Approval

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Abstract

I developed a stochastic population model in a Bayesian decision analysis framework to evaluate management options for the depleted Cultus Lake, British Columbia, sockeye salmon stock. I sought state-dependent harvest rules that met three management objectives reflecting the probability of recovery within a specified period, the probability of abundance remaining above a conservation threshold, and the economic value of the harvest. This method produced quantitative information about tradeoffs between competing objectives. I found that recovery is feasible for the Cultus Lake sockeye stock under a number of harvest rules that allow harvesting in most years. Results were highly sensitive to pre-spawning mortality rate, indicating the need for a better understanding of that factor. Allowing the Cultus stock to recover may permit other late-run stocks to rebuild, thus partially offsetting the economic losses associated with reduced catches during recovery of the Cultus stock.

Keywords

recovery planning, Bayesian decision analysis, salmon management, fisheries simulation model, conservation

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(*Ptychocheilus oregonensis*) (Schubert et al. 2002). Adult pikeminnow are known to be predators of sockeye fry and smolts in Cultus Lake (Ricker 1941; Steigenberger 1972; Mossop et al. 2004).

Concern about the unusually high PSM rate and the dramatic decline in Cultus spawner abundance prompted increased assessment by Fisheries and Oceans Canada (DFO) (Schubert et al. 2002), as well as a public petition for emergency assessment by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). COSEWIC designated the population as Endangered by emergency assessment in November 2002 and by full committee in May 2003 (COSEWIC 2003), prompting DFO to form a Recovery Team for this stock. The COSEWIC assessment was sent to the Federal Government for the Cultus Lake sockeye salmon to be considered for listing under SARA. However, in 2004 the Canadian Minister of the Environment chose not to list this stock under SARA, because listing the Cultus sockeye stock would have triggered a ban

activities were specifically authorized through a permit under SARA or as part of the recovery strategy or action plan for the Cultus sockeye stock (Canada Gazette 2005). Any resulting reduction in the harvest rate of Cultus Lake sockeye would have also decreased opportunities to harvest co-migrating late-run Fraser River sockeye in the mixed-stock fishery in marine and estuarine waters, potentially reducing the value of that fishery by millions of dollars annually. The resulting social and economic costs were deemed unacceptably high.

Regardless of the legal status of the Cultus Lake sockeye salmon stock under SARA, DFO committed to continue developing a recovery strategy and subsequent

action plan for this stock. No matter what DFO subsequently does with that recovery strategy, the research reported here developed methods to help inform fisheries managers about the relative merits of management options in terms of the probability of recovery for this stock and the revenues from harvests on co-migrating salmon stocks. Furthermore, the procedures used here, as well as some qualitative findings, may be more widely applicable to recovery planning for other fish populations.

Population modeling

Most models of salmon population dynamics that have been used in analyses of conservation issues have been stochastic, PVA-type models (population viability analyses) that focused on estimating the chance that a population would either go extinct or reach some other undesirable level of abundance. A few of those models were developed to identify recovery strategies for achieving recovery goals for various Pacific salmon populations or to identify de-listing criteria (to define when to safely remove a stock from formal listing as "endangered"). Examples of such models are Botsford (1994), Botsford and Brittnacher (1998), McElhany et al. (2000), Peters and Marmorek (2001), Peters et al. (2001), Ford et al. (2001), and Ruckelshaus et al. (2002). It is clear from these and other cases that stock-specific, as opposed to general, models are needed to evaluate rebuilding options in the context of fully-specified, stock-specific recovery goals (Botsford 1994; Peters and Marmorek 2001; MacCall 2002). My research project aimed to meet this need for Cultus Lake sockeye salmon by developing a model to determine harvest strategies that have a high probability of meeting recovery goals in a timely manner.

The research reported here also extended previous salmon risk assessment models by incorporating into one analysis several factors that may have an important influence on the chance that any fish population, including the Cultus Lake sockeye population, will recover under a given set of natural and harvesting conditions. These factors are:

(1) Implementation uncertainty in the fishery;
(2) Changing, complex, and conflicting management objectives;
(3) Biological factors such as pre-spawning mortality; and
(4) Structural uncertainty in functional forms of model components, in particular, depensatory mortality in fresh water.

Each of these factors is important to include in analyses of Cultus Lake sockeye for several reasons. First, implementation uncertainty (i.e., deviation from the annual target escapement or target percent harvest rate) is important but is still not often included in models (Bocking and Peterman 1988; Rice and Richards 1996; Robb and Peterman 1998). Implementation uncertainty can occur in salmon fisheries for multiple reasons. First, the annual preseason forecast of recruit abundance, on which the target harvest rate is based, is imperfect, and in-season updates are often difficult. Second, the actual harvest rate in a fishery usually deviates from the target harvest rate. For example, large recruitment tends to lead to over-escapement because by the time in-season estimates indicate high salmon abundance, it is usually too late to harvest all the desired fish and

various problems in fisheries management (Lord 1976; Walters 1986; Robb and Peterman 1998; Schnute et al. 2000; Macgregor et al. 2002). Both risk assessment and decision analysis have also been applied in the management of endangered species (Maguire 1986; Ludwig 1996; Taylor et al. 1996; Marmorek and Peters 2001; Peters and Marmorek 2001; Peters et al. 2001).

My decision analysis for the management of Cultus Lake sockeye had eight components, as detailed in the next sections: (1) management objectives, (2) alternative management actions, (3) models for estimating consequences or outcomes for each combination of management action and uncertain state of nature, (4) uncertain states of nature to consider explicitly, (5) probabilities on each uncertain state of nature, (6) rankings of management actions, and (7) sensitivity analyses (Peterman and Anderson 1999). The eighth component, a decision tree, illustrates connections among these components for a limited subset of example management options, uncertain states of nature, and outcomes (Figure 2).

Management objectives

- typically left to the discretion of the recovery planners (Tear et al. 2005), as was the case for the Cultus Sockeye Recovery Team. Thus, for the purpose of this paper, I deemed the Cultus Lake sockeye stock to be

the 4-year running average (arithmetic mean) of spawner abundance (S) exceeded a recovery goal (X) by some year (T - 4-year running average of spawner abundance (S) remaining above a quasi-extinction level (Q) for (Y) years after recovery had been achieved. Use of the 4-year arithmetic mean

which the minimum proportional harvest rate, H_{min}, was the management target, and U was the Cultus recruit abundance above which the maximum proportional harvest rate, H_{max}, was the target. Between L and U, targets were a linear function of abundance. This state-dependent, time-independent harvest rule generated the desired, or target, harvest rate, H_{tar}, from the simulated annual abundance of Cultus sockeye recruits. Alternative management actions (different harvest rules) were defined by different combinations of values for L, H_{min}, U, and H_{max}.

I did a preliminary analysis in which I explored a wide range of shapes of harvest rules, as defined by these ranges of parameters: $1000<L<50{,}000$, $0.1<H_{min}<0.95$, $1000<U<200{,}000$, and $0.1<H_{max}<0.95$. This preliminary analysis indicated that values of L and H_{min} at the higher ends of these ranges resulted in lower long-term gross commercial revenues than other parameter values, even though the biological conservation objectives may have been met. Those harvest rules were thus sub-optimal and were not considered further. Therefore, I more thoroughly explored parameter values in these ranges: $1000<L<10{,}000$, $0.1<H_{min}<0.2$, $1000<U<140{,}000$, and $0.1<H_{max}<0.95$ and only report those results here.

Ideally, implementation uncertainty would be represented as a relation between annual recruitment and the resulting actual escapement (e.g., Robb and Peterman 1998) with stochastic variation around it. However, the available data for the late-run Fraser River sockeye stocks showed no such relation. Instead, to generate random implementation uncertainty on the target harvest rate, I used a *beta* distribution (Morgan and Henrion 1990) to represent the deviation of the actual harvest rate, H_{act}, from the

target proportional harvest rate, H_{tar}, which was calculated each year from the harvest rule. This distribution constrained the actual proportional harvest rate to between 0 and 1:

(1) $H_{act} = beta(\ _h\ ,\ _h)$

where values of $_h$ and $_h$ were the *beta* distribution's shape parameters, with $_h = H_{tar}$ for a given year and $_h = 0.1$. In years with Cultus recruit abundance less than L, H_{tar} and H_{act} were both set to zero to simulate a closure of the fishery.

Model to calculate outcomes, taking into account uncertainties

I first provide a general overview of the model; details follow in the next sections. I simulated annual changes in abundance of the Cultus Lake sockeye stock using a stochastic population model that incorporated uncertainties in each life stage and implementation uncertainty in harvest rate (Figure 4). I also modeled the population dynamics of other major late-run Fraser River sockeye stocks that migrate through fishing areas along with Cultus sockeye. The model calculated the abundance of, and harvest taken from, each stock at the end of every year. At the end of each year during the recovery period (1 to T, or 20 years, for the baseline recovery objective), the model determined whether the Cultus stock had recovered (whether the 4-year running average of spawner abundance reached X, or 20,000). If the Cultus stock successfully recovered within T years, the model continued to simulate and check abundance at the end of each year (T to $T + Y$ years, as indicated in the long-term survival objective) to determine whether the 4-year running average of spawner abundance had dropped below the quasi-extinction threshold Q, or 1000. At the end of a simulation of 120 ($T + Y$) years, the model calculated the long-term gross commercial revenue from the price and harvest of all late-run stocks over $T + Y$ years, as well as the mean annual gross revenue.

The above life history model was embedded in a stochastic simulation framework to calculate values for the three main indicators of the objectives (Pr_{rec}, Pr_{qext}, and expected gross commercial revenue from the catch) using the methods described below. Various management options (i.e., sets of parameter values that determined the shapes and axis scales of state-dependent harvest rules, as in Figure 3) were evaluated in the context of stochastic processes that represented several uncertain states of nature. Uncertainties included here were (1) parameters of the spawner-to-smolt relation for the Cultus stock, which reflected uncertainty about depensatory mortality, (2) a stochastic

1930s because large predator-control projects and hatchery experimentation took place at Cultus Lake during those years. I did not use data from 1995 to the present because of extremely high pre-spawning mortality rates during those years (Schubert et al. 2002, PSC 2003). Also, the spawner abundances for 1988 and 1989 were adjusted upward because the counting fence was in operation for an unusually brief time in those years (Mike Bradford, personal communication, DFO, Burnaby, B.C.). Although predator-control projects could have affected smolt production for the 1967 and 1989-1991 brood years, M. Bradford (personal communication) concludes that these projects were small enough that they likely had little-to-no effect on the smolt-per-spawner ratio for those years. Estimates of pre-spawning mortality rates for the Cultus Lake sockeye stock were from Schubert et al. (2002).

Cultus stock

The model of the Cultus Lake sockeye stock was divided into several life stages. First, it was initialized with spawner abundances from 1998-2001 (Table 2). A modified Beverton-Holt model (Myers et al. 1995) incorporated depensation into the Cultus sockeye spawner-to-smolt relation:

(2) $Sm_t = ((a*S_t^d)/(1 + (S_t^d/K)))*\exp(v_t)$

where Sm_t is the abundance of smolts generated from the spawners, S_t, in a given brood year t, and a, d, and K are parameters; v_t is assumed to be a normally distributed error term with a mean of 0 and a variance of $\mathring{u}^2_v$. Equation 2 represents a standard Beverton-Holt curve when $d = 1$; depensation occurs when $d > 1$, and hypercompensation occurs when $d < 1$ (Myers et al. 1995)

probability distribution (Gelman et al. 2004) based on historical spawner-to-smolt data for the Cultus stock. These data and the best-fit relation are shown in Figure 5. Appendix 1 gives details of the Bayesian calculations that produced marginal posterior probability distributions for the parameters *a*, *d*, and *K* (Figure 6).

The Cultus smolt-to-adult-recruits relation was

(3) $R_t = c\, Sm_t^{\,b} \exp(g_t)$

where R_t is the abundance of Cultus adult recruits from brood year *t*, Sm_t is Cultus smolts from brood year

where *PSM* is a fixed proportional pre-

as for the Cultus stock (eq. 5 and 6). The actual harvest and pre-spawning mortality rates for the Cultus stock in a given year were also applied to all other late-run stocks in that year.

Performance measures

The gross commercial revenue from harvesting late-run Fraser River sockeye in each year was the sum of fish harvested from each stock multiplied by a fixed price per fish (estimated in Appendix 2). During a simulation of 120 ($T + Y$) years, the model recorded whether the Cultus stock recovered and, if so, the year of recovery (to determine whether the stock met the recovery objective, objective #1), as well as whether the Cultus stock went quasi-extinct and, if so, the year of quasi-extinction (to determine whether the stock met the long-term survival objective, objective #2). The model also recorded the long-term gross commercial revenue from the harvest of all late-run Fraser River sockeye stocks over the 120 years.

Monte Carlo trials for decision analysis

The Monte Carlo procedure for this decision analysis (Figure 7) began with calculating a posterior probability for every combination of parameters *a*, *d*, and *K* of the Cultus spawner-to-smolt relation (one combination = a scenario). As illustrated in Figure 6 and described in Appendix 1, I used 16 different values for *a*, 14 for *d*, and 15 for *K*, for a total of 3360 different combinations of these parameters, or different scenarios .

I simulated the life history and harvest of all late-run stocks for 120 years using Monte Carlo (MC) trials for each scenario of Cultus spawner-to-smolt parameters in

Sensitivity analyses

To identify key uncertainties that have the greatest effect on the choice of management actions, I performed sensitivity analyses on pre-spawning mortality rate and the parameters of the management objectives (Table 1). This model easily allows for changes to other assumptions and factors that I did not explore because they were beyond the scope of this project. Those factors include the impacts of future changes in adult body size on both fecundity and revenue from harvest, the effect of using different values of the parameters of the beta distribution used to calculate implementation uncertainty, and the inclusion of a more comprehensive economic indicator resulting from a full economic analysis of the costs and benefits associated with the harvest of late-run Fraser River sockeye.

Results

The analysis produced many cases of individual Monte Carlo trials for which, within the first 20 years, the Cultus stock recovered, did not recover, or recovered but then went quasi-extinct (Figure 8). Results of all simulations across different harvest rules can be efficiently described in terms of Pr_{rec}, or the estimated probability of recovery for Cultus sockeye, which was compared to Z_1, the desired probability of recovery (Figure 9). Each harvest rule has four parameters, so to represent different harvest rules in this figure, I fixed H_{min} at either 0.1 or 0.2 and L at either 1000 or 10,000 and varied U and H_{max} for each of these four combinations of L and H_{min}. I used these four combinations of L and H_{min} because, as mentioned previously, preliminary simulations indicated that higher values of L and H_{min} resulted in lower long-term

Because every harvest rule that met a recovery objective (defined by its X, T, and Z_1) also met the long-term survival objective (defined by Q, Y, and Z_2), I ranked all harvest rules meeting a given recovery objective according to the expected gross commercial revenue from the harvest of late-run Fraser River sockeye (Tables 5-8 for Z_1 = 0.6, 0.7, 0.8, and 0.9, respectively). Rankings are shown, as well as both the expected long-term and mean annual gross commercial revenue from the harvest for each harvest rule. For the baseline case, when Z_1 = 0.9, harvest rule #43 met that recovery goal as well as provided the highest long-term gross revenue from the harvest (Table 5). That rule's shape parameters were L = 10,000, H_{min} = 0.2, U = 65,000, H_{max} = 0.63 (Figure 10). The expected gross revenue from this harvest rule was $5.241 billion over 120 years or a mean of $43.68 million annually.

Although a single expected (weighted average) gross commercial revenue was calculated for each harvest rule, there was a range of possible economic outcomes with varying probabilities of occurrence, such as in Figure 11, which was based on the 3360 scenarios of parameters for the Cultus spawner-to-smolt relation. To calculate the expected gross revenue, each individual outcome was weighted according to the posterior probability for the scenario that produced it.

For harvest rules that allowed the Cultus stock to recover under baseline conditions and management objectives (Z_1 = 0.9), t 0gross reven8as7172u3 TmsETBTetowllion annually

long-term survival objectives for Cultus sockeye. To achieve this, in the harvest rule of Figure 3, a manager would want to minimize *L*, the number of Cultus recruits below which no harvest is taken, given the other constraints. Many harvest rules with low *L* did not meet the recovery and survival objectives; however, all harvest rules in Tables 5-8 did meet them and had either $L = 1000$ or $L = 10{,}000$. In most simulations with harvest rules that allowed Cultus sockeye to recover to a spawner abundance of 20,000 by year 20, the trajectory of population growth was such that Cultus sockeye were able to produce 1000 recruits in the first few years.

the conservation objectives for the baseline case (in which $Z_1 = 0.9$) are ranked by gross revenue from the catch, there is relatively little difference in gross revenue among the top 40 rules but considerable difference in the proportion of years with little or no fishing (Figure 15A). If managers wished to have no closures, the harvest rule that ranked 4th economically (rule #22, Table 5) would be best (no closures). However, if 3% of years with little or no fishing were acceptable, any of the rules ranked 1-3 (rules #43, 44, and 42) would be appropriate, but would produce a less than 1% increase in expected gross

#43, Table 5), but I then performed the analysis with PSM set to 0.2 and 0.3. This represented situations in which PSM is underestimated and, therefore, a sub-optimal harvest rule is used. When the PSM rate was set to 0.2, the Cultus stock had a 0.7 probability of recovery (Pr_{rec}), and when PSM rate was set to 0.3, the probability of recovery dropped to 0.42 (Table 9). Gross revenue also decreased when the actual PSM was higher than estimated. Expected mean annual gross revenue decreased by about $1.2 million when PSM was 0.2 (2.7% less than the baseline expected value), and dropped another $1.5 million when PSM was 0.3 (6.1% less than the baseline expected value).

Price per fish

The estimated price per fish (Appendix 2) was based on body size data from a troll test fishery. The size-selectivity of the gear in that test fishery may differ from that of the gear used in the commercial fishery, which would lead to a somewhat inaccurate estimate of the commercial price per fish. More importantly, future prices for fish cannot be known. Changes in price per fish would not lead to changes in the rank order of harvest rules in Tables 5-8; they would only lead to a change in the magnitude of gross commercial revenue for each harvest rule. For example, a 10% increase from $6.96 to $7.65 in mean processed price per kg round would lead to a corresponding 10% increase in gross revenue for each harvest rule and would cause the curve in Figure 13 to shift upward by 10%. Similarly, if a 2- or 3-decade decrease in body weight per fish were to occur again as observed in the past, a 10% decrease in mean weight per fish from 3.14 kg to 2.83 kg would lead to a corresponding 10% decrease in gross revenue for each harvest rule and would cause the curve in Figure 13 to shift downward by 10%.

Biological feasibility of recovery

Part of the mandate of recovery teams under SARA is to determine whether the

Although the model indicated that recovery of the Cultus stock is biologically feasible, recovery of the Cultus stock has not been seen in recent years. One likely reason for the discrepancy between the modeling results and the actual state of the Cultus stock is that in the model the target harvest rate in each year was based solely on the abundance of Cultus recruits, and the harvest rules were chosen with the purpose of allowing the Cultus stock to recover. In reality, the target harvest rate has historically generally been set by the Fisheries and Oceans Canada with the entire late-run aggregate in mind, particularly the much more abundant stocks, and with much less importance placed on smaller stocks such as the Cultus stock. Also, factors not included in my model, such as unusually low freshwater or marine survival rates, or elevated pre-spawning mortality rates such as those seen in the mid-1990s, can hold the stock at lower abundances in the field than in the model.

The ability of any harvest rule to meet conservation objectives was critically dependent upon the assumed pre-spawning mortality rate (PSM), for which we do not understand the causes of variation. This result emphasizes the need to better understand the elevated PSM rates for late-run Fraser River sockeye in the late 1990s and early 2000s and to improve predictions of PSM. An example is the research being conducted by Cooke et al. (2004). Although at this time little is known about the exact causes and interactions among contributing factors, Cooke et al. are exploring possible causes for early migration to freshwater and its associated elevated PSM. Their hypotheses are related to energetics, osmoregulation, oceanic conditions, in-river conditions, and parasites, among others. Since in my model the Cultus stock did not recover at PSM rates of 0.5 or higher, enhancement may become increasingly important for survival of the

Cultus stock if PSM rates rise above 0.5 again. However, I simulated PSM as a constant. Episodic patterns of PSM rates may permit the Cultus stock to recover if PSM only rises above 0.5 for a few years, although harvest rules may need to be more conservative than when PSM is a constant at 0.1. Because underestimating PSM can severely reduce the probability of recovery and the economic value of harvest, managers may wish to build a conservative safety margin into their choice of harvest rules until scientists are better able to predict PSM rates. These arguments concerning PSM are equally appl

the objectives to be explored, which is useful because there is no single easily-agreed-upon objective

rules may change. Ideally, managers may use results from this type of model to find management actions that perform well (are robust to) a variety of management objectives, such as maximizing expected gross revenue while minimizing the expected number of years with no harvest.

For endangered stocks and species for which recovery may have large decreases in economic benefits, such as the Cultus sockeye, these types of results can allow managers to determine the economic value of protecting or not protecting the stock. The Canadian Minister of the Environment cited excessive costs as a reason to not list the Cultus Endangered under the Species at Risk Act, but this conclusion was based on analyses (e.g., GSGislason and Associates, Ltd. 2004) that focused on costs and overlooked social and economic benefits associated with protecting and generating recovery of the stock. The Gislason report only examined the economic costs of restricting harvest on the late-run Fraser River sockeye to achieve various levels of Cultus sockeye spawner escapement for one year, 2004. The report did not include corresponding decreases in costs associated with a reduced harvest, such as reduced costs of labor, maintenance, fuel, and boats, and did not include any projections of long-term economic value (Gross et al. 2004). Depending on the economic factors included in the model and the parameter values used, stochastic simulation models such as the one used here may give a more accurate and complete assessment of costs and benefits associated with recovery and may show that the decreased harvest rates necessary to allow Cultus sockeye to recover may also allow other late-run stocks to rise to higher abundances, leading to higher catch and greater benefits in the long run than initially expected.

In this model, the starting abundances for most simulated late-run stocks were below S_{msy} for each given stock (Table 2). Also, the late-run Fraser River sockeye stocks tend to have relatively high harvest rates at MSY (H_{msy}) (Table 2). The lower harvest rates that allowed the Cultus stock to recovery also allowed the other late-run stocks to be rebuilt, which may explain why the expected revenue showed a relatively weak dependence on the choice of harvest rule. As illustrated in Figure 14, when Pr_{rec} declined by 11% from 0.9 to 0.8, expected gross revenue only declined 6% from $46.4 to $43.7 million. If the other late-run stocks were

the recovery period led to fewer recruits produced per spawner, and as a result the stock took longer to achieve the recovery goal.

For all harvest rules that allowed the Cultus stock to recover to a level of 20,000 spawners by year 20 and achieved a desired probability of recovery of 0.9, the expected year of recovery was consistently around year 15 (Table 5, Figure 14) . This is because the first four years of the model were seeded with actual spawner abundances from 1998-2001 (Table 2). In years 1 and 2 (1998 and 1999) the Cultus stock had relatively high spawner abundances compared to years 3 and 4. These more abundant cycle lines returned in years 5 and 6, 9 and 10, and 14 and 15. The rate of recovery of the population under relatively light fishing was such that these more-abundant cycle lines did not typically exceed the recovery goal until the middle of the second decade of the simulation. Depending on values of stochastic processes and probability of recovery, the weighted average year of recovery across Monte Carlo trials could be shifted forward or back in time, but only by a year or two (Figure 14). Note, though, that compared to that weighted average recovery date, the date was much more variable among individual Monte Carlo trials for a given harvest rule (Figure 12).

My results indicate that a harvest rate that increases along with abundance of Cultus Lake sockeye recruits is economically beneficial up to a certain abundance, above which a constant proportional harvest rate maximizes gross revenue. For example, when $Z_1 = 0.9$, the harvest rule with the highest gross revenue had $U = 65{,}000$ and $H_{max} = 0.63$ (rule #43, Table 5), even though the stock could still meet the recovery and survival objectives with U as high as 140,000. This occurred because when U was set to a higher value, such as in rule #51 where $U = 100{,}000$ (Table 5), H_{max} had to be correspondingly

a reversal of oceanographic conditions that persisted during substantial decreases in age-specific body size of Pacific salmon in the previous decades (Bigler et al. 1996; Pyper and Peterman 1999; Lapointe et al. 2004). Sensitivity analyses could be conducted using hypothesized increasing or decreasing body sizes over time, which would affect expected economic yields. These trends in body size are rarely accounted for in models, even though fecundity clearly depends on body size, as should parameters of the spawner-to-smolt relation.

The decision analysis performed here could be a useful tool in recovery planning for the Cultus sockeye. However, as cautioned above, there are still many unknown processes of variation that were not included in this model. Any one of them could potentially affect the ability of harvest rules to meet conservation and harvesting objectives. Furthermore, decisions should never be made based solely on results of models such as this one. Many other factors must be taken into account when making management decisions, including those that cannot be quantified, such as changes in biological diversity or social benefits associated with fishing. Decision analysis is by nature. De295.1dbodpro(. Mpr)3(oc)4as 8(ende)4(dm[(auld beti)-3(ment de)-t)4(ludede(e)(s.(na)4(tuma3

As Irvine et al. (2005) note in the context of Canada's Species at Risk Act (SARA),

> Unfortunately, making tradeoffs to conserve diversity raises socioeconomic issues that can lead to hesitancy to fully embrace the goal of protect salmon diversity SARA provides an opportunity and legal means for management to concentrate harvest at the point where it is biologically most appropriate. It highlights that harvest remains possible even if it is not where society has previously wished to operate. SARA requires that Canadians consider the economic and social implications of guaranteeing the protection of biodiversity at these fine levels by evaluating implications prior to making a decision to legally list. In the end, society will decide the level of salmon diversity that it will protect.

Tables

Table 1. Baseline

Table 3. Parameters of the Cultus smolt-to-adult-recruit relation (eq. 3 and 4), where *c* and *b*

Table 4. Stock-specific parameter values for non-Cultus late-run Fraser River sockeye stocks, where $\check{U}_s$ and $\acute{o}_s$ are parameters of the Ricker relation (eq. 7), $\ _s$ is the autocorrelation coefficient for residuals (eq. 8), $\mathring{u}^2_{u,s}$ is the variance of residuals of equation 8, and $p_{4,s}$ is the proportion of the stock that returns at age 4 (eq. 4). Harrison Rapids sockeye return at age 3 and age 4, so

Table 5. Results for the baseline case (Table 1). Harvest rules for which the estimated probability of recovery (Pr_{rec}) for the Cultus stock meets or exceeds a desired probability of recovery (Z_1) of 0.9, where L, H_{min}, U, and H_{max} are parameters of the harvest rule.

Pr_{rec}

Table 5 continued.

14	1	0.2	10	0.42	0.914	0.00	4285	35.71	0.2	0.2	0.002	0.002	14.9	49
15	1	0.2	20	0.43	0.925	0.00	4350	36.25	0.2	0.2	0.002	0.002	14.6	48
16	1	0.2	20	0.45	0.915	0.00	4570	38.08	0.2	0.2	0.002	0.002	14.8	46
17	1	0.2	50	0.50	0.938	0.00	4737	39.47	0.2	0.2	0.002	0.002	14.6	43
18	1	0.2	50	0.52	0.918	0.00	4929	41.07	0.2	0.2	0.002	0.002	14.8	34
19	1	0.2	60	0.56	0.907	0.00	5088	42.40	0.2	0.2	0.002	0.002	15.0	23
20	1	0.2	70	0.60	0.902	0.00	5187	43.22	0.2	0.2	0.002	0.002	15.1	8
21	1	0.2	80	0.63	0.910	0.00	5175	43.12	0.2	0.2	0.002	0.002	15.3	10
22	1	0.2	90	0.67	0.904	0.00	5205	43.38	0.2	0.2	0.002	0.002	15.2	4
23	1	0.2	100	0.70	0.902	0.00	5141	42.84	0.2	0.2	0.002	0.002	15.3	19
24	1	0.2	100	0.71	0.903	0.00	5167	43.06	0.2	0.2	0.002	0.002	15.4	12
25	1	0.2	120	0.77	0.904	0.00	5012	41.76	0.2	0.2	0.002	0.002	15.4	28
26	1	0.2												

Table 5 continued.

Harvest rule	L (1000s)	H_{min}	U (1000s)	H_{max}	Pr_{rec}	Pr_{qext}			Number years no harvest	Number years small harvest	Proportion years no harvest	Proportion years small harvest	Year of recovery	Economic ranking
41	10	0.2	20	0.49	0.903	0.00	4907	40.89	4.1	4.1	0.034	0.034	14.7	35
42	10	0.2	60	0.61	0.907	0.00	5229	43.57	4.1	4.1	0.034	0.034	15.0	3
43	10	0.2	65	0.63	0.906	0.00	5241	43.68	4.1	4.1	0.034	0.034	15.1	1
44	10	0.2	70	0.65	0.906	0.00	5234	43.62	4.1	4.1	0.034	0.034	15.1	2
45	10	0.2	80	0.67	0.927	0.00	5134	42.78	4.0	4.0	0.034	0.034	14.9	20
46	10	0.2	80	0.68	0.919	0.00	5172	43.10	4.1	4.1	0.034	0.034	15.1	11
47	10	0.2	80	0.69	0.906	0.00	5192	43.27	4.1	4.1	0.034	0.034	15.1	7
48	10	0.2	100	0.73	0.947	0.00	4986	41.55	4.0	4.0	0.034	0.034	14.8	31
49	10	0.2	100	0.74	0.938	0.00	4998	41.65	4.1	4.1	0.034	0.034	14.9	30
50	10	0.2	100	0.76	0.916	0.00	5020	41.83	4.1	4.1	0.034	0.034	15.1	27
51	10	0.2	100	0.77	0.913	0.00	5056	42.13	4.1	4.1	0.034	0.034	15.2	25
52	10	0.2	120	0.84	0.915	0.00	4821	40.17	4.2	4.2	0.035	0.035	15.1	39

Table 6. Results for the baseline parameters (Table 1), except for Z_1, which is 0.8. Harvest rules for which the probability of recovery (Pr_{rec}) for the Cultus stock meets or exceeds a desired probability of recovery (Z_1) of 0.8. Column headings are as defined in Table 5.

Table 6 continued.

				H_{max}	Pr_{rec}	Pr						Proportion years small harvest	Year of recovery	Economic ranking
27	1	0.2	100	0.71	0.892	0	5171	43.09	0.2	0.2	0.002	0.002	15.4	36
28	1	0.2	100	0.72	0.891	0	5185	43.21	0.2	0.2	0.002	0.002	15.6	34
29	1	0.2	100	0.75	0.836	0	5249	43.74	0.2	0.2	0.002	0.002	15.8	26
30	1	0.2	100	0.76	0.820	0	5262	43.85	0.2	0.2	0.002	0.002	15.9	23
31	1	0.2	100	0.77	0.804	0	5249	43.74	0.2	0.2	0.002	0.002	16.1	25
32	1	0.2	140	0.91	0.821	1.25E-04	4745	39.54	0.2	0.2	0.002	0.002	15.8	51
33	10	0.1	20	0.55	0.817	0	5500	45.83	4.3	5.6	0.036	0.046	15.3	6
34	10	0.1	40	0.61	0.819	0	5506	45.88	4.1	8.0	0.035	0.066	15.4	5
35	10	0.1	50	0.61	0.888	0	5252	43.77	4.0	9.1	0.034	0.075	14.9	24
36	10	0.1	60	0.67	0.851	0	5246	43.72	4.1	10.3	0.034	0.086	15.3	27
37	10	0.1	60	0.68	0.814	0	5278	43.98	4.1	10.3	0.034	0.086	15.4	19
38	10	0.1	65	0.68	0.889	0	5166	43.05	4.1	10.8	0.034	0.090	15.2	37
39	10	0.1	80	0.76	0.874	0	4988	41.56	4.1	12.5	0.034	0.104	15.4	47
40	10	0.1	80	0.78	0.808	0	4953	41.27	4.1	13.0	0.034	0.108	15.6	49
41	10	0.1	100	0.85	0.887	0	4588	38.23	4.4	15.9	0.036	0.132	15.2	56
42	10	0.1	100	0.88	0.804	2.88E-15	4476	37.30	5.2	17.8	0.043	0.148	15.5	57
43	10	0.1	120	0.93	0.879	1.76E-03	3988	33.24	8.4	23.7	0.070	0.198	14.9	59
44	10	0.1	120	0.94	0.855	3.43E-03	3857	32.14	9.9	25.5	0.083	0.212	15.0	61
45	10	0.1	120	0.95	0.820	8.14E-03	3726	31.05	11.4	27.2	0.095	0.227	14.9	62
46	10	0.2	20	0.54	0.828	0	5430	45.25	4.2	4.2	0.035	0.035	15.2	11
47	10	0.2	20	0.55	0.802	0	5527	46.06	4.3	4.3	0.036	0.036	15.2	3
48	10	0.2	40	0.55	0.892	0	5186	43.22	4.1	4.1	0.034	0.034	14.9	33
49	10	0.2	40	0.56	0.886	0	5271	43.93	4.1	4.1	0.034	0.034	15.0	22
50	10	0.2	40	0.57	0.863	0	5353	44.61	4.1	4.1	0.034	0.034	15.1	16
51	10	0.2	40	0.59	0.830	0	5499	45.83	4.1	4.1	0.034	0.034	15.2	7
52	10	0.2	40	0.60	0.807	0	5569	46.41	4.2	4.2	0.035	0.035	15.3	1
53	10	0.2	60	0.62	0.890	0	5284	44.03	4.1	4.1	0.034	0.034	15.1	18
54	10	0.2	60	0.62	0.888	0	5276	43.97	4.1	4.1	0.034	0.034	15.1	20
55	10	0.2	60	0.66	0.802	0	5459	45.49	4.1	4.1	0.035	0.035	15.6	8
56	10	0.2	80	0.70	0.889	0	5240	43.67	4.1	4.1	0.034	0.034	15.3	29

Table 6 continued.

57	10	0.2	80	0.73	0.818	0	5272	43.93	4.1	4.1	0.034	0.034	15.6	21
58	10	0.2	100	0.78	0.890	0	5025	41.87	4.1	4.1	0.034	0.034		

6025

Table 7. Results for the baseline parameters (Table 1), except for Z_1, which is 0.7. Harvest rules for which the probability of recovery (Pr_{rec}) for the Cultus stock meets or exceeds a desired probability of recovery (Z_1) of 0.7. Column headings are as defined in Table 5.

1	1	0.1	10	0.52	0.732	0.00	5409	45.07	0.2	1.4	0.0019	0.0114	15.9	21
2	1	0.1	10	0.53	0.703	0.00	5521	46.01	0.2	1.3	0.0019	0.0112	16.0	17
3	1	0.1	40	0.61	0.727	0.00	5668	47.23	0.2	3.7	0.0019	0.0312	15.8	7
4	1	0.1	50	0.64	0.732	0.00	5585	46.54	0.2	4.4	0.0019	0.0364	15.8	12
5	1	0.1												

Table 8. Results for the baseline parameters (Table 1), except for Z_1, which is 0.6. Harvest rules for which the probability of recovery (Pr_{rec}) for the Cultus stock meets or exceeds a desired probability of recovery (Z_1) of 0.6

Table 9. Results when the constant pre-spawning mortality rate (PSM) is 0.2 or 0.3, but when the harvest rule is used that has the highest expected gross revenue satisfying $Z_1 = 0.9$ in a case where PSM = 0.1 (rule #43, Table 5). The harvest rule parameters are L = 10,000, $H_{min} = 0.2$, U = 65,000, $H_{max} = 0.63$. Column headings are as defined in Table 5.

PSM	Pr_{rec}	Pr_{qext}	Long-term revenue ($mil.)	Annual revenue ($mil.)	Number years no harvest	Number years small harvest	Proportion years no harvest	Proportion years small harvest	Year of recovery
0.1	0.906	0.00	5241	43.68	4.1	4.1	0.0339	0.0339	15.07
0.2	0.702	0.00	5095	42.46	4.3	4.3	0.0361	0.0361	16.04
0.3	0.419	0.00	4918	40.98	4.7	4.7	0.0395	0.0395	16.66

Figures

Figure 1. Annual abundance of Cultus Lake sockeye adult spawners (escapement), 1925-2001.

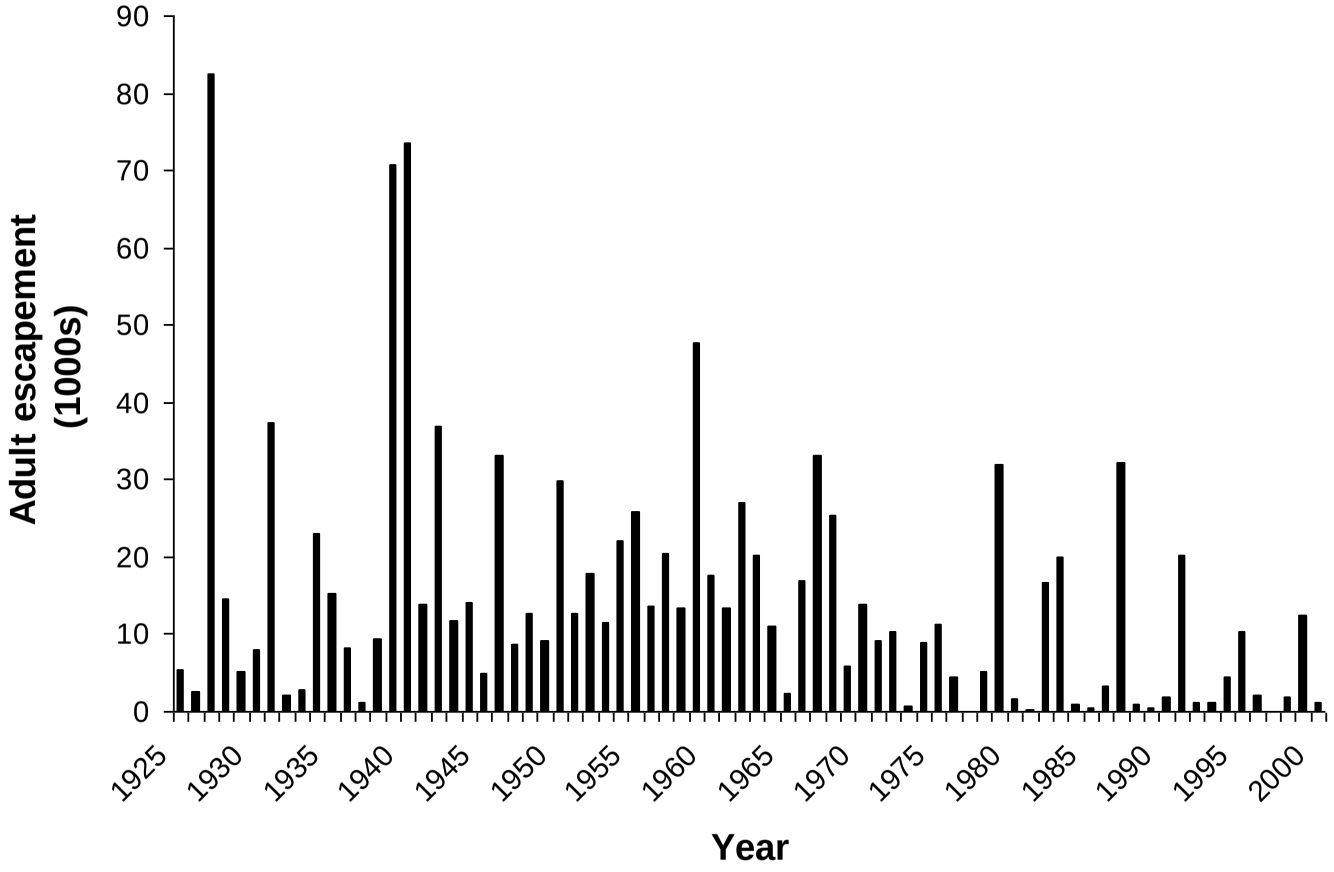
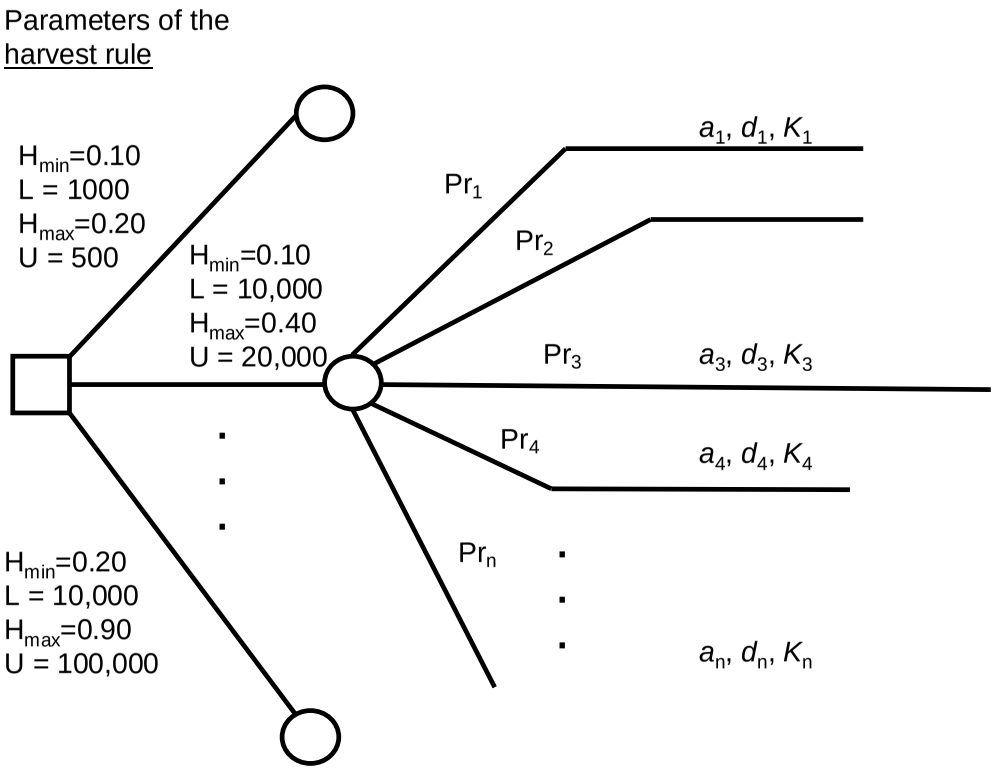

Adult escapement (1000s)
90
80
70
60
50
40
30
20
10
0
1925
1930
1935
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year

Figure 2. Decision tree illustrating the main structure of this analysis. Branches emanating from the square node represent different harvest rules, each one described by a set of parameters as illustrated in Figure 3. Branches emanating from round nodes are uncertain states of nature. For each possible harvest rule, there is an uncertainty node that has a branch for every possible state of nature (combination of parameter values for the Cultus spawner-to-smolt model). The relative weighting (or probability, Pr_n) on each uncertain state is the Bayesian joint posterior probability for a given combination of those parameters. The figure only shows a subset of the many harvest rules and uncertain states of nature.

Management options

Uncertain states of nature and their respective probabilities of occurrence

Outcomes



Pr (S > X by year T)

Pr (S < Q over next Y years after recovery)

Gross revenue from harvest of late-run Fraser River sockeye salmon

L =

Figure 3. Harvest rule to calculate the target harvest rate, H_{tar} (before implementation uncertainty was imposed). L is the abundance of Cultus Lake sockeye recruits at which H_{min} was the management target and below which no harvest was taken. The maximum proportional harvest rate, H_{max}, was the target above Cultus recruit abundance U.

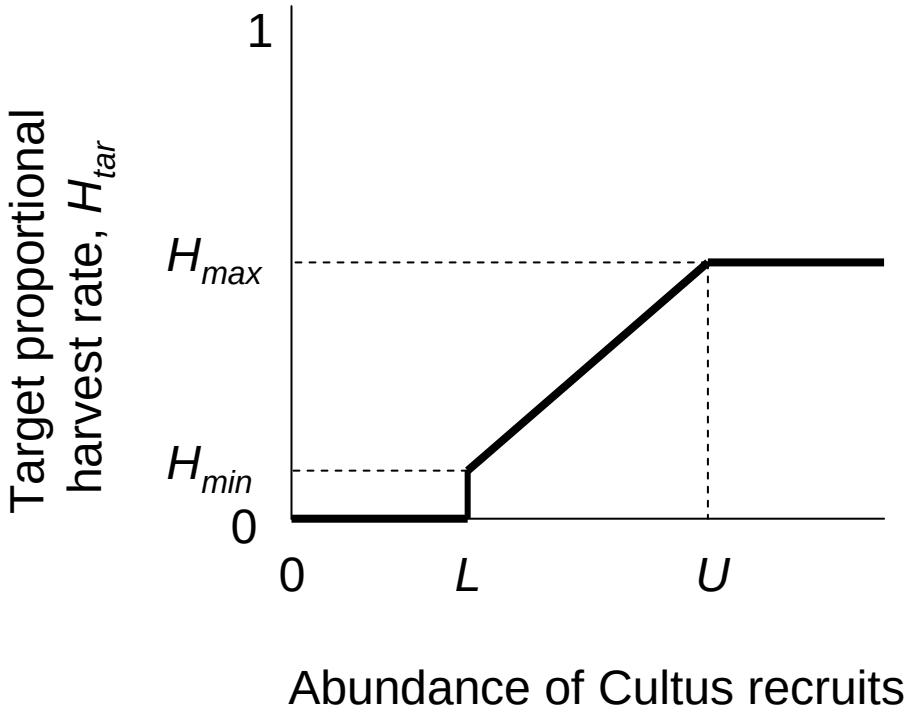

Target proportional harvest rate, H_{tar}
1
H_{max}
H_{min}
0
0
L
U
Abundance of Cultus recruits

Figure 4. Flow chart of the simulation model of life histories and management of the Cultus Lake and other late-run Fraser River sockeye stocks. PSM is pre-spawning mortality of adults that occurs in the lake, *T* is the time frame for recovery, and *Y* is the time frame for long-term survival subsequent to recovery.

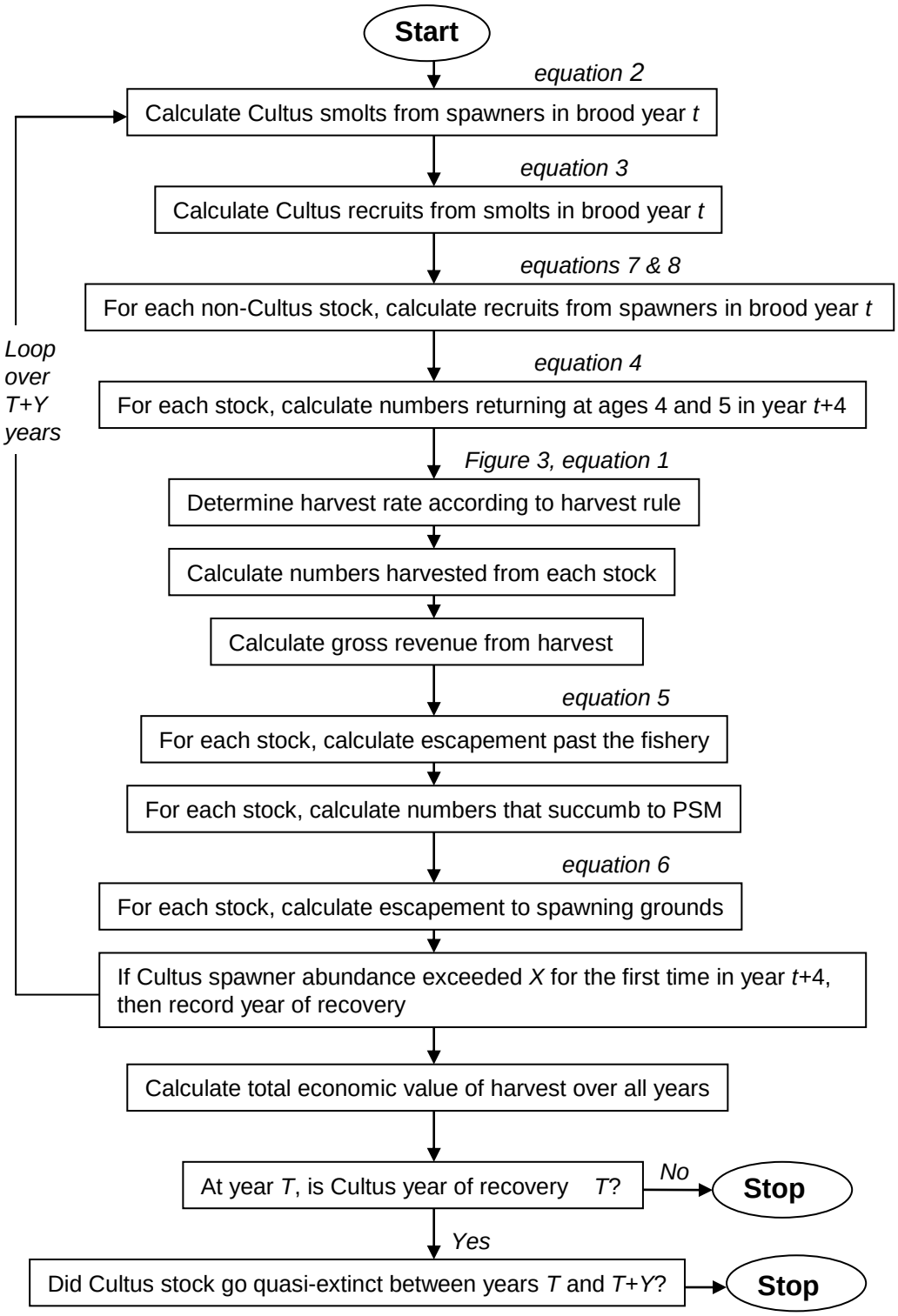
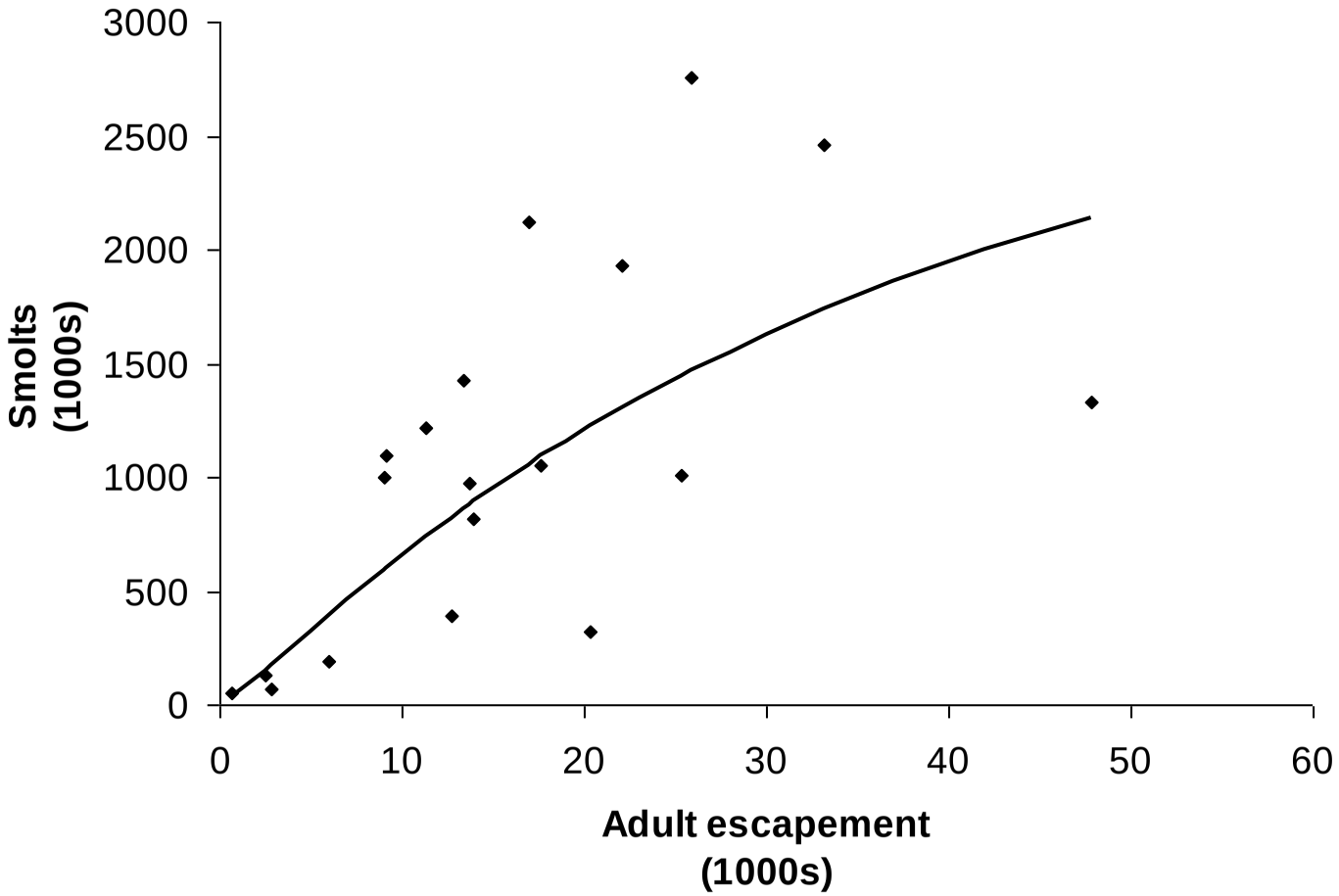

Start
equation 2
Calculate Cultus smolts from spawners in brood year t
equation 3
Calculate Cultus recruits from smolts in brood year t
equations 7 & 8
For each non-Cultus stock, calculate recruits from spawners in brood year t
Loop over T+Y years
equation 4
For each stock, calculate numbers returning at ages 4 and 5 in year t+4
Figure 3, equation 1
Determine harvest rate according to harvest rule
Calculate numbers harvested from each stock
Calculate gross revenue from harvest
equation 5
For each stock, calculate escapement past the fishery
For each stock, calculate numbers that succumb to PSM
equation 6
For each stock, calculate escapement to spawning grounds
If Cultus spawner abundance exceeded X for the first time in year t+4, then record year of recovery
Calculate total economic value of harvest over all years
At year T, is Cultus year of recovery T?
No
Stop
Yes
Did Cultus stock go quasi-extinct between years T and T+Y?
Stop

Figure 5. Smolt and spawner data for the Cultus Lake sockeye stock (1951, 1954-1960, 1965-1971, 1974-1975, and 1988-1989 brood years). The curve is the best-fit modified Beverton-Holt curve (eq. 2 fit using least squares regression). The best-fit parameter values are a = 55.597, d = 1.153, and K = 69.375.


3000
2500
2000
1500
1000
500
0
Smolts (1000s)
0
10
20
30
40
50
60
Adult escapement (1000s)

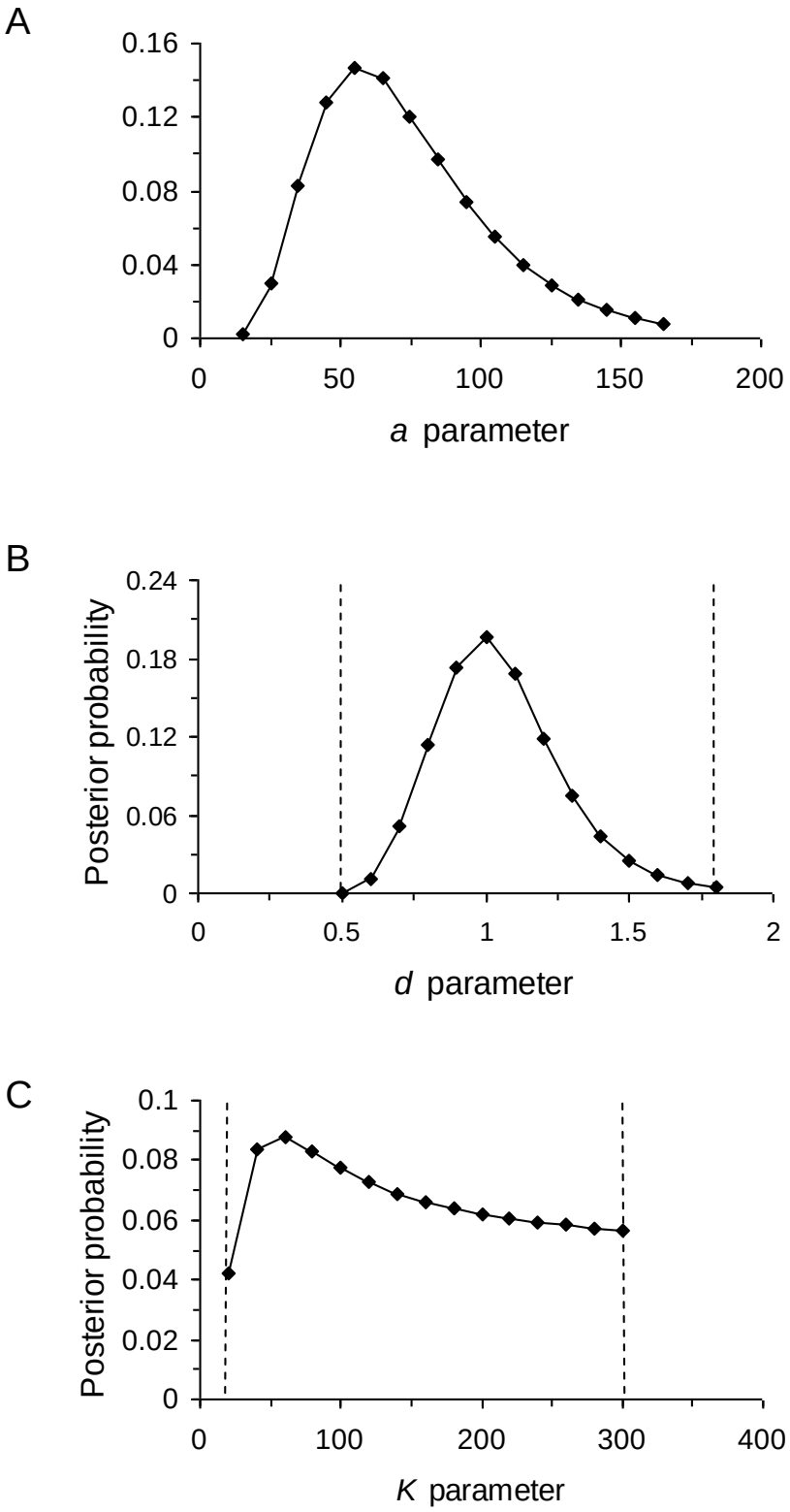

A
0.16
0.12
0.08
0.04
0
0
50
100
150
200
a parameter
B
0.24
0.18
0.12
0.06
0
Posterior probability
0
0.5
1
1.5
2
d parameter
C
0.1
0.08
0.06
0.04
0.02
0
Posterior probability
0
100
200
300
400
K parameter

Figure 7. Flow chart of the Monte Carlo procedure for finding harvest rules that satisfy the stated management objectives. Symbols are defined in the text.

Calculate Bayesian posterior distribution for all combinations of *a*, *d*, and *K* parameters of Cultus spawner-to-smolt relation.

Set harvest rule parameters:

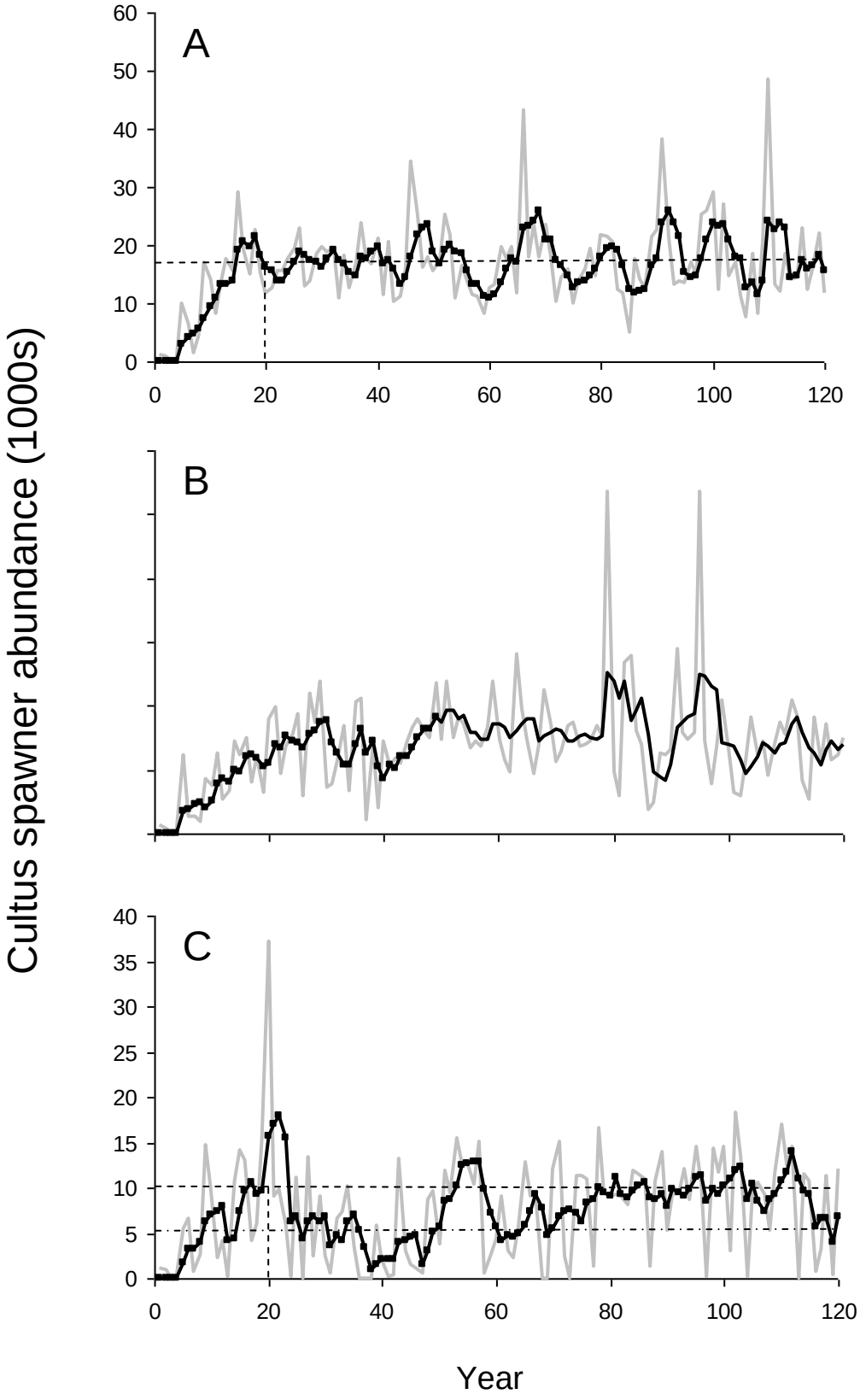

A
B
C
Cultus spawner abundance (1000s)
Year
0
10
20
30
40
50
60
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100
120

Figure 9. Isopleths of Pr_{rec}, or estimated probability of recovery for the Cultus stock, compared to Z_1, the desired probability of recovery, for combinations of harvest rule parameters L, H_{min}, U, and

Figure 10. Shapes of harvest rules that met both the recovery and long-term survival objectives (management objectives 1 and 2) under baseline parameters (Table 1). The boldfaced harvest rule is the highest-ranked harvest rule based on maximizing gross commercial revenue that also achieved $Z_1 = 0.9$ and is defined by $L = 1{,}000$, $H_{min} = 0.2$, $U = 65{,}000$, and $H_{max} = 0.63$ (rule #43, Table 5).

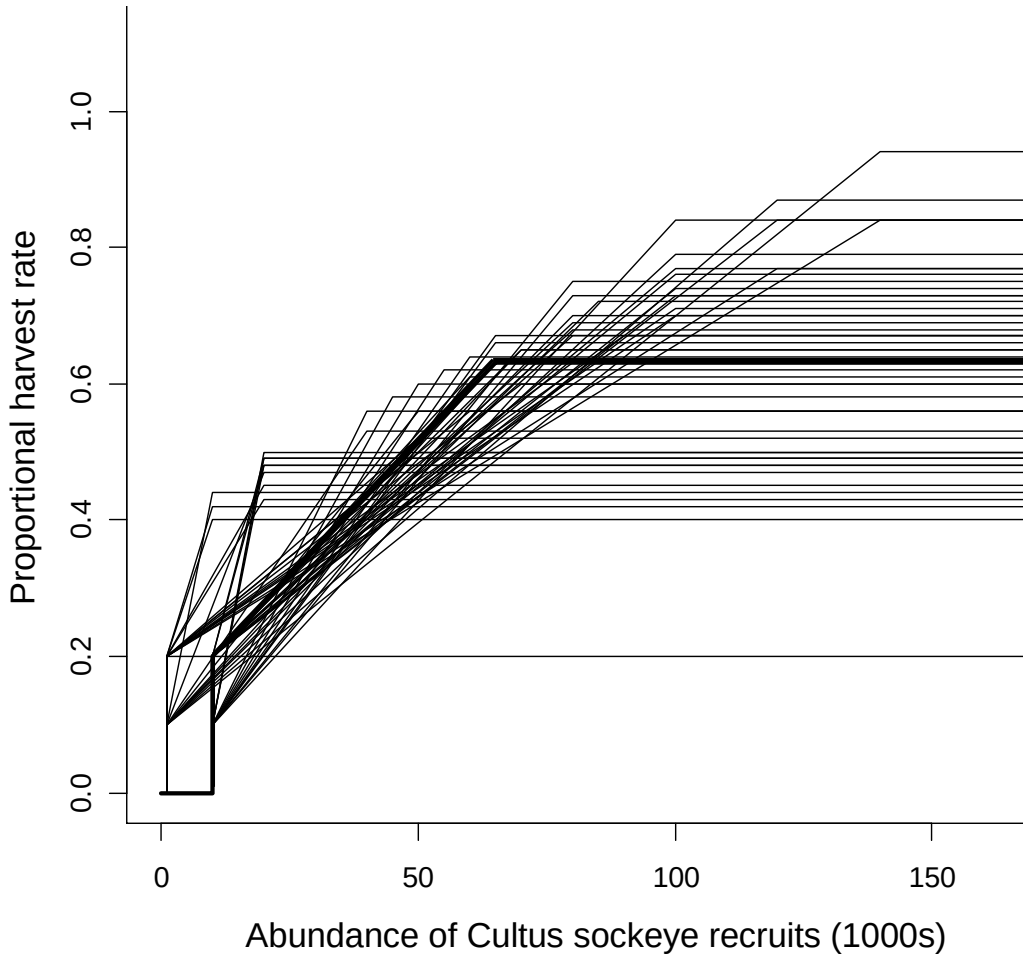

Proportional harvest rate
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
Abundance of Cultus sockeye recruits (1000s)

Figure 11. Example probability distribution of the expected annual gross revenue from the harvest of late-run Fraser River sockeye (average over 120 years). The distribution is from 134,400 Monte Carlo trials under baseline conditions (Table 1) and a harvest rule where L = 10,000, H_{min} = 0.1, U = 100,000, and H_{max} = 0.93. For economic values not shown on the graph (less than $29.17 million), the cumulative probability is less than 0.01. Labels on the x-axis are the midpoint for each interval. The dashed vertical line represents the expected value of $33.59.

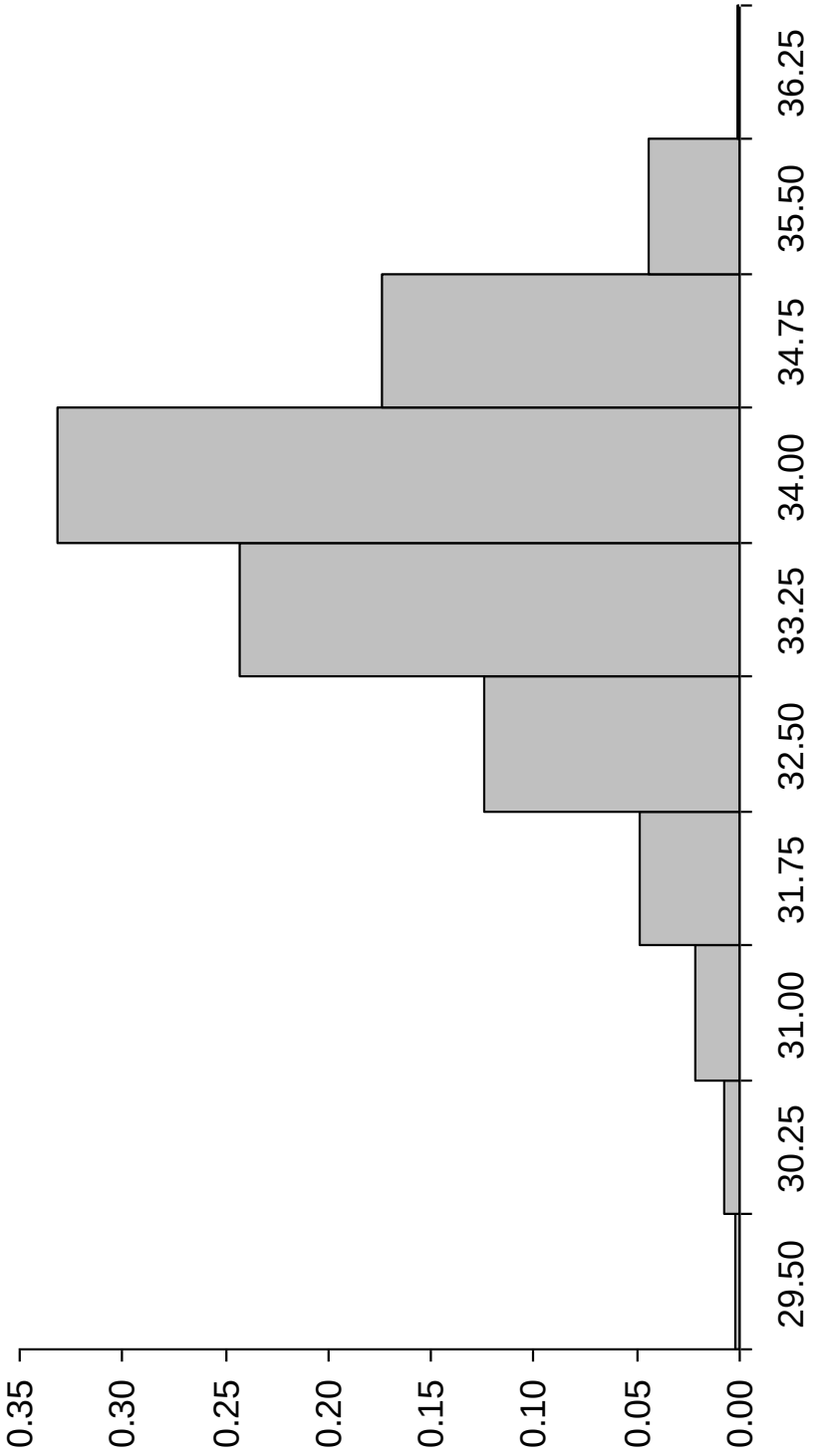

0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
29.50
30.25
31.00
31.75
32.50
33.25
34.00
34.75
35.50
36.25

Figure 12. Example probability distribution of year of recovery for the Cultus sockeye stock for the portion of 134,400 Monte Carlo trials in which the stock recovered to a spawner abundance of 20,000 by year 20, based on baseline conditions (Table 1) and a harvest rule where L = 10,000, H_{min} = 0.2, U = 65,000, and H_{max} = 0.63. For years of recovery not shown on the graph (below year nine), the cumulative probability was less than 0.001. The dashed vertical line represents the mean year of recovery, 15.02.

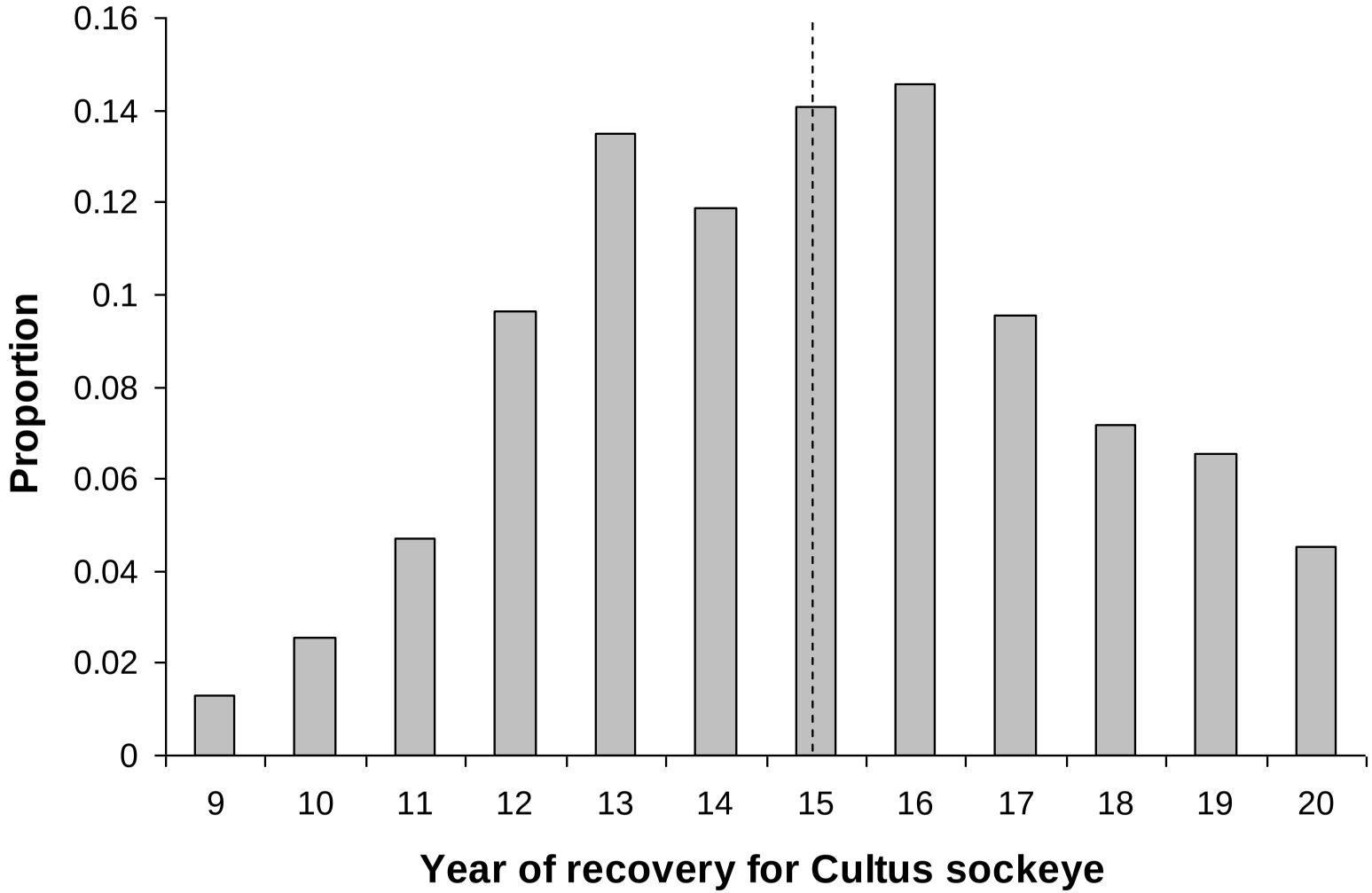

0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Proportion
9
10
11
12
13
14
15
16
17
18
19
20
Year of recovery for Cultus sockeye

Figure 13. Expected mean annual gross revenue ($ millions) under the highest-ranked harvest rule (based on expected revenue) from the harvest of late-run Fraser River sockeye over the next 120 years as a function of the desired probability of recovery for the Cultus Lake sockeye salmon stock (Z_1).

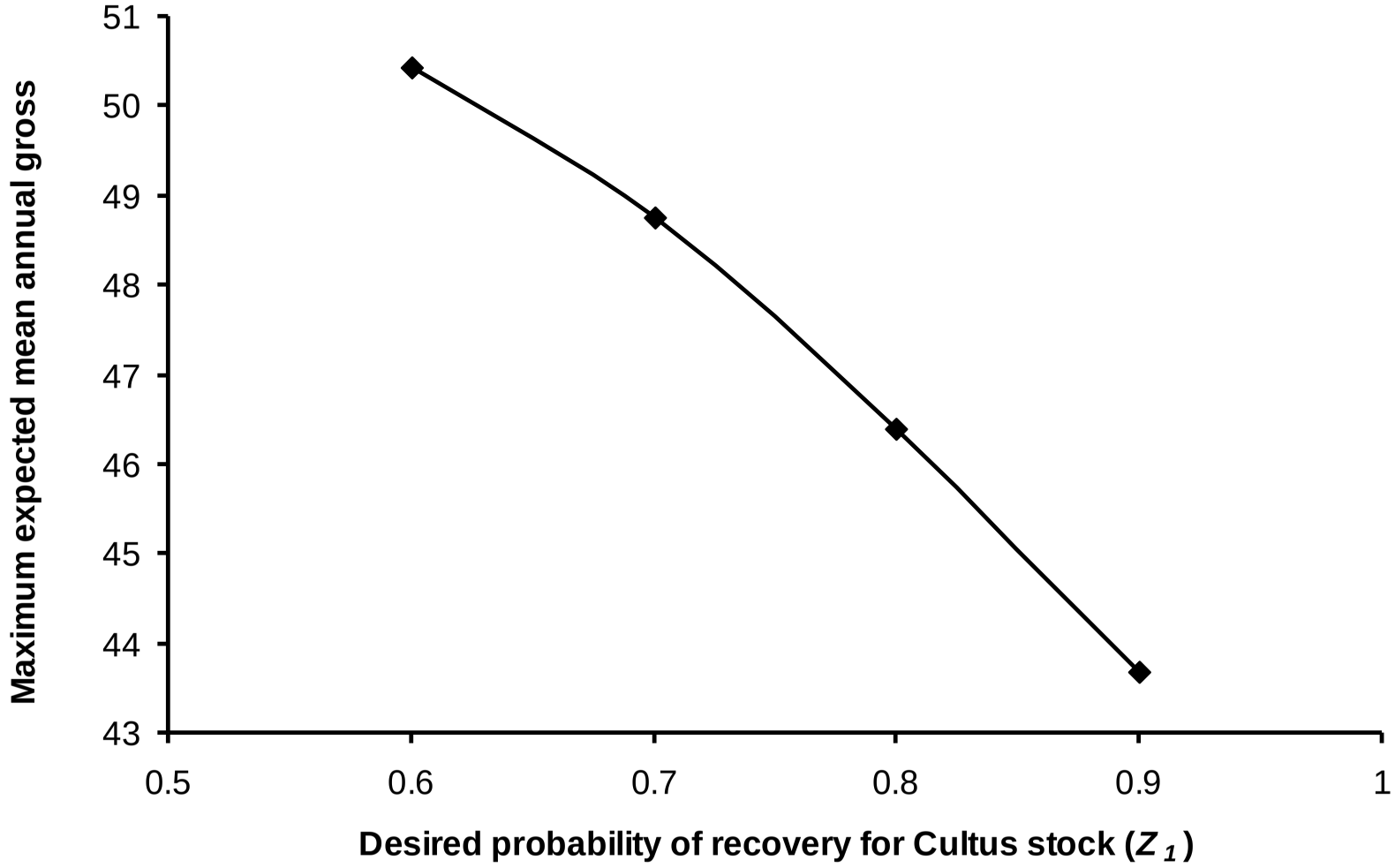

Maximum expected mean annual gross
51
50
49
48
47
46
45
44
43
0.5
0.6
0.7
0.8
0.9
1
Desired probability of recovery for Cultus stock (Z_1)

Figure 14. Expected year of recovery for the Cultus sockeye stock and expected mean annual gross revenue ($ millions) from the harvest of the late-run Fraser River sockeye as a function of probability of recovery (*Pr*

Figure 15. Expected mean annual gross revenue from the catch ($ millions) and the

A

B

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Appendices

Appendix 1. Bayesian estimation of the Cultus sockeye spawner-to-smolt relation

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Appendix 2. Gross commercial revenue

To estimate an indicator of the economic value of future late-run Fraser River sockeye harvests, I calculated the average commercial dollar-value per fish, which represents the gross commercial revenue from harvest. In these future projections of economic value, I have not used a discount rate or accounted for costs associated with the harvest, because I was only interested in the relative merits of alternative harvest rules, not the actual dollar benefits. Furthermore, little is know about future discount rates and costs associated with harvesting and processing or technological advances that may occur. I also did not consider social costs and benefits in this model because these are difficult to quantify and beyond the scope of this study.

Using data from Table A1, the mean length of fish is 56.25 cm. Post-orbital-fork (POF) length was converted to weight using the following equation (Steve Latham, Pacific Salmon Commission, Vancouver, B.C., personal communication):

(A2) $WGT = (0.1613 \times POF) - 5.9358$

where WGT is weight in kg and $r^2=0.83$.

Using this equation, the mean weight per fish came to 3.14 kg.

Using data in Table A2, the mean processed price per kg round was $6.96. Using the mean price per kg and mean weight per fish, the mean gross revenue per fish came to $21.83.

In this analysis I assumed that all sockeye caught are worth the same commercial processed price, whether they were caught in commercial, aboriginal, or other fisheries. I made this assumption because there is little information about how catch will be divided between First Nations and commercial fisheries in the future. Further, there is no accurate