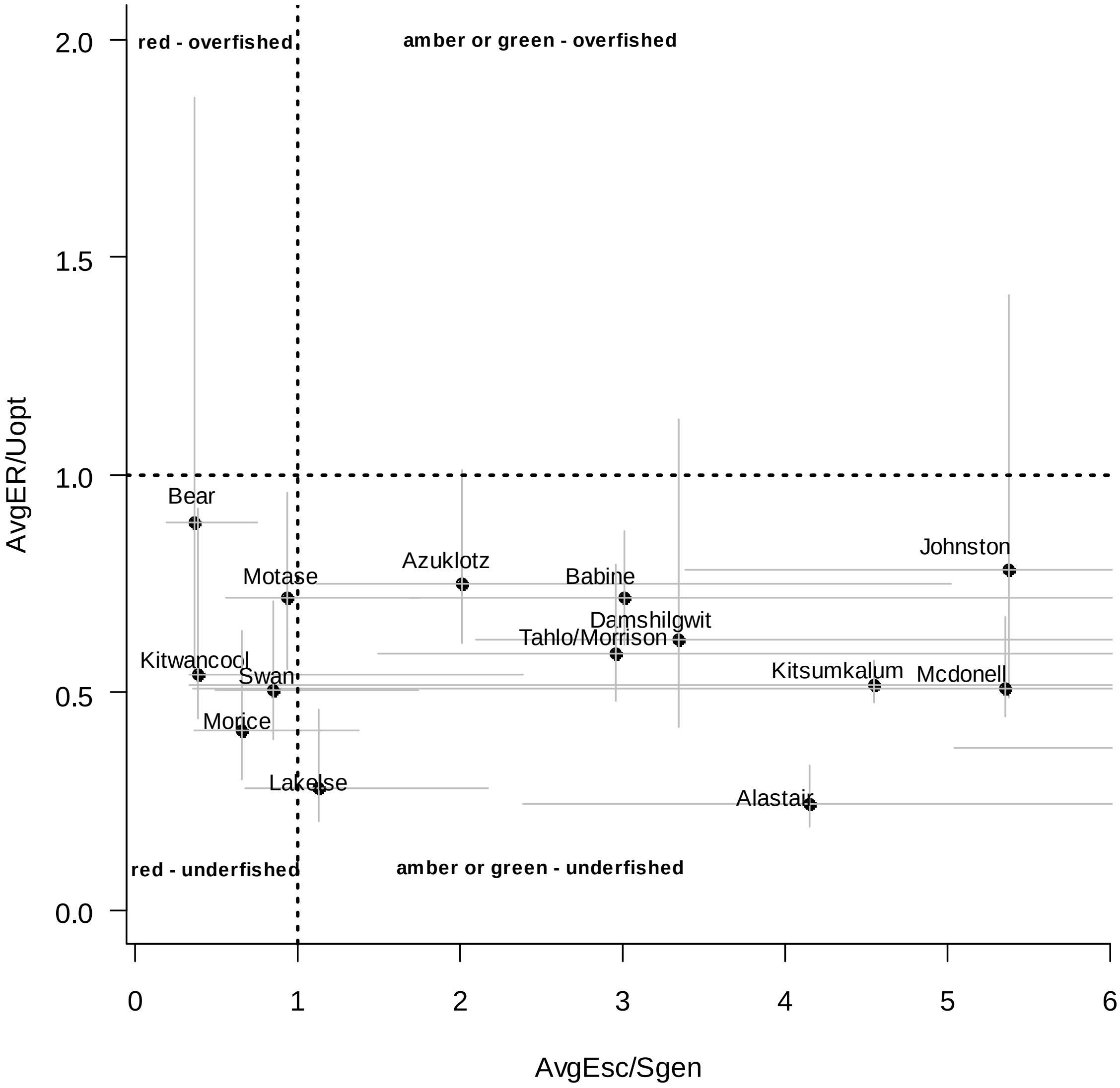

Figure 11. Status of 15 lake sockeye CUs in the Skeena based on the last 5 years of escapement and exploitation rate data relative to abundance and exploitation benchmarks. The x-axis is the ratio of the average escapement over the last 5 years of available data relative to the lower benchmark (Sgen). CUs with ratios less than one would be in the red status zone. The y-axis is the ratio of the average exploitation rate over the last 5 years of available data 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 Stephens CU is not shown as the AvgEsc/Sgen ratio was greater than 8 and exceeded the x-axis scale (this CU has a AvgER/Uopt ratio of 0.37, so the stock is in the green status zone and under fished).

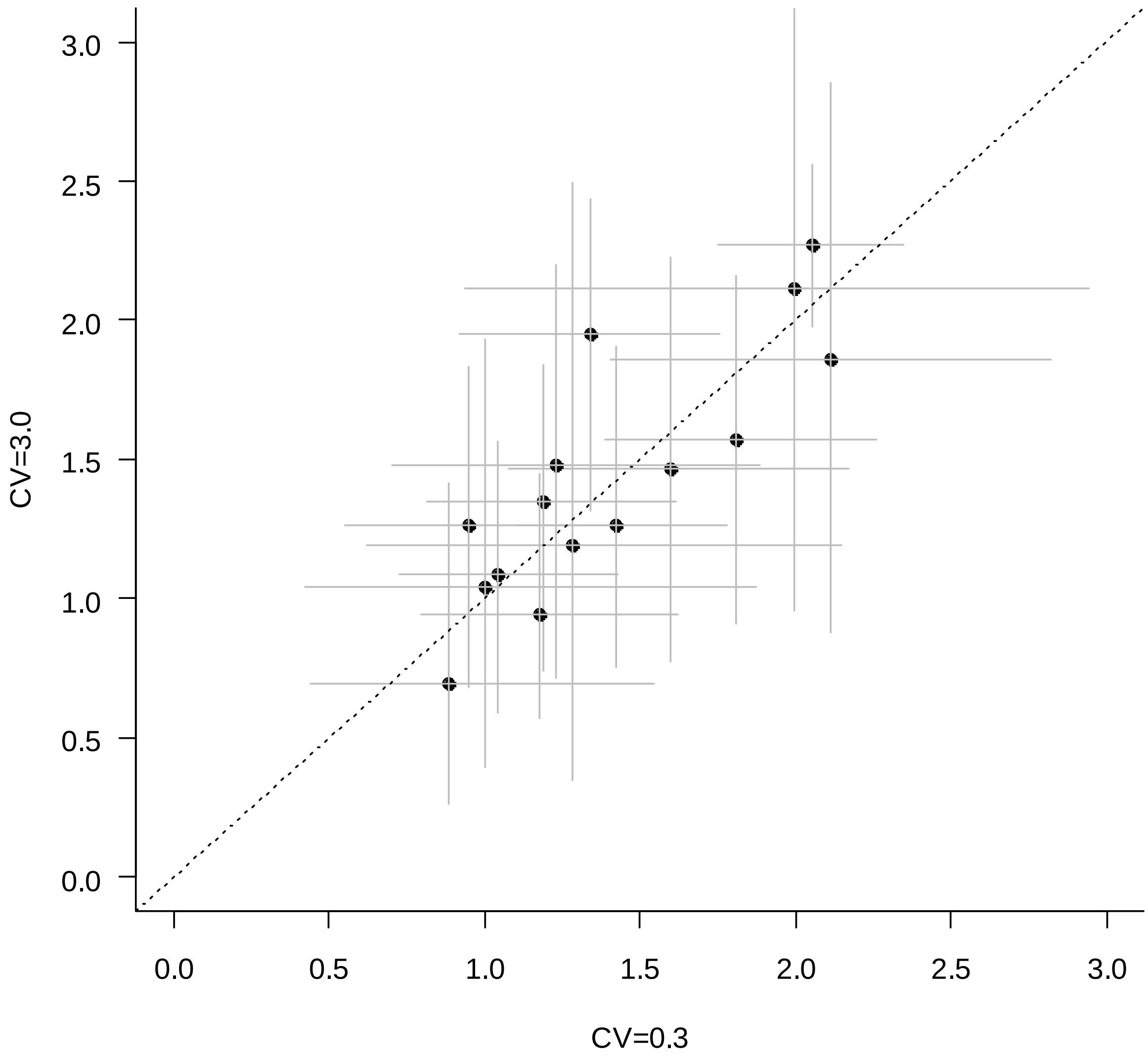

Figure 12. Comparison of HBM-based CU-specific estimates of α_i estimated with informative (CV=0.3) and uninformative (CV=3) prior distributions on Smax. Solid points and lines represent mean estimates and 95% credible intervals, respectively.

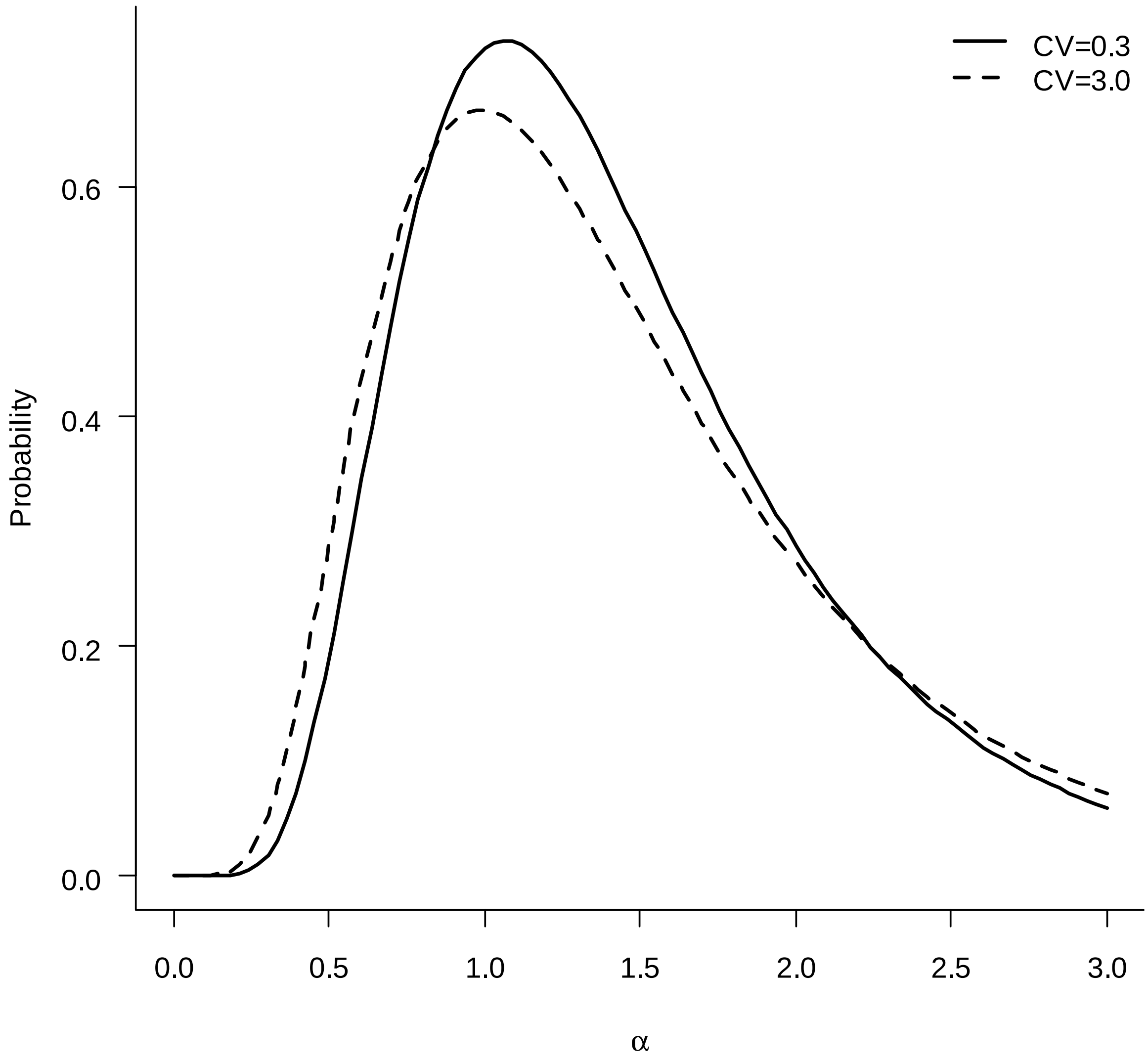

Figure 13. Comparison of mean hyper-distributions of α estimated with informative (CV=0.3) and uninformative (CV=3) prior distributions on Smax.