An Examination of

Harvest Rates and Brood-

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1. Introduction

Pacific salmon (*Oncorhynchus* spp.) have declined not only in abundance, but benchmarks based on the available data for individual CUs (Holt and Ogden 2012). The Wild Salmon Policy stipulates that for a stock in the red zone, (1) managers should immediately begin to consider remedial actions, and (2) the primary drivers for processes that generates values for those indicators. The overall decision analysis further involves (4) a ranking of management options based on their indicators and (5) sensitivity analyses to assess the robustness of the ranking of management options and other model outputs to key uncertainties (Peterman 2004).

1.1. Research goals

My primary research goal was to develop a management support tool that includes the above components of risk and decision analysis, which would quantify outcomes of potential

However, as with other Canadian Pacific salmon stocks, it does not yet have agreed-upon benchmarks under the Wild Salmon Policy. It is also an indicator stock for the lower Georgia Strait under the *Pacific Salmon Treaty* (PSC 2012). The mature Cowichan Chinook salmon, mostly aged 3 and 4 years, usually return to spawn from late August to October (DFO 1999). They have the ocean-type life history, and juveniles out-migrate from the natal stream within three months of emergence from the gravel in early spring (Healey 1991, Nagtegaal et al. 2004). This stock is considered one of the two largest remaining naturally-spawning Chinook populations in the Lower Strait of Georgia (DFO 1999), although it has input from a small conservation hatchery. -

the early 1990s (Figure 3). Subsequently, DFO decreased harvest rates and initiated hatchery programs in an attempt to rectify the poor escapements of lower Strait of Georgia Chinook stocks (DFO 1999). However, the decline in Cowichan Chinook returns has continued despite Chinook non-retention areas and temporal closures designed to decrease Canadian commercial and recreational exploitation rates on the stock (DFO

2.2. Simulation model

2.2.1. Data sources

Parameters of most production functions were based on abundance estimates of natural-spawner abundance, natural-origin smolt numbers, hatchery releases (summed fry and pre-smolt), and natural-origin recruits produced from each brood year from Appendix 9 of Tompkins et al. (2005). Here, “recruits” are the number of Cowichan Chinook salmon available at the onset of fishing in all fisheries (Table 2). For parameter estimation of the linear hatchery-production function, hatchery release (summed fry and pre-smolt) data were used from 1979-2008 (Georgia Basin Salmon Stock Assessment, DFO, Nanaimo, B.C.) in combination with the number of age-3+ hatchery brood fish reported in DFO’s nuSEDs database for those years (DFO 2011b). The annual hatchery budget was $452,000 (Tom Rutherford, pers. comm., DFO, South Coast office, Nanaimo, B.C.).

In the spreadsheets that Tompkins et al. (2005) used to generate natural-origin recruits (available from Arlene Tompkins, DFO, Nanaimo, B.C.), they first estimated total terminal returns-at-age from each brood year, and then subtracted hatchery-origin terminal returns-at-age by brood year. They then used the resulting natural-origin terminal returns-at-age from each brood year as the basis for calculating natural-origin recruits-at-age from each brood year. Appendix 7 of Tompkins et al. (2005) reported the summed (estimated) age-3+ recruits (both hatchery and natural origins) from each brood year. The number of hatchery-origin recruits was estimated here as follows. I first generated total-recruit numbers from both hatchery-origin and natural-origin Chinook salmon by using the same method as used by Tompkins et al. (2005), but without subtracting hatchery-origin fish at the step in which they subtract them. Instead, to determine number of hatchery-origin recruits, I subtracted natural-origin recruits (published in Tompkins et al. 2005) from total recruit numbers.

I then followed the procedure of Tompkins et al. (2005) and used recruitment estimates from brood years 1985 and 1988-2000 as the basis of most parameter estimations, and excluded

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years 1986-1987 out of their analysis in part because the data in those years were questionable due to river-flow conditions leading to enumeration difficulties.

To model the FSC harvest function, I used terminal return data and FSC annual harvest from DFO's nuSEDs database for 1990 through 2009 (DFO 2011b). NuSEDs data were also used to initialize the

relationship between natural-origin smolts and all age-3+ age classes of recruits (denoted smolt-recruit, *sr*) from brood year *t* (Figure 9) was:

$$(4)\quad R_{n,3+} = \frac{a_{sr} J_{n,t\ \ 1}}{b_{sr} \quad J_{n,t\ \ 1}} e^{w_m \quad sr},$$

where $R_{n,3+}$ was abundance of natural-origin recruits originating from brood year t, a_{sr} and b_{sr} were parameters, w_m was the same random variable used in Equation 2, $_{sr}$ was the population standard deviation of the $\log_e$ residuals, and was the same value for the marine survival multiplier used in Equation 2. Total recruitment, $R_{tot,3+}$, was the sum of hatchery-origin and natural-origin fish originating from spawners from brood year t:

$$(5)\quad R_{tot,3+} = R_{h,3+} + R_{n,3+}.$$

Next, the recruits in a given simulation year, *yr*, were the sum of the age-3, 4, and 5 recruits originating from spawners in previous simulation years, and that returned in year *yr*.

$$(6)\quad Z_{yr,3} = p_3 R_{totyr\text{-}3}$$

$$(7)\quad Z_{yr,4} = p_4 R_{totyr\text{-}4}$$

$$(8)\quad Z_{yr,5} = p_5 R_{totyr\text{-}5}$$

where $Z_{yr,3}$ were the age-3 recruits originating from spawners that returned three years previously in yr - 3, and similarly for $Z_{yr,4}$ and $Z_{yr,5}$. Also, p_3 was mean proportion of estimated age-3 adult spawner returns, averaged over 1982-2004, and p_4 and p_5 were analogous parameters for age-4 and 5 fish, respectively. The proportions-at-age were proportions of the total number of adult returning fish only, and the sum of proportions was 1. For example, returns in simulation year yr = 6 (calendar year 2014) consisted of age-5, 4, and 3 recruits generated by spawners that returned in yr = 1, 2, and 3 (2009, 2010 and 2011), respectively. Calendar year 2014 corresponded to the first simulation year, y =1.

Next, the total number of recruits, W_{yr} that returned in simulation year *yr* was:

$$(9)\quad W_{yr} = Z_{yr,3} + Z_{yr,4} + Z_{yr,5}$$

Total ocean harvest (commercial and recreational) in numbers of fish was:

(10) $H_{yr} = rW_{yr}$

where r was harvest rate, which reflects all ocean fisheries in which Cowichan Chinook salmon were caught during their return year. Harvest rate was varied to generate different management strategies (Section 2.5).

Terminal return in a given year was abundance of total recruits in return year yr minus total ocean harvest:

(11) $T_{yr} = W_{tot,yr} - H_{yr}$

Terminal return was therefore abundance of all age-3+ fish returning to the river, including fish spawning naturally, fish subsequently removed as FSC harvest, and fish taken as hatchery brood stock.The FSC catch was given by the disjunct function (Figure 10):

$$(12)\quad F_{yr} = \begin{cases} cT_{yr}, & T_{yr} < L \\ \bar{f} + w_F \sigma_F, & T_{yr} \geq L \end{cases}$$

where L = 2,000 was the break-point of the function, c = 0. 2615 was the FSC catch per terminal return, i.e., the slope of the line between (0,0) and ($L,\bar{f}$), $\bar{f}$ = 523 was the mean of the FSC catch data for 1990-2009, w_F was the random variable drawn from the standard normal distribution ~$N(\mu = 0, \sigma = 1)$, and σ_F was population standard deviation of residuals as estimated from those data. The parameter value for L was chosen because most of the historical FSC harvest occurred at terminal return abundances above 2,000 (Figure 10) and Cowichan Tribes restrict fishing effort at low terminal returns (Tom Rutherford, pers. comm.). There were insufficient data to use a catch-per-unit-effort model for the First Nations' fishery.

The annual in-river FSC catch, F_{yr}, was then subtracted from terminal return numbers to yield total escapement from all fisheries,

(13) $E_{yr} = T_{yr} - F_{yr}$.

Next, hatchery brood stock in number of adults was,

(14) $S_{h,yr} = min(sE_{yr}, S_{h,max})$,

which was the smaller of either the brood-take rate (*s*) multiplied by escapement, or the maximum brood stock number that the hatchery could handle, $S_{h,max}$ = 526, made up of equal numbers of male and female fish. The brood-take rate was one of the management actions that I varied to generate different management strategies (Section 2.5), and the maximum rate is set by DFO at 33% of escapement for conservation hatcheries such as the Cowichan River hatchery (DFO 2005b). The maximum brood stock of 526 was 80% of the number of fish that would yield 1 million releases, which is the maximum current hatchery capacity (

2.4. Marine survival-regime scenarios

The density-independent marine survival values for the hatchery- and natural-origin juvenile-to-recruit production functions (Equations 2 and 4) were

(16) $O_{rr} = \dfrac{a_{rr}}{b_{rr}}$ and

(17) $O_{sr} = \dfrac{a_{sr}}{b_{sr}}$,

where O_{rr} was the estimate for hatchery and O_{sr} for natural recruits. For the total-recruit-per-smolt calculation, hatchery fry and pre-smolt releases were counted as smolts.

As mentioned earlier, to generate different marine survival scenarios, I altered density-independent marine survival rates by applying a set of multipliers, , to b_{rr} and b_{sr} for the ocean life stages of hatchery- and natural-origin fish, respectively (Equations 2 and 4, Table 4). "Scenarios" refer here to different marine survival regimes. In the Bevertonfor all recruits, $\bar{R}_{tot,3} \;/ \bar{J}_{tot,t\;\;1}$, whereas mean survival rate (smolt-recruit, brood years 1993-2003) from data (estimated) was 0.0039. The marine survival rate has been ≤ 0.01 since 1993, and 2003 was the last brood year for which data were available for a complete cohort (Figure 2). Thus,   = 7 represents a scenario in which marine survival was actually not as poor as has been seen in recent years. *Intermediate marine survival* used   = 4; $\bar{R}_{tot,3} \;/ \bar{J}_{tot,t\;\;1}$ was 0.007 for the predicted time series. The *good marine survival* scenario (marine survival multiplier   = 1) was intended to correspond to a favourable survival condition such as occurred during the brood years used here to estimate model parameters (1985 and 1988-2000). The average marine survival rate (smolt-recruit, based on CWT-based survival data, Table 4) during those years was 0.01, whereas the $\bar{R}_{tot,3} \;/ \bar{J}_{tot,t\;\;1}$ value calculated from the model-predicted time series for good marine survival was slightly higher (i.e., 0.0155). In contrast, a review by Bradford (1995) found an average marine survival rate of 0.044 for ocean-type Chinook.

2.5. Management objectives and performance indicators

The potential management objectives analysed here were related to concerns about conservation, First Nations' harvest, ocean harvest, and hatchery performance. The first three of these came from guiding principles of the Wild Salmon Policy (WSP, DFO 2005a), and the last was added because managers might also want to consider hatchery indicators in their decision-making, such as a per-fish cost of hatchery operations and the proportion of hatchery3o5(as ad(c)11(erns)]1 461.26so e)8(c)1u-8(l)5 0 1 1-54<004B00

Four management objectives addressed conservation concerns, and each was associated with one or more performance indicators (Table 5). The recovery objective was defined as rebuilding abundance of natural spawners to meet or surpass a three-year running average of 6,514 fish at least once at or before year 15 of the simulation (calendar year 2023). This abundance level management objective was to maintain the natural spawner abundance at 6,514, with a corresponding indicator of median abundance of natural spawners, S_{nat}, which was calculated as the median abundance of natural spawners over all Monte Carlo trials.

The remaining management objectives addressed possible management concerns involving First Nations' harvest, ocean harvest, and hatchery performance, and were also calculated for all Monte Carlo trials. The FSC harvest objective was to maximize Cowichan Tribes' catch up to the historical average of 523 fish caught annually (Section 2.2.1). My FSC harvest indicator was H_{fsc}, and was calculated as the median FSC harvest.

The ocean harvest objective was to maximize commercial and recreational catch of the Cowichan Chinook stock, and its performance indicator was median ocean harvest, H_{oce}. Managers are likely to prefer higher rather than lower ocean harvest rates for Cowichan Chinook salmon, because higher rates are likely to correlate with higher harvest rates of other stocks and salmon species that are caught in the same mixed-stock fisheries. Finally, there were two management objectives involving hatchery performance. DFO recommends that hatchery-origin returns should not exceed 50% of the natural spawners for conservation hatcheries (DFO 2005b), and a conservation plan for the Cowichan Chinook stock involving public consultation also recommended ≤ 50% of returns to be hatchery-origin fish once the population had recovered (Tompkins et al. 2005). In addition, due to a number of concerns regarding hatchery supplementation as expressed in the scientific literature (Section 4.2.2), a plausible management objective would be to keep the proportion of hatchery-origin fish among natural spawners as low as possible, but definitely below 0.5. Thus, my performance indicator Pr_{hat} was the mean proportion of hatchery-origin spawners among natural spawners. The second hatchery performance objective involves cost. The Cowichan hatchery operates with a fixed budget (Tom Rutherford, pers. comm.), and presumably managers would prefer the per-fish cost of the hatchery to be as low as possible. Thus, *C* was the indicator for median annual hatchery operation cost per hatchery-origin recruit. Because the hatchery budget is fixed, to minimize *C* is essentially to maximize hatchery recruits, but it may be useful to managers to track the hatchery output with this cost-per-recruit indicator.

2.6.

Finally, there was the *combined* strategy, having both medium harvest rate (r = 0.5) and high brood-take rate (s = 0.33). I chose that combination of rates on the basis of the response of performance indicators to both rates applied together for intermediate marine survival (Section 2.3).

2.7. Ranking of management strategies

The different management strategies were ranked by each indicator separately and for each of the three marine survival scenarios. Ranks of management strategies based on values of the relevant indicators were ordered highest-to-lowest except for the hatchery objective indicators, Pr_{hat} and C, which were ordered lowest-to-highest because lowest values are most desirable. Where the 95% confidence intervals for indicators S_{nat}, H_{fsc}, and H_{oce} overlapped, management strategies were assigned tied ranks. All other indicators were represented by non-integer values, so tied ranks were assessed at the second decimal place. The same ranking method was used for sensitivity analyses of hatchery survival multipliers (next section) as for different marine survival-regime scenarios.

2.8. Sensitivity analyses

I conducted two sensitivity analyses. First, to determine their effect on the relative ranking of management strategies, I explored the relative marine survival of hatchery fish compared to natural-origin fish. Beamish et al. (2012) found that in 2008, natural-origin Cowichan Chinook juveniles may have survived six to 24 times better during early ocean residence than hatchery-origin juveniles. I used the same marine survival multipliers for both hatchery- and natural-origin production functions as described above (= 1, 4, and 7), but in addition, I varied a second parameter, (= 0.5, 1, and 2), which was multiplied with b_{rr}, the Beverton-Holt b-parameter for the marine production function for hatchery fish. Equation 2 for hatchery-origin recruits was therefore modified as follows:

$$18.\ R_{h,t} = \frac{a_{rr} J_{h,t}}{b_{rr} \quad J_{h,t}} e^{w_m \quad rr},$$

whereas Equation 4 for natural-origin recruits was the same as before. Here too, higher

3. Results

Figures 11B and C show examples of annual population trajectories of individual Monte Carlo trials with the superimposed three-year running average of spawner abundance that was used for calculating two indicators--probability of recovery (P_{rec}) and the proportion of years in which the three-year average persistence goal was met of 1000 natural spawners (Pr_{pers}). The low brood-take rate management strategy (r = 0.4, s = 0.22) and poor marine survival scenario (= 7) was used to generate those figures as well as Figure 11A, which shows the median annual natural spawner abundance across all 600 Monte Carlo trials.

3.1. Harvest rate and brood-take rate

Contour plots show isopleths of values for the eight performance indicators as response variables for ranges of brood-take rates and harvest rates, and for poor, intermediate, and good marine survival scenarios (Figures 12 and 13). Grey shading on the contour plots indicates undesirable areas, i.e., performance indicator values less than proposed targets, for the five indicators having targets. For example, at the good marine survival condition, there were no undesirable contour surface areas for the range of harvest rates and brood-take rates used.

For a majority of indicators and marine conditions, indicator values were relatively insensitive to brood-take rates and more sensitive to harvest

of hatchery-origin fish among natural spawners, Pr_{hat}, showed a narrow range of favourable predicted values, 0.237 to 0.270. Furthermore, the good marine survival scenario was the only case natural-origin fish. Therefore, a marine survival ratio of 1.3 represents the case of hatchery fish surviving better than in the base ratio of 0.65.

Sensitivity analyses that thus varied the relative marine survival rates showed that ranks of four out of eight management strategies did not change much according to most indicators, especially for the four highest-ranked strategies. This generalization is true for differential survival ratios for indicator values of Pr_{low}, i.e., the proportion of years with 500 natural spawners (Table 9), and most of those values for Pr_{pers} as well, the proportion of years with 1,000 spawners (Table 10). The exception for Pr_{pers} was for

4. Discussion

4.1. Overview

There were four main implications of my results. (1) When marine survival was poor, there was nothing that managers could do to produce a high probability of recovery (≥ 0.8) of the Cowichan Chinook stock from among the management strategies examined, although there were strategies with low harvest rates that they could employ to promote other conservation objectives, such as attempting to maintain the natural spawning stock at ≥ 500. (2) The status-quo management strategy was not optimal for any marine survival scenario according to any indicator examined. Furthermore, when marine survival was as poor as it has been in recent years, the Cowichan Chinook stock barely adequate to rebuild the stock within 15 years to its recovery target with probability ≥ 0.80.

If managers were to make conservation and/or FSC harvest of the Cowichan Chinook stock a priority, and if no other indicators were considered, they would choose the lowest harvest-rate strategy (r = 0.30) when marine survival is poor, or an even lower harvest rate if possible. Even the lowest harvest-rate management strategy predicted poor long-term stock abundance, and the low harvest rate strategy (r = 0.4) resulted in unfavourable environmental problems (DFO 2005). However, when marine survival is extremely poor, a biologically conservative objective that managers might adopt, instead of recovery, is to keep th

hatchery-origin steelhead trout (Araki et al. 2007). In addition, one study found negative density-dependent effects of hatchery-origin spawners upon natural fish to be five-times higher than that of natural-origin spawners (Buhle et al. 2009). None of these possible negative effects of hatchery-origin fish were included in my model or

The highest brood-take-rate strategy provided only marginal improvements in some conservation indicators compared to the status-quo strategy, and that was only when marine survival was intermediate or poor. For the other management objectives, the highest brood-take rate strategy also performed only slightly better in comparison to other low-ranked strategies. This minor improvement differs from life history modelling results from some other studies that found that increasing supplementation in supportive-breeding hatcheries substantially increased stock abundance and/or probability of recovery in at least some circumstances (e.g., Amos 2008, Korman and Grout 2008). Those other analyses, which were for Cultus sockeye, may differ from mine because of higher marine survival rates of hatchery fish used in the models for that system. Reg million releases annually (Mel Sheng, pers. comm., DFO, Nanaimo, B.C.). This number would result from a maximum annual adult brood take of 326, based on the historical relationship between brood take and hatchery releases (Figure 6). Given that the maximum brood number that will be used in the future at the Cowichan hatchery is uncertain, and the demonstration that the current maximum brood number affects some performance indicator contours when marine survival is good, future research should include sensitivity analyses of the effect of the assumed maximum brood number in the hatchery.

4.2.3. Management strategies for particular objectives

Some management strategies best met particular management concerns. The rankings of the management strategies were nearly identical across the four management objectives dealing with conservation, and the FSC-harvest objective, and were nearly identical for all marine survival scenarios. These strategies can thus be considered together. The two lowest harvest-rate strategies were consistently better and also performed similarly for the indicators associated with both conservation and FSC harvest. In contrast, ranks of management strategies varied considerably for the ocean-harvest objective across the different marine survival scenarios. When marine survival was poorest, the top four strategies for ocean harvest were again the strategies with the lowest harvest rates. This result arose because when marine survival was poor, decreasing harvest rate from its high values led to a larger stock, which then produced more absolute harvest, a characteristic of the system that was reflected in the contour plot for the ocean harvest indicator (Figure 13). Therefore, there was a trade-off between ocean harvest and all other objectives and their corresponding indicators, except the proportion of hatchery-origin spawners for harvest rates < 0.3 for poor and intermediate ocean survival. However, when marine survival was good, the best strategies for ocean harvest were medium to high harvest-rate strategies ($r = 0.50$ and 0.65); in this case, there were no trade-offs between ocean harvest and other management objectives (Figures 12 and 13).

4.3. Simulation model

The life history model employed in the current study was similar to other published models. The main components of the model presented here were a stochastic multi-stage stock-abundance. Korman and Grout (2008) used a

4.6. Conclusion

Making accurate predictions of future stock abundance is not usually possible in the uncertain context of fisheries management, but evaluating alternative management policies relative to each other is one legitimate use of single-species fisheries models (Walters and Martel 2004). An advantage of the ranking method employed here in the context of a decision analysis is in the explicit reference to specific management actions and their relative rank according to a variety of indicators of interest. The

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Appendices

Appendix A
Tables

Table 1. **Estimated average percentage of annual abundance of adult Cowichan Chinook salmon removed by fishing (includes incidental mortality) and remaining as escapement (next-to-last line) (PSC 2011).**

Region	Fishery	1985-1995	1996-1998	1999-2011

Table 2. **Data used to determine parameter values and initialization of the model. Hatchery brood take numbers, natural spawners, terminal return and FSC harvest data are from DFO's nuSEDs database (DFO 2011), some**

Table 2 continued

Brood year	Hatchery brood take	Juvenile hatchery releases	Hatchery-origin recruits	Natural spawners

Table 3. Model parameters.

Symbol	Value	Equation	Definition
k	1,537	1	Number of juveniles released per adult fish taken as brood stock
cv_h	0.231	1	Constant coefficient of variation of linear regression
a_{rr}	10,573	2	Beverton-Holt *a* parameter for hatchery-origin juveniles-to-recruits
b_{rr}	538,703	2	Beverton-Holt *b* parameter for hatchery-origin juveniles-to-recruits
$_{rr}$	0.676	2	Population standard deviation from the $\log_e$ residuals for hatchery-origin juveniles-to-recruits
a_{ss}	1,977,843	3	Beverton-Holt *a* parameter for natural-origin spawners-to-juveniles
b_{ss}	6,410	3	Beverton-Holt *b* parameter for natural-originspawners-to-juveniles
$_{ss}$	0.598	3	Population standard deviation from the $\log_e$ residuals for natural-origin spawners-to-juveniles
a_{sr}	38,260	4	Beverton-Holt *a* parameter for natural-origin juveniles-to-recruits
b_{sr}	1,257,591	4	Beverton-Holt *b* parameter for natural-origin juveniles-to-recruits
$_{sr}$	0.736	4	Population standard deviation from the $\log_e$ residuals for natural-origin juveniles-to-recruits
p_3	0.48	6	Mean proportion of estimated age-

Table 4. **Marine survival multipliers ( ) and the corresponding density-independent and density-dependent annual survival rates for hatchery- and natural-origin juveniles-to-recruits.**

Table 5. Variable names of performance indicator and their descriptions. All indicators were calculated over 600 Monte Carlo trials for the indicated range of simulation years.

Category	Indicator	Description
Conservation	P_{rec}	Probability of recovery to ≥ 6,514 3-year running average natural spawners at least once by year 15
	Pr_{pers}	Proportion of years, in years 18-50, with 3-year running average ≥ 1,000 natural spawners
	Pr_{low}	Proportion of years, in years 16-50, with ≥ 500 natural spawners
	S_{nat}	Median annual natural spawner abundance in years 16-50
First Nations' harvest	H_{fsc}	Median annual First Nations' harvest in years 16-50
Ocean harvest	H_{oce}	Median annual ocean harvest in years 16-50
Hatchery performance	Pr_{hat}	Mean proportion of enhanced spawners among natural spawners in years 16-50
	C	Median annual cost per enhanced recruit in years 16-50

Table 7. Same as Table 6, but for intermediate marine survival (= 4).

Management strategy	Indicator or parameter	***r***	***s***	P_{rec}	Pr_{pers}	Pr_{low}	S_{nat}	H_{fsc}	H_{oce}	Pr_{hat}	***C* ($)**
	Target			0.80	0.90	0.95	6,514	523		0.5	
Status quo	Value	**0.65**	**0.22**	0	0.314	0.617	642	261	2,075	0.445	390.67
	Rank			4	7	5	5	5	6	5	4
Lowest harvest rate	Value	0.3	**0.22**	0.795	0.999	1.0	5,919	513	2,986	0.326	163.74
	Rank			1	1	1	1	1	4	1	1
Low harvest rate	Value	0.4	**0.22**	0.597	0.993	0.999	4,370	508	3,620	0.350	165.02
	Rank			2	2	1	2	1	2	2	1
Medium harvest rate	Value	0.5	**0.22**	0.333	0.930	0.982	2,624	468	3,678	0.389	185.17
	Rank			3	4	2	3	2	2	3	2
Combined strategy	Value	0.5	0.33	0.285	0.9	1.0	2,797	477	3,832	0.411	168.63
	Rank			3	3	2	3	2	1	4	1
Low brood-take rate	Value	**0.65**	0.15	0	0.220	0.476	471	184	1,393	0.358	791.62
	Rank			4	8	6	6	6	7	2	5
High brood-take rate	Value	**0.65**	0.33	0.030	0.434	0.726	758	335	2,889	0.519	231.51
	Rank			4	6	3	4	4	5	6	3
Highest brood-take rate	Value	**0.65**	0.5	0	0.492	0.674	766	372	3,356	0.572	178.62
	Rank			4	5	4	4	3	3	7	2

Table 8. Same as Table 6, but for good marine survival (= 1).

Management strategy	Indicator or parameter	r	s	P_{rec}	Pr_{pers}	Pr_{low}	S_{nat}	H_{fsc}	H_{oce}	Pr_{hat}	C ($)
	Target										

Table 9. **Sensitivity of rank order of management strategies (based on the performance indicator, *Pr_{low}*, the proportion of years with ≥ 500 natural spawners) to different ratios of density-independent survival of hatchery-origin juvenile Cowichan Chinook, relative to natural-origin smolts, under poor and intermediate marine survival scenarios. Boldface type indicates a different rank compared to the baseline ratio of survival rates of 0.65. The ratio of 0.65 represents the base-case difference in density-independent survival, which is the ratio of the first column to the second column survival rate values in Table 4 (with allowance for rounding error). A survival ratio of 1.3 results in a 30% improvement of hatchery over natural marine survival and a survival ratio of 0.32**

	Poor marine survival, = 7			Intermediate marine survival, = 4		
	Survival ratio			Survival ratio		
Management strategy	1.3	0.65	0.32	1.3	0.65	0.32
Status quo	**7**	6	**5**	**3**	5	5
Lowest harvest rate	1	1	**2**	1	1	1
Low harvest rate	2	2	**1**	1	1	**2**
Medium harvest rate	4	4	**3**	1	2	**4**
Combined	3	3	**4**	**1**	2	**3**
Low brood-take rate	**8**	6	***nBTF***			

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Table 10. Same as for Table 9, but for the proportion-spawners 1,000 performance indicator, *Pr_{pers}*.

	Poor marine survival, = 7 Survival ratio			Intermediate marine survival, = 4 Survival ratio		
Management strategy	1.3	0.65	0.32	1.3	0.65	0.32
Status quo	**7**	6	***4***	**4**	7	**5**
Lowest harvest rate	1	1	1	1	1	1
Low harvest rate	2	2	2	1	2	2
Medium harvest rate	4	4	**3**	**1**	4	4
Combined	3	3	3	**1**	3	3
Low brood-take rate	**8**	6	***4***	**5**	8	**5**
High brood-take rate	6	6	***4***	**3**	6	**5**
Highest brood-take rate	5	5	***4***	**2**	5	5

Table 11. Same as for Table 9, but for the ocean harvest performance indicator, H_{oce}.

	Poor marine survival, = 7 Survival ratio			Intermediate marine survival, = 4 Survival ratio		
Management strategy	1.3	0.65	0.32	1.3	0.65	0.32
Status quo	**6**	7	7	**3**	6	**7**
Lowest harvest rate	**4**	1	1	**5**	4	**2**
Low harvest rate	2	2	2	**4**	2	**1**
Medium harvest rate	**3**	4	4	2	2	**4**
Combined	**1**	3	3	2	1	**3**
Low brood-take rate	7	7	**8**	**5**	7	**8**
High brood-take rate	**5**	6	6	**2**	5	**6**
Highest brood-take rate	**1**	5	5	**1**	3	**5**

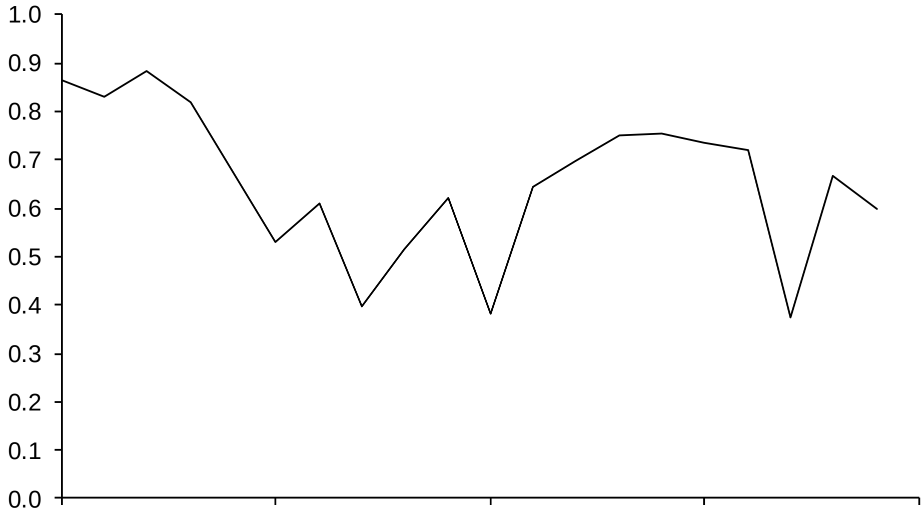
Table 12. Same as for Table 9, but for the proportion-hatchery-spawners performance indicator, Pr_{hat}.

	Poor marine survival, = 7 Survival ratio			Intermediate marine survival, = 4 Survival ratio		
Management strategy	1.3	0.65	0.32	1.3	0.65	0.32
Status quo	**4**	3	**2**	5	5	**4**
Lowest harvest rate	**1**	2	**3**	1	1	**2**
Low harvest rate	**2**	3	**2**	2	2	**3**
Medium harvest rate	3	3	**2**	3	3	**4**
Combined	4	4	4	**3**	4	**5**
Low brood-take rate	1	1	1	**4**	2	**1**
High brood-take rate	5	5	**4**	6	6	6
Highest brood-take rate	6	6	**5**	**6**	7	7

Appendix B
Figures

Figure 1. **Time series of total Chinook returns to the Cowichan River and age-3+ naturally-spawn**

Figure 2. **Estimated marine survival rate for the smolt-to-adult-recruit life stage (data from Salmon Assessment Section of the Salmon and Freshwater Ecology Division, DFO, Nanaimo, B.C.). Brood year is year of spawning of the parental population.**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0.8
0.7
0.6
0.5
0.4
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0.2
0.1
0.0

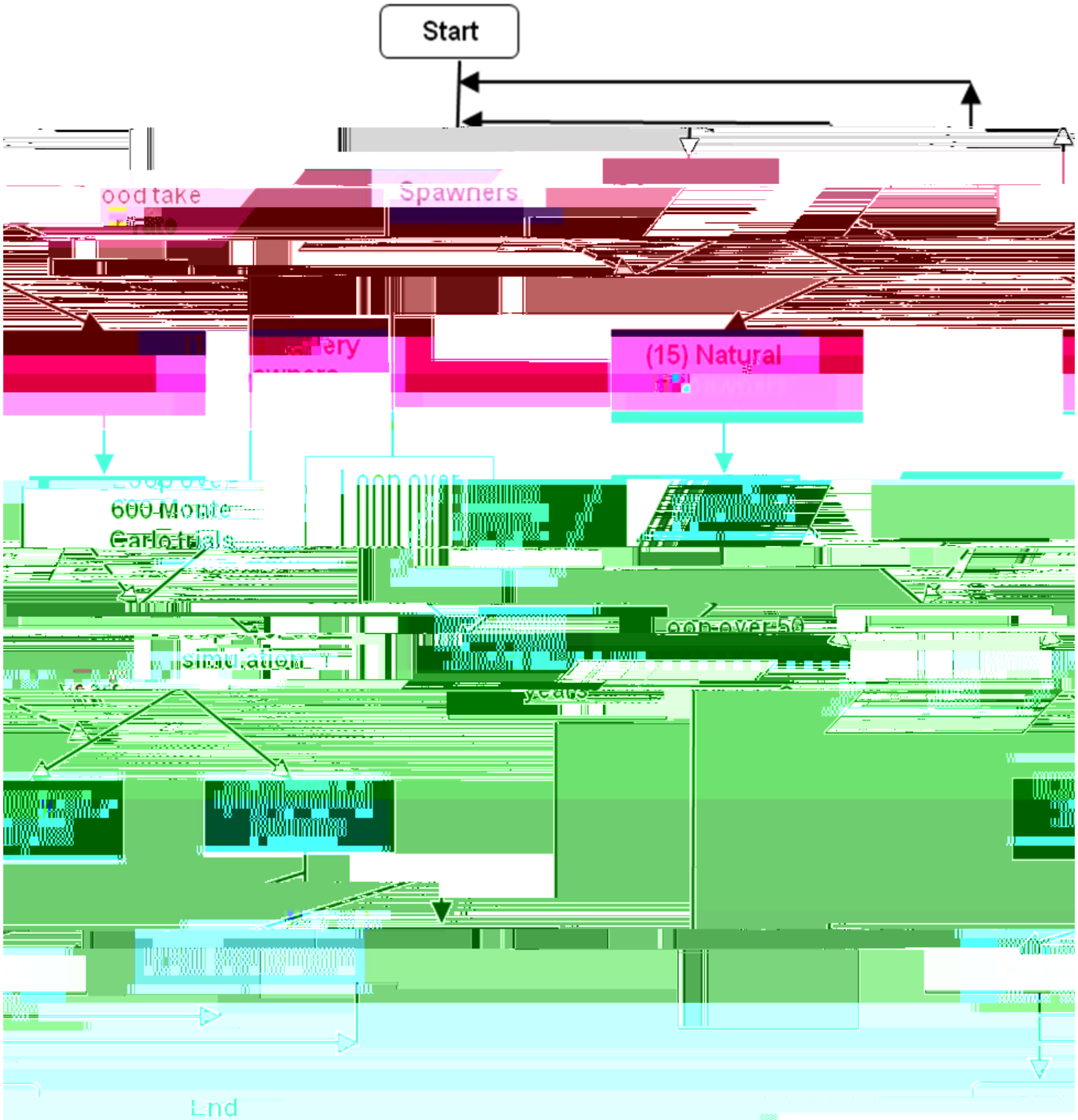

Figure 5. ***Flow chart of the Cowichan River fall Chinook salmon simulation model, indicating life-history components (shaded) and variables that changed according to different management strategies and marine survival rates (parallelograms). Numbers in parentheses indicate corresponding equation numbers (Section 2.2.2).***

Figure 6. **Hatchery releases as a function of number of age-3+ adults in the brood stock (brood years 1979-2008). Parameter values of the linear regression (Equation 1) were k = 1,537, and cv_h = 0.231.**

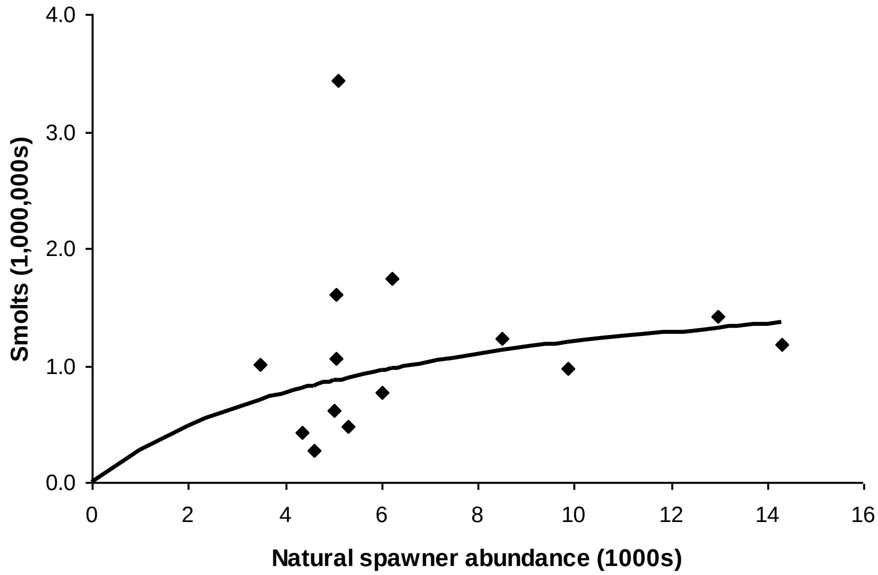

Figure 8. **Natural-origin smolts as a function of naturally-spawning age-3+ fish (brood years 1985 and 1988-2000). Best-fit Beverton-Holt parameter values (Equation 3) were a_{ss} = 1,977,843, b_{ss} = 6410, $_{ss}$ = 0.598.**

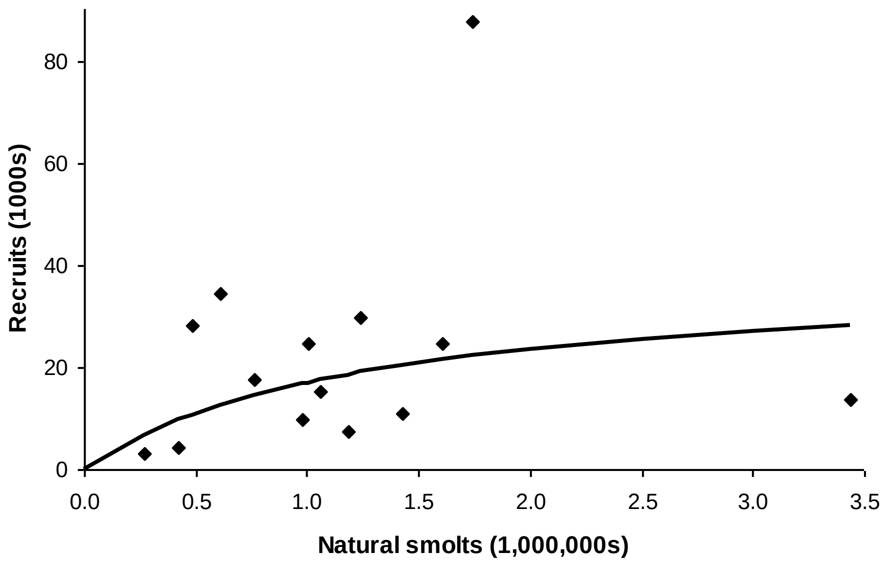

Figure 9. **Natural-origin recruits as a function of natural-origin smolts (brood years 1985 and 1988-2000). The curve is the best-fit Beverton-Holt curve (Equation 4), with parameter values a_{sr} = 38,260, and b_{sr} = 1,257,591, and $_{sr}$ = 0.736.**

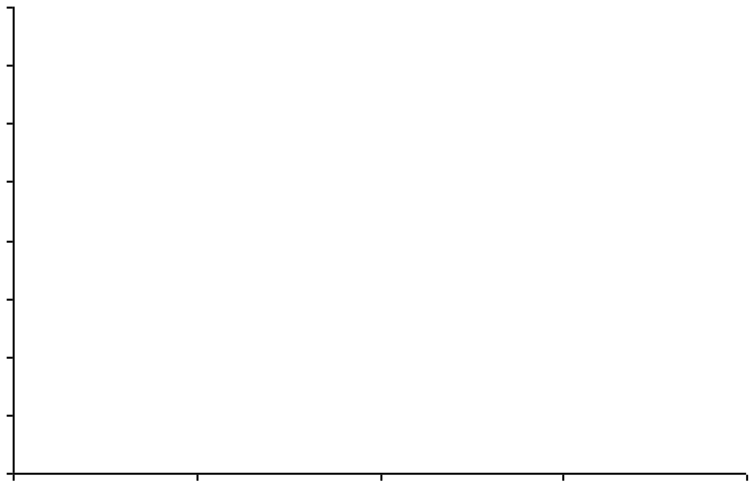

Figure 10.

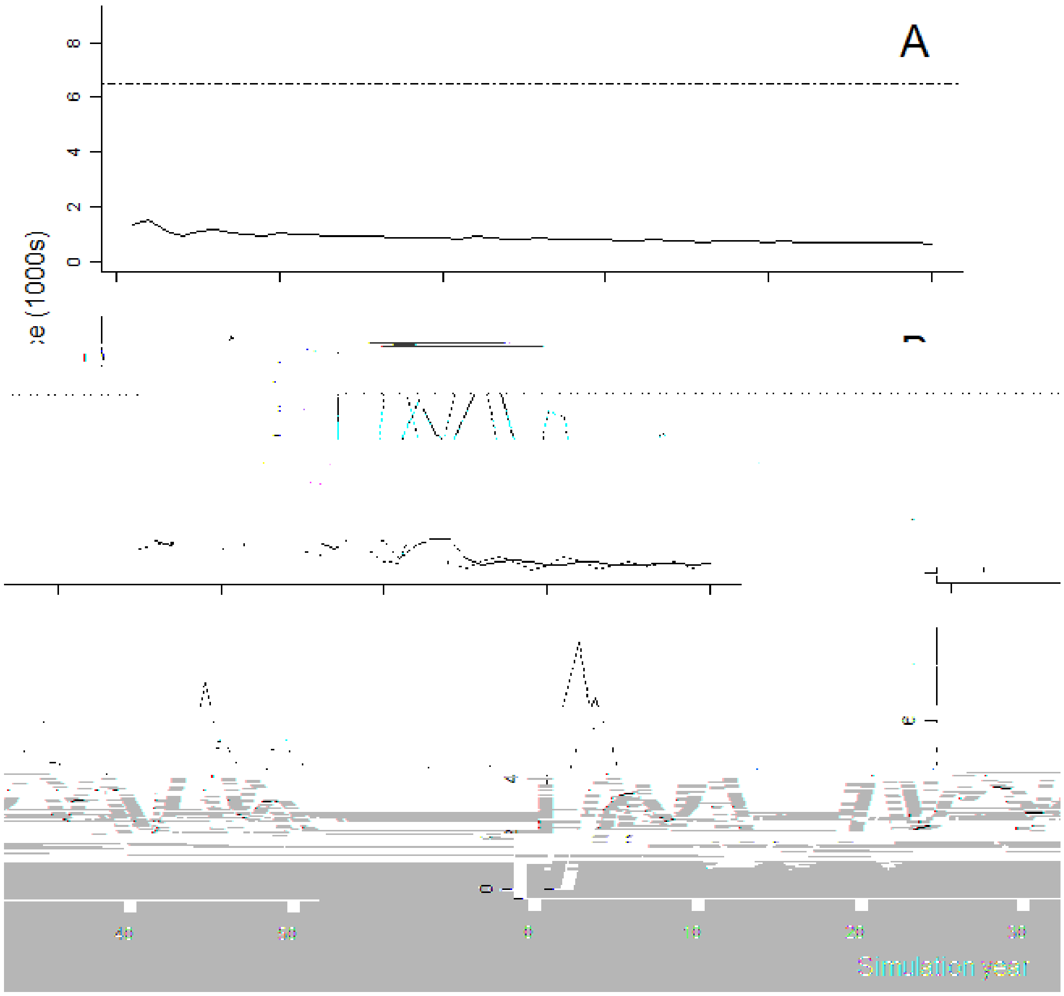

Figure 11. **Example model simulations for the low harvest-rate management strategy (*r* = 0.4; *s* = 0.22) under poor ocean survival (= 7). The horizontal line indicates target natural spawner abundance, 6,514. (A) Median natural-spawner abundance over 600 Monte Carlo trials; 95% confidence intervals were very small, so are not shown. (B) A population trajectory from a single Monte Carlo trial showing recovery before year 15, but subsequent reduction of spawners to lower than persistence levels. (C) A single population trajectory not showing recovery, but a more abundant stock later in the period than in (B). For (B) and**

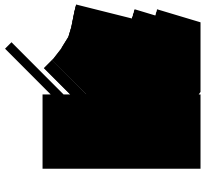

Figure 13. Same as for Figure 12, but for the four performance indicators for harvest and hatchery objectives (rows). FSC harvest,ocean harvest, and cost per hatchery-origin recruit indicators are unshaded because they had no proposed targets.