# An Examination of Harvest Rates and Brood-Take Rates as Management Strategies to Assist Recovery of Cowichan River Chinook Salmon

**by**

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# Abstract

The Cowichan River fall-run Chinook salmon (*Oncorhynchus tshawytscha*) population has been a serious conservation concern since 1997. I developed a stochastic life-history simulation model of both hatchery-origin and naturally-spawning Chinook in this system to evaluate management options involving specific harvest and hatchery brood-take rates. Ocean harvest was more influential than supplementation on the stock's abundance. My results suggest that this stock's recovery is unlikely to occur under current poor marine survival conditions and either the status-quo management strategy or lower harvest rates that managers are likely to find realistic. Model outputs also allowed analysis of trade-offs among management objectives involving conservation, Food, Social and Ceremonial and ocean harvests, and hatchery operations. Analyses of these performance indicators showed that under poor or intermediate marine survival conditions, the best management strategies (according to most indicators, including ocean harvest) involved the lowest ocean harvest rates examined here, i.e., 30% or 40% annually.

**Keywords**: Recovery planning, hatchery supplementation, fisheries simulation model, salmon management, decision analysis, conservation

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# 1. Introduction

Pacific salmon (*Oncorhynchus* spp.) have declined not only in abundance, but also in numbers of populations. For example, in the American Pacific Northwest and California, an estimated 29% of 1,400 Pacific salmon and steelhead trout populations have been extirpated since Euro-American contact (Gustafson et al. 2007). Also, half of the 52 evolutionarily significant units (ESUs) for salmon have substantially lower abundance compared to historical levels, and are listed as threatened or endangered under the U.S. *Endangered Species Act* (Good et al. 2007). The situation is similar for Canadian Pacific salmon stocks. In the 1990s, many Canadian salmon stocks declined, and catches were among the lowest in 50 years (Walters and Korman 1999). Slaney et al. (1996) found 142 documented stock extinctions from among the 5,487 Canadian populations for which there were sufficient data, and 624 populations with high extinction risk. According to the draft of Fisheries and Oceans Canada's (DFO) *2012 Salmon Stock Outlook*, 33 stock groups out of the 87 assessed (i.e., most of the B.C. and Yukon fished salmon stocks) were forecast to be of some conservation concern (status category 1 or 2) (DFO 2011a).

In recent years, the emphasis in Pacific salmon conservation management has shifted from conserving abundance to protecting genetic diversity (NRC 1996, Gustafson et al. 2007) as the best strategy to increase resilience in future salmon stocks, especially in the presence of environmental variability (McElhany et al. 2000, Hilborn et al., 2003). For example, the first objective in *Canada's Policy for Conservation of Wild Pacific Salmon* (hereafter the "Wild Salmon Policy") is to maintain the genetic diversity of wild Pacific salmon (DFO 2005a). In accordance with the Wild Salmon Policy, and in order to accomplish this objective, DFO has identified salmon Conservation Units (CUs; DFO 2009), and has begun to develop benchmarks of stock status (Holt et al. 2009, Holt 2009). The system of benchmarks divides each stock's biological status into red, amber, and green zones to indicate low, medium, and high spawning abundance and distribution. Software is in development that determines stock status indicators and 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 management decisions for such CUs should be biological considerations. In addition, for a CU in the amber or green zone, managers should also take into account social and economic considerations. However, these guidelines do not suggest specific management actions to achieve those recommendations. This is where management-decision support can play a crucial role.

Fisheries management requires decision making in the presence of uncertainty (Peterman 2004). Uncertainties in fisheries science and management are legion and stem from the vast complexity and variability of aquatic ecosystems, the difficulties of monitoring them (Bednarek et al. 2010), and the inaccuracy and imprecision involved in measuring them (Walters and Ludwig 1981). In particular, variability in ocean conditions can profoundly affect the survival of salmon such that when the ocean phase of their lifecycle is favourable, their marine survival may be as high as 10-22%, as in the example of coho in the Georgia Strait of British Columbia in the 1970s (Beamish et al. 2000), whereas the same stocks recently had less than 1% marine survival when ocean conditions were unfavourable (Beamish et al. 2010). This temporal variation makes it difficult to model the productivity of individual salmon stocks, and even more difficult to forecast how they will behave with unpredictable future ocean conditions (Mueter et al. 2002). The significance of such pervasive uncertainties for fisheries management is that they create risks (Peterman 2004).

The process for adequately addressing uncertainties and the risks they create in fisheries management includes, at a minimum, quantitative decision analysis and risk assessment (Peterman 2004). Decision analysis provides decision support by quantitatively evaluating alternative management options while taking uncertainty into account (Peterman and Anderson 1999), and a risk assessment can be conceptualized as a sub-component of a decision analysis (Peterman 2004). Although risk and decision analysis methods differ somewhat among different fisheries scientists, some of the more essential components of each are as follows. A risk assessment includes (1) management objectives, (2) quantitative performance indicators that are used to assess when those objectives are met, and (3) a stochastic model of the relevant system 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 management actions in the case of an at-risk Pacific salmon Conservation Unit, the Chinook salmon stock (*O. tshawytscha*) from the Cowichan River, B.C. Management actions to support conservation of Pacific salmon will vary by CU (or ESU), but two important ones coastwide are reductions in harvest (NRC 1996, PSC 2009) and the establishment of supplementation hatcheries (MacKinlay et al. 2004, Waples et al. 2007). These were the two management options evaluated in this case study. In addition to accommodating systemic risks, managers have to make difficult choices regarding trade-offs among conservation, harvest, and other values, and between allocation of catch to different groups, including First Nations, sport, and commercial fisheries. Therefore, as additional support for management decisions, this research provides managers with quantitative assessments of key trade-offs between management objectives. Therefore, my specific research objectives were (1) to determine the ranks of management actions that involve combinations of harvest rates and brood-take rates for a supplementation hatchery according to different operational management objectives, each reflected by one or more performance indicators, and (2) to evaluate how robust those ranks were to key uncertainties.

## 1.2. Cowichan River Chinook

The population of Cowichan River fall-run Chinook salmon (hereafter the “Cowichan Chinook”) is important for its biological, cultural, and economic values. It is the more abundant population of two, which together comprise the East Vancouver Island Cowichan and Koksilah Chinook Conservation Unit (DFO 2009, DFO 2011b).

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 Cowichan Chinook stock is also of cultural importance to the Cowichan Tribes local First Nation, who catch it in their traditional, in-river spear fishery, and it is valued by non-First Nations residents of the Cowichan basin as well (Westland 2005). The commercial, sport, and First Nations' fisheries that depend on all salmonid species in the Cowichan River were valued at up to $10 million annually (Westland, 2005), whereas the Chinook fisheries alone were estimated to be worth between $5.4 and $6.2 million (McMullan, 2006).

The Cowichan Chinook stock has been a serious conservation concern since 1997 (CTC 2012). It is managed as part of the Georgia Strait fall Chinook (wild and small hatchery operations) stock group and is listed as having category-1 status ("stock of concern") (DFO 2011a). Historically, total annual spawner returns (adults and jacks) were often 5,000-10,000 fish, and have been estimated at up to 25,000 (DFO 2011b, Figure 1). The current target escapement for adult natural spawners is 6,500 (PSC 2012); however, the abundance of annual naturally-spawning adult Chinook salmon was less than 2,000 between 2003 to 2009. Although adult spawners increased to 2,419 and 2,786 in 2010 and 2011 (DFO 2011b), the Cowichan Chinook stock continues to be one of five *Pacific Salmon Treaty* Chinook indicator stocks that is not meeting its target escapements (PSC 2012).

The two main causes of poor Cowichan Chinook stock returns in recent years are poor marine survival and high harvest rates (DFO 1999). Marine survival of the Cowichan Chinook stock, based on coded wire tag data, has declined substantially, especially since the mid-1990s (Figure 2). The stock was over-fished in the 1970s and early 1980s (DFO 1999), and total functional fishing mortality rates (exploitation plus incidental mortality) on the Cowichan Chinook stock were estimated as high as 0.88 in 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 2010). Canada has met its “general obligation” under the *Pacific Salmon Treaty* to decrease the harvest rate on this stock 1999-2008, but the United States (U.S.) has not (PSC 2011). However, U.S. commercial fisheries from 1990 to the present account for less than 15% of the total fishing mortality on the Cowichan Chinook stock (PSC 2011). One reason why harvest rates may not have been reduced further is that Cowichan Chinook salmon are caught in mixed-stock and mixed-species fisheries from southeast Alaska and down the B.C. coast to Washington and Oregon (Table 1). This means that managers’ ability to reduce Cowichan Chinook harvest is limited if they allow harvest of more abundant stocks in those fisheries, especially in the Georgia Strait sport fishery. That fishery constitutes by far the largest portion of total percentage harvest rate (Table 1).

The Cowichan hatchery is operated as a conservation hatchery in accordance with the *Operational Guidelines for Pacific Salmon Hatcheries* (DFO 2005b) (Figure 4). This means that not more than 1/3rd of the naturally-spawning escapement in a given year can be used as brood stock (i.e., brood-take rate must be ≤ 33%), and their offspring are released into the same natural population. Upstream of where the Food, Social and Ceremonial (FSC) fishery occurs, hatchery brood stock (both sexes) is taken from the fish that are returning to spawn, irrespective of whether fish are of natural or hatchery origin. The hatchery typically releases into the river 1-3 million 3-g fry in April and 5 to 6-g pre-smolts in May (Nagtegaal et al., 2006). The Wild Salmon Policy endorses such judicious use of hatchery supplementation to rebuild wild stocks (DFO 2005a). The hatchery also provides local employment for Cowichan Tribe members through the community economic development program (Tompkins et al. 2005, DFO 2009).

# 2. Methods

## 2.1. Overview

To accomplish the research objectives set out earlier (Section 1.1), I built a stochastic life history model (Figure 5) to simulate the population dynamics of the natural-origin and hatchery-origin cohorts of the Cowichan Chinook stock, as well as the ocean harvest and in-river First Nations' harvest. I compared the outcomes of various management strategies against objectives that potentially concern fisheries managers of this system. Specific management objectives fell into four general categories: conservation, First Nations' harvest, ocean harvest, and hatchery performance (Section 2.5).

As a general overview of the model, I simulated annual abundance of key life history components of the Cowichan Chinook stock by using stochastic production functions to model two life stages: spawners-to-juveniles and juveniles-to-adults for each of the hatchery- and natural-origin cohorts. Stochasticity also entered into the FSC catch function, which predicted the First Nations' annual catch and was applied to numbers of Chinook salmon returning to the river (terminal returns) (Figure 5). This model was run for 50 years after five years' initialization using spawner data. Marine survival rates, brood-take rates, and ocean-harvest rates were set according to different management strategies (Section 2.5) and marine survival scenarios (Section 2.4), and were held constant across all years of each simulation. Performance indicators summarized Monte Carlo trial results (Sections 2.2.3 and 2.5), allowing management strategies to be ranked quantitatively for different marine-productivity regimes (Section 2.7).

## 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 jacks (age-2) from all analyses because they were not included in calculations of target escapement in Tompkins et al. (2005). They left brood 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 natural spawners and brood stock numbers for 2005 through 2009 (Table 2) to start the simulation model. The maximum brood-take number for a hatchery capacity of 1 million eggs was based on average fecundity estimated from brood stock biosample data (Appendix 10 of Tompkins et al. 2005). Average recruits-at-age, for both hatchery-origin and natural-origin Chinook salmon, came from estimates of age-at-return of all age 3+ fish to the Cowichan River from return years 1982-2004 (Appendix 3 of Tompkins et al. 2005).

### 2.2.2. *Parameter estimation and simulation model*

Because the Cowichan Chinook stock consists of two contemporaneous cohorts, hatchery-origin and natural-origin fish, I modelled their life histories separately, but in parallel; each cohort had freshwater and ocean life stages. Table 3 shows model parameters. Parameters for the relevant relationships were determined for Equations 2-4 (below), based on the observed (i.e., estimated) data (Table 2), by minimizing the sum-of-square differences of $\log_e$(observed) - $\log_e$(predicted). The model was written in the R programming language (R Development Core Team 2011).

The relationship between hatchery brood stock from the previous year and the subsequent year's hatchery releases (Figure 6) was linear with a constant coefficient of variation around it:

$$(1)\ J_{h,t+1} = kS_{h,t} + cv_h\, kS_{h,t}w_h\ ,$$

where $J_{h,t+1}$ was the number of hatchery-origin ($h$) juveniles (fry and pre-smolts) released in year $t$+1 from brood stock collected in year $t$, $k$ was the number of juveniles released per adult (age 3+), $S_{h,t}$ was the number of adults in the hatchery brood stock (both male and female), $w_h$ was a random variable drawn from the standard normal distribution, $\sim N(0, \sigma = 1)$, and $cv_h$ was the constant coefficient of variation, which was calculated from the observed minus predicted residuals and the mean predicted value of the linear regression. Parameter values and their descriptions are given in Table 3.

I modelled the two production functions for the two life stages of the natural-origin portion of the stock, and also the juvenile-to-adult relationship for hatchery-origin recruits, using Beverton-Holt relationships, assuming the well-documented multiplicative $\log_e$-normal error structure (Hilborn and Walters 1992). All age-3+ age classes of adult hatchery-origin ($h$) recruits, $R_{h,3+}$ originating from brood year $t$, (Figure 7) were:

$$(2)\quad R_{h,3+} = \frac{a_{rr} J_{h,t+1}}{\varphi b_{rr} + J_{h,t+1}} e^{w_m \sigma_{rr}} ,$$

where $a_{rr}$ and $b_{rr}$ were parameters (denoted releases-to-recruits, $rr$), $\sigma_{rr}$ was the population standard deviation from the $\log_e$ residuals, and $w_m$ was a random variable drawn from the standard normal distribution and used for the marine stage (denoted $m$) of both hatchery-origin and natural-origin fish in order to represent the same random events happening to both hatchery- and natural-origin cohorts. Using $w_m$ in this way assumes that all random variation in the ocean phase of the Cowichan Chinook life history occurs during the first year of ocean residence. The marine survival multiplier, $\varphi$, with a default value of 1.0, was applied to both hatchery- and natural-origin recruits, but its value was altered later in sensitivity analyses (Section 2.4). A marine survival multiplier of $\varphi = 2$, for example, decreases the density-independent marine survival by one-half compared to a multiplier of $\varphi = 1$.

The relationship between naturally-spawning fish and smolt abundance (denoted spawner-to-smolt, $ss$) (Figure 8) was:

$$(3)\quad J_{n,t+1} = \frac{a_{ss} S_{n,t}}{b_{ss} + S_{n,t}} e^{w_{ss} \sigma_{ss}} .$$

Here, $J_{n,t+1}$ was abundance of natural-origin ($n$) smolts produced by spawners from brood year $t$, $S_{n,t}$ represented natural spawner abundance, $a_{ss}$ and $b_{ss}$ were parameters, $w_{ss}$ was a random variable drawn from the standard normal distribution, and $\sigma_{ss}$ was the population standard deviation of $\log_e$ residuals. Note that naturally-spawning fish, $S_n$, may originate either from naturally-spawning parents or hatchery brood stock. 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:

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

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, $\sigma_{sr}$ was the population standard deviation of the $\log_e$ residuals, and $\varphi$ 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*:

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

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*.

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

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

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

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:

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

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

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 $(L,f)$, $f$ = 523 was the mean of the FSC catch data for 1990-2009, $w_F$ was the random variable drawn from the standard normal distribution $\sim N(\mu = 0, \sigma = 1)$, and $\sigma_F$ 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 (Krista Lange, pers. comm., DFO, Campbell River, B.C.), not including space in another hatchery for overflow . After the subtraction of hatchery brood fish, the naturally-spawning fish, $S_{n,yr}$, remained:

(15)$S_{n,yr} = E_{yr} – S_{h,yr}$

### *2.2.3. Simulation procedures*

Each combination of brood-take rate and harvest rate constituted a single management strategy (Section 2.5). To generate summary statistics, for each combination of management strategy and marine survival scenario (Section 2.4), I ran the Cowichan Chinook salmon life history model for 50 brood years and across 600 Monte Carlo trials, which independent sensitivity analyses showed were sufficient to give stable results. Stochasticity thus entered into the model at Equations 1-4 and 12.

## 2.3. Management parameter surface plots

Harvest rate, brood-take rate, and the marine survival multiplier were varied across a wide range of values to evaluate the behaviour of the model system based on indicator values (i.e., response variables). Evaluated harvest rates ranged from 0 to 0.7 in increments of 0.05, and brood-take rates were 0 to 0.5 in 0.05 increments. The marine survival multiplier was varied to represent poor, intermediate, and good marine survival (next section).

## 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

$$(16) O_{rr} = \frac{a_{rr}}{\varphi b_{rr}} \text{ and}$$

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

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, $\varphi$, 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 Beverton-Holt functions used for the marine life history phase (Equations 2 and 4), density-independent survival at the origin is represented by $a_{rr} / b_{rr}$ and $a_{sr} / b_{sr}$ (Hilborn and Walters 1992). Thus, changing that ratio effectively altered marine survival rate of juvenile fish to recruits in the simulated time series. Each simulation used the same multiplier, $\varphi$, for both natural-origin and hatchery-origin marine production functions. The marine survival scenarios examined here were poor, intermediate, and good. Higher multipliers ($\varphi$) resulted in the simulation of lower survival rates. To determine approximate density-dependent marine survival in the simulated time series that corresponded to $\varphi$ multipliers, I conducted a sensitivity analysis of mean recruits per juvenile across a range of marine survival multipliers, using the status-quo harvest rate ($r = 0.65$) and brood-take rate ($s = 0.22$) parameters (next section). Comparison of the marine survival estimated from data (Equations 16 and 17) with the simulated mean recruits per juvenile (simulation years 16-50), calculated across all Monte Carlo trials for natural-origin, hatchery-origin, and summed-origin fish, confirmed that the simulated mean proportions (Table 4) were similar to those estimated from data (Table 2). The scenario for *poor marine survival* ($\varphi = 7$) was intended to be similar to recent years in which marine survival was very low. The value was 0.0044 for mean recruit per juvenile for 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, $\varphi = 7$ represents a scenario in which marine survival was actually not as poor as has been seen in recent years. *Intermediate marine survival* used $\varphi = 4$; $\bar{R}_{tot,3+} / \bar{J}_{tot,t+1}$ was 0.007 for the predicted time series. The *good marine survival* scenario (marine survival multiplier $\varphi = 1$) 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 hatchery-origin fish among natural spawners. Strictly speaking, the WSP does not apply to a stock such as the Cowichan Chinook, in which not all fish are "wild" according to the definition in the WSP. That is, not all fish have lived entirely in the wild and were the offspring of parents that were also naturally-spawned and lived continuously in the wild. Therefore, I refer to naturally-spawning Chinook salmon and their offspring in this system as "natural" rather than "wild." However, especially given that the stock has been assigned to a WSP Conservation Unit, managers may want to take the same considerations into account as they would for a wild stock.

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 was suggested by the target age-3+ escapement abundance determined in Tompkins et al. (2005). I used year 15 as a reference year to calculate some indicators because the mean model outputs tended to stabilize by then if they were going to (i.e., in the intermediate and good marine survival scenarios). My recovery indicator was the probability of stock recovery, $P_{rec}$, i.e., the chance of the three-year running average meeting the target of 6,514 natural spawners at least once by year 15, and it was calculated as the proportion of Monte Carlo trials in which that occurred. I used a desired probability of recovery of $P_{rec} \geq 0.80$ as the performance indicator target.

The next conservation-related management objective involved two persistence targets. Because managers have not established targets for Cowichan Chinook stock recovery or persistence, these candidate persistence levels were based on those from the Cultus sockeye recovery strategy (Cultus Sockeye Recovery Team 2009). That document recommended a target escapement of a four-year running average of at least 1,000 spawners ($Pr_{pers}$), with a minimum of 500 spawners in any one year ($Pr_{low}$), which I used here for the persistence management objective for the Cowichan Chinook stock, except I used a naturally-spawning three-year running average because the weighted mean age of return is approximately 3 years. Bradford and Wood (2004) accepted these targets for the Cultus sockeye stock, which like the Cowichan Chinook, matures at multiple ages and returns to a relatively confined geographic area. The $Pr_{pers}$ indicator was the proportion of years between simulation years 18-50 (inclusive) in which a three-year running average of at least 1,000 natural spawners persisted, and was calculated as the number of times, out of 600 Monte Carlo trials, that the goal was met; I used a target proportion of $Pr_{pers} \geq 0.90$. The time series begins in year 18 because that year was the first in which a three-year average could be calculated, i.e., including only years > 15. All other indicators were calculated for years 16-50. The indicator $Pr_{low}$ was the proportion of years in which at least 500 naturally-spawning fish returned in a single year, and the suggested target proportion was $Pr_{low} = 0.95$; otherwise it was calculated the same way as $Pr_{pers}$, but for the lower target. The final conservation-related 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. Alternative management strategies

Management strategies represented different combinations of harvest rate and brood-take rate, the only management actions that were modelled in the current study. “Strategies” will refer to combinations of a specific harvest rate and brood-take rate comprising individual management actions (summarized in columns 1-4 of Table 6). The *status-quo* strategy had a harvest rate of $r$ = 0.65, which was the average historical (1990-2009) ocean harvest rate, including incidental mortality (Figure 3), and its brood-take rate was $s$ = 0.22, the average over years 1999-2009 (Figure 4). The brood-take rate has been higher in recent years. Management strategies labelled as lowest, low, and medium harvest rate all held brood-take rate constant at the status-quo level. The *low harvest-rate* strategy ($r$ = 0.40) was intended to represent a realistically low harvest rate; it is roughly the lowest harvest rate that has been attained in the last 20 years during which managers have attempted to decrease harvest on the Cowichan Chinook stock (Figure 3). However, to assess what would happen to the stock if it were possible to decrease the harvest rate further, the *lowest harvest-rate* strategy was set at $r$ = 0.30. The *medium harvest-rate* strategy had a rate, $r$ = 0.5, intermediate between that of the status-quo strategy and the lowest harvest rate case. Based on the assumption that managers would be most interested in management strategies in which the stock has a good chance of recovery, I did not evaluate strategies with harvest rates in excess of $r$ = 0.65.

Low, high, and highest brood-take-rate strategies varied the brood-take rate, whereas the harvest rate was held constant at 0.65. Because the stock is part of the coded wire-tag (CWT) program as an indicator stock for the *Pacific Salmon Treaty*, it is unlikely that managers would eliminate or further curtail the hatchery program. The rate for the *low brood-take-rate* strategy was set at $s$ = 0.15, whereas for the *high brood-take-rate* strategy, $s$ = 0.33, the maximum allowable under the designation of conservation hatchery, as mentioned previously (DFO 2005b). The *highest brood-take-rate* strategy ($s$ = 0.5) represented an emergency situation in which the terminal returns were very low, and half of the returning spawners were taken into the hatchery, as has been done with the Cultus Lake Sockeye (Bradford et al. 2011).

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 ($\varphi$ = 1, 4, and 7), but in addition, I varied a second parameter, ($\psi$ = 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. $R_{h,t} = \dfrac{a_{rr} J_{h,t}}{\psi \varphi b_{rr} + J_{h,t}} e^{w_m \sigma_{rr}}$ ,

whereas Equation 4 for natural-origin recruits was the same as before. Here too, higher multipliers simulated poorer-survival scenarios. For example, for $\psi$ = 0.5, the density-independent marine survival of *hatchery* fish would be double that based on the parameterization of *hatchery*-origin releases-to-recruits ($\psi$ = 1), but only 30% greater than density-independent marine survival of *natural*-origin fish. For $\psi$ = 1 (i.e., the base case in the absence of sensitivity analyses), density-independent marine survival of *hatchery* fish was 65% that of *natural*-origin fish. For $\psi$ = 0.5, density-independent marine survival of *hatchery* fish was only 32% that of *natural*-origin fish.

Second, I also examined whether ranks of management strategies would change for different standard deviations for variation around the juvenile-to-adult relationships. A range of standard deviations was used to change one or the other of Equations 2 (for hatchery fish) or 4 (for natural-origin fish), while the other was held at the baseline standard deviation. Baseline parameter values were: $\sigma_{rr}$ = 0.676 (Equation 2) and $\sigma_{sr}$ = 0.736 (Equation 4). The range of values explored for hatchery-origin recruitment standard deviation was $\sigma_{rr}$ = 0.25, 0.5, 0.676, and 1; the natural-origin values were $\sigma_{sr}$ = 0.25, 0.5, 0.736, and 1.

# 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 ($\varphi$ = 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 intermediate marine survival, the probability of recovery performance indicator (Figure 12) shows isopleths ranging from $P_{rec}$ = 0.1 to 0.9. Those values are averages across the 600 Monte Carlo trials of the probabilities of the stock's recovery to 6,514 natural spawners by year 15. More than half of that plot is shaded, i.e., for values of $P_{rec}$ ≤ 0.8, which is the target recovery probability.

For poor marine survival, the probability of recovery and median natural spawner abundance indicators showed only undesirable values for the plotted range (Figure 12), and FSC harvest showed a maximum value of 510, which was just below the desired historical average of 523 (Figure 13). For intermediate marine survival, the four conservation indicators (those defined in the top half of Table 5) and the proportion of hatchery-origin spawners showed both desirable and undesirable values, whereas for 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 rates. This result was most evident for conservation indicators (Figure 12) and for ocean harvest with good marine survival (Figure 13), as reflected by contour lines that were nearly vertical for much of those indicators' management-parameter space. However, the greatest sensitivity to brood-take rates was seen at $s \leq 0.2$, with lower rates leading to poorer stock abundance indices. For the good marine survival scenario ($\varphi = 1$), median natural spawner abundance (Figure 12) and ocean harvest (Figure 13) were very insensitive to brood-take rate, except when $s < 0.05$, where the sensitivity was relatively dramatic. In contrast, the indicators that were most sensitive across a wider range of brood-take rates were FSC harvest and cost per hatchery-origin recruit, $C$, for poor and intermediate marine survival scenarios, and proportion of years with ≥ 500 spawners for poor marine survival, with brood take rate $0 \geq s \leq 0.3$ (Figures 12 and 13). However, these indicator responses exhibited an interactive effect between brood-take and harvest rates, as indicated by angled contours (Figures 12 and 13). In addition, $C$ was very sensitive to brood take rates approaching zero.

For poor and intermediate marine survival, two indicators demonstrated especially variable responses to harvest rates across the range examined (Figure 13). For intermediate marine survival, ocean harvest, $H_{oce}$, was highly responsive to harvest rate, except at brood-take rates of less than approximately 0.2, where the indicator's performance switched to being relatively insensitive to harvest rate and very sensitive to brood take rate, especially for harvest rates between approximately $r = 0.4$ to 0.6. The shape of the $H_{oce}$ indicator surface was similar for poor marine survival, but the number of harvested fish was lower (a maximum of approximately 1,250 here, compared to 3,500 for intermediate survival). The proportion of hatchery-origin spawners indicator ($Pr_{hat}$) for intermediate ocean survival ranged from 0 to over 0.6 and was also very sensitive to harvest rate and very insensitive to brood-take rate for a range of low harvest rates ($r$) and high brood-take rates ($s$), but then switched to insensitivity where $s = 0.1$ to 0.2. The performance of $Pr_{hat}$ for poor marine survival was similar, and for harvest rates higher than about $r = 0.3$, the majority of natural spawners was of hatchery origin. Most of the eight specific management strategies examined here (indicated by symbols in Figures 12 and 13) for poor and intermediate marine survival conditions resulted in $Pr_{hat}$ values higher than the brood-take rates that generated them, but this generalization was not true of all harvest and brood-take rate combinations generating the response surface.

## 3.2. Marine survival scenarios and management strategies

### *3.2.1. Poor marine survival*

The low and lowest harvest-rate management strategies were clearly the best for the poor marine survival scenario, where they ranked first and second, respectively, based on the target values for all indicators except for the proportion of hatchery-origin spawners, $Pr_{hat}$ (Table 6). The status-quo strategy ranked last or second-to-last out of the eight strategies for all indicators except $Pr_{hat}$. The best-performing management strategies based on ocean harvest, $H_{oce}$, also had the two lowest harvest rates. The third-best strategy for $H_{oce}$ was the combined strategy, which also had a harvest rate lower ($r = 0.5$) than that of the status-quo strategy ($r = 0.65$). For any given management strategy, the two worst-performing indicators predicted very low or undesirable values: probabilities and proportions of ≤ 0.02 for $P_{rec}$, $Pr_{pers}$, and $Pr_{low}$, $S_{nat} = 21$, $H_{fsc} = 9$, $H_{oce} = 62$, and $C$ = \$27,077.

Even for the highest-ranked management strategies (i.e., lowest rank number), predicted conservation indicators were often well below desired values for the poor marine survival scenario. For instance, the probability of recovery was only 0.15 for the lowest harvest rate, and 0.087 for the low harvest-rate strategy, and the predicted probability of persistence was 0.78 and 0.43, respectively (Table 6). The median natural spawner indicator for the low harvest-rate strategy did not reach the proposed target of 1,000, and annual medians of natural-spawner abundance for the same strategy showed a declining trend (Figure 11A). The values of the highest-ranked indicators for cost per hatchery-origin recruit and ocean harvest also fell outside of desired ranges, as did the FSC harvest indicator (with catch = 411), which was below the desired catch of 523.

Overall, management strategies with harvest rates that were reduced from the status-quo value of 0.65 outperformed strategies with increased brood-take rate. This trend was also evident when the combined strategy ($r$ = 0.5) was compared to the high brood-take-rate strategy ($r$ = 0.65), both of which had the same brood-take rate ($s$ = 0.33); the combined strategy was better for all indicators.

### *3.2.2. Intermediate marine survival*

For intermediate marine survival ($\varphi$ = 4), the highest-ranking management strategies were again the lowest and low harvest-rate strategies for seven out of eight of the indicators, although here ocean harvest was the exception (Table 7). The rank order of strategies was similar for conservation, FSC harvest, and hatchery performance objectives, and the status-quo strategy ranked last, or second or third-to-last for six out of eight indicators. Based on the ocean harvest indicator ($H_{oce}$), the combined strategy ($r$ = 0.5) was best, with the medium ($r$ = 0.5) and low ($r$ = 0.3) harvest-rate strategies tied for second, whereas the strategy with the highest brood-take rate ranked third. However, for the medium harvest-rate and combined strategies, their median natural spawners and recovery-probability indicator values were approximately half to two-thirds of those of the lower harvest rate strategies, whereas their ocean harvests were comparable to that of the low harvest-rate strategy and less than 30% better than the ocean harvest of the lowest harvest rate strategy. So even though the medium harvest rate and combined strategies were better for ocean harvest, they did not provide much gain, while being worse for two of the conservation indicators.

For this intermediate case of marine survival, the two low harvest-rate strategies ranked highest for most indicators, but one of the conservation indicators met its target only for the lowest harvest rate strategy, and another did not meet the proposed minimum desirable value (Table 7). The lowest harvest rate strategy barely achieved a predicted 0.80 probability of recovery, but even if managers were to set a lower target of $P_{rec}$ = 0.60, the low harvest-rate strategy would barely meet it. For the proportion-persistence indicator ($Pr_{pers}$), only strategies with harvest rates less than the status quo predicted $Pr_{pers}$ > 0.90. These same four strategies were the only ones with $Pr_{low}$ > 0.95, the proportion of years meeting the low abundance constraint. The predicted abundance of natural spawners did not reach the target escapement of 6,514 for any strategy for intermediate marine survival.

Among the lower-ranking management strategies, it is possible to make some generalizations based on ranks. The combined strategy ($r$ = 0.5) performed consistently better than the high brood-take-rate strategy ($r$ = 0.65; $s$ = 0.33 for both), and slightly better than medium harvest rate ($r$ = 0.5) for most indicators, except for hatchery performance indicators. The high and highest brood-take-rate strategies performed better than the status quo for all indicators except $P_{rec}$ (tied) and proportion hatchery-origin spawners ($Pr_{hat}$), and the high brood-take rate ranked higher than the low brood-take-rate strategy for all indicators except for the probability of recovery and $Pr_{hat}$.

### 3.2.3. Good marine survival

In contrast with the other marine survival results, the good marine survival case ($\varphi$ = 1) did not show much spread in management-strategy rankings (Table 8). There were many more ties here between management strategies than there were for the other two marine survival scenarios, and even those that ranked lowest still reflected a healthy stock abundance. All seven management strategies were tied for highest rank based on the following indicators: probability of persistence ($Pr_{pers}$), proportion of years with ≥ 500 natural spawners ($Pr_{low}$), FSC harvest ($H_{fsc}$), and cost ($C$). Management strategies with status-quo harvest rate of $r$ = 0.65 were tied for second rank according to the probability of recovery ($P_{rec}$), tied for fourth according to median natural spawners ($S_{nat}$), and tied for third according to proportion hatchery-origin spawners ($Pr_{hat}$). The lowest and low harvest-rate strategies were highest-ranked for the conservation indicators, but lowest ranked for the ocean harvest indicator ($H_{oce}$). Tied for highest rank for $H_{oce}$ were all strategies with the status-quo harvest rate ($r$ = 0.65), combined with various brood-take rates.

For the indicators of probability of recovery, median natural spawners, proportion of hatchery origin spawners and ocean harvest, the predicted values were consistently favourable for all management strategies (Table 8). For the probability of recovery indicator, even the management strategy that was ranked last had a point estimate of $P_{rec}$= 0.97. For all strategies, median natural spawners were predicted to be well in excess of the stock's target escapement, ranging from 8,164 to 19,827. The proportion 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 in which $Pr_{hat}$ sometimes fell below the brood-take rate of the management strategy used to generate those predictions. Even where the point estimate for $Pr_{hat}$ was higher than the brood-take rate, the difference was small, in contrast to the other marine survival scenarios.

### *3.2.4. Trade-offs between management strategies*

For poor and intermediate marine survival scenarios, there were trade-offs between ocean harvest and six of the seven other management objectives to some degree (Figures 12 and 13). Generally, increased ocean harvest rates resulted in better outcomes for ocean harvest and poorer outcomes for other objectives. However, due to the non-linear response of ocean harvest to harvest rates, these trade-offs were not apparent across the whole range of harvest rates examined here. For example, for the poor marine survival scenario, ocean harvest improved as harvest rates increased from zero to about 0.3, at a brood take rate of about 0.33, but harvest rates > 0.3 caused poorer ocean harvest (Figure 13). Therefore, the trade-off between conservation and FSC harvest objectives and ocean harvest occurred only at harvest rates of about $r < 0.3$ for poor marine survival and for about $r < 0.4$ for intermediate ocean survival. There was essentially no trade-off between ocean harvest and proportion of hatchery-origin spawners for poor and intermediate marine survival scenarios and brood-take rates $s > 0.2$; for harvest rate ranges that were unfavourable for $H_{oce}$, they were unfavourable for $Pr_{\mathrm{pers}}$ as well. For good marine survival scenarios, there was also no trade-off between management objectives and their performance indicators.

## 3.3. Sensitivity analyses

The survival multipliers used in sensitivity analyses on the relative survival of hatchery- and natural-origin fish, as described in Section 2.8 (Equation 18), can be understood in terms of marine survival ratios. For example, a ratio of 1.3 indicates a 30% improvement of hatchery over natural marine survival, and a ratio of 0.32 indicates a 68% decrease in hatchery marine survival compared to natural fish. The base case survival ratio, 0.65, represents a 35% poorer survival of hatchery-origin, compared to 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 $Pr_{\mathrm{low}}$, 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 increased marine survival of hatchery-origin fish for intermediate survival ($\varphi = 4$), where the medium and combined harvest rate strategies tied for first rank, compared to fourth and third rank, respectively, for the baseline marine survival ratio. Differential hatchery survival ratios caused the most changes in relative rankings of the management strategies at intermediate and poor marine survival scenarios, with the greatest effects on ocean harvest ($H_{oce}$) and the proportion of hatchery-origin fish among natural spawners ($Pr_{hat}$) (Tables 10 and 11). Also, there were a few switches in rank for the four lowest-ranked indicators compared to the base-case density-independent survival. In particular, for poor and intermediate ocean survival conditions, the highest brood-take rate and the status-quo strategies tended to change rank position for different relative hatchery survival ratios for a single marine survival condition. Not all such rank changes are shown here in the tables, but one is shown in the comparison of the survival ratio 1.3 and 0.32 to the base case of 0.65 for the intermediate ocean survival scenario for the $Pr_{low}$ indicator (Table 9).

Specifically, for $H_{oce}$ for intermediate marine survival, the top-ranked two management scenarios differed among the survival ratios (Table 11). Interestingly, the strategy for lowest harvest rate ranked second-highest for a survival ratio of 0.32, but ordered last for ratio of 1.3. For poor ocean survival, where the ratio was 0.65 and 1.3, the ranks of management strategies were almost identical for $H_{oce}$, with the two highest-ranked strategies being the lowest and low harvest rate, in order, as they also were for seven out of eight indicators (not shown). However, when marine survival of hatchery fish was better than in the base ratio, the low harvest rate ranked second, and the combined and highest brood-rate strategies tied for first rank (Table 11).

For poor marine survival ($\varphi = 7$), the low brood-take rate ranked first across all hatchery multipliers based on the $Pr_{hat}$ indicator (Table 12), whereas the lowest, low, and medium harvest rate strategies ranked in the top three. The status quo ranked fourth for a survival ratio of 1.3 and second for 0.32. The most substantial change in rank according to $Pr_{hat}$ during intermediate marine survival ($\varphi = 4$) was for the low brood-take rate strategy, which ranked first and second for survival ratios of 0.32 and 0.65, respectively, but fourth for 1.3.

Sensitivity analyses on standard deviations for ocean production functions showed that performance indicator values changed most for the poor marine survival scenario compared to other scenarios, and more for the standard deviation on the natural-origin ocean smolt-recruit function than the standard deviation of the hatchery-origin release-recruit function. However, the resulting changes in rank of management strategies were minor and will not be considered further.

# 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 would be very unlikely to persist given status-quo harvest rates ($r = 0.65$). (3) When marine survival was poor, low levels of hatchery brood take substantially increased indices of stock abundance compared to no hatchery supplementation. (4) A management strategy involving high brood-take rates ($s = 0.5$) provided minimal improvement in rank over the status-quo brood-take rate ($s = 0.22$) for most indicators when marine survival was intermediate to poor, but that result varied across relative survival rates of hatchery and natural fish.

## 4.2. Management Implications

### *4.2.1. Harvest rates*

The most striking impact of potential management actions upon performance indicators (as shown in Figures 12 and 13) came from harvest rate. Furthermore, there was no acceptable level of harvest rate for low ocean survival conditions for two of four conservation indicators, given the suggested performance indicator targets, and the FSC harvest did not reach the historical average of 523 fish for any harvest rate. Even for intermediate marine survival, the lowest harvest rate strategy ($r = 0.3$; $s = 0.22$) was 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 a population trajectory with a continual, downward spawner-abundance trend (Figure 11A). The best management strategies for most indicators and marine survival scenarios were the low and lowest harvest-rate strategies. The status-quo management strategy was not optimal for any of the marine survival scenarios analysed in this study; even for intermediate marine survival, it was unlikely to result in persistence. Recall also that marine survival in recent years has been even lower than that represented by the poor marine survival scenario in this study (Figure 2), which makes using management strategies with low harvest rates all the more crucial.

For the poor marine survival scenario, managers would be unable to rebuild the Cowichan Chinook stock using the strategies considered. The predicted probability of recovery for the lowest harvest-rate strategy ($r = 0.30$; $s = 0.22$) was only 0.15; furthermore, regardless of brood-take rate, the recovery probability never exceeded 0.18. The situation was somewhat better for harvest rates lower than those in the assessed management strategies. The probability of recovery during poor marine survival was between 0.37 to 0.71 in the complete absence of harvest, depending on the brood-take rate (Figure 12). However, as argued in the Introduction, it is unlikely that managers will be able to decrease harvest rate on this stock further than $r = 0.40$ (represented by the low harvest-rate strategy), which has a proportion of years with natural spawners ≥ 1,000 fish ($Pr_{pers}$) of 0.43 for poor marine survival (Table 6). Nevertheless, the lowest harvest-rate strategy may be a reasonable solution while marine survival remains poor, with $Pr_{pers} = 0.78$. Because depensation effects at low population numbers are unknown for this system and have not been included in this model, it is important to maintain the stock above the persistence level of 1,000 natural spawners that was recommended in Bradford and Wood (2004). The Wild Salmon Policy acknowledges that it might not be possible to preserve all salmon CUs in the face of 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 the stock from going extinct while they wait for marine survival to improve.

An impediment to further decreasing the harvest rate is that the Cowichan Chinook salmon are caught in mixed-stock and mixed-species fisheries. For a Conservation Unit (CU) in the amber zone, once the Wild Salmon Policy is fully-implemented, economic issues can be considered regarding more productive CUs caught together with the amber-status stock (DFO 2005, p. 17). However, for red-status CUs, only biological considerations are supposed to guide management. So far, management actions in Canadian fisheries that benefit the Cowichan Chinook stock have included decreasing harvest of this stock by reducing fisheries exploitation in areas and at times where the most impact has occurred, including additional Chinook non-retention areas and closed areas instituted in 2009-2011 (DFO 2010). For other Canadian stocks of concern having the problem of interception in multiple fisheries, managers have implemented a variety of strategies. The COSEWIC-listed Cultus Lake sockeye is caught in economically important mixed-stock fisheries (Cultus Sockeye Recovery Team 2009). Partly due to concerns for Cultus sockeye, managers have decreased harvest rates on the entire late-run Fraser River sockeye aggregatewhich includes the Cultus sockeye stock (Bradford et al. 2010). Additional management actions have included hatchery supplementation from capture of returning fish, a captive-brood program, and in-lake predator control of northern pikeminnow (Bradford et al. 2010). The Interior Fraser coho salmon (*O. kisutch*) is another stock (comprised of 5 CUs) that, like the Cowichan Chinook, has low abundance and is caught in a number of mixed-stock fisheries (DFO 2002, DFO 2010). Management actions planned for its conservation include non-retention, and temporal and area closures in multiple fisheries and areas. The goal is to reduce Canadian exploitation rates on Interior Fraser coho salmon to 0.03 (DFO 2010). Recent exploitation rates on this stock were estimated at 0.13 for combined U.S. and Canadian fisheries (Interior Fraser Coho Recovery Team 2006), which are significantly less than those for the Cowichan Chinook stock.

In contrast, for the good marine survival scenario considered here, it would not matter much which management strategy managers were to employ when marine survival was good; all management strategies resulted in desirable outcomes for all indicators. This result is a reflection of the strength of the stock historically, and it helps to explain why the stock has not been extirpated, even in the face of historical harvest rates that were estimated sometimes higher than 0.85 (Figure 3). Therefore, during good marine conditions, managers might be guided solely by the highest-ranked management strategy for ocean harvest. Indeed, the highest-ranked management strategy (high brood-take rate, with $H_{oce} = 17{,}231$) produced almost double the median ocean harvest compared to the lowest (lowest harvest-rate strategy with $H_{oce} = 8{,}952$). However, the suggestion that managers would be safe to use ocean harvest and hatchery objectives to guide them when ocean survival is favourable depends on their having a reasonable expectation that marine survival would continue to be good.

### *4.2.2. Hatchery*

The value of hatchery supplementation was especially apparent in contour plots of indicator values as functions of both brood-take and harvest rates (Figures 12 and 13). The positive effect of hatchery supplementation upon recruit abundance was most evident at poor and intermediate marine survival scenarios for conservation and FSC harvest indicators; brood-take rates of $s \leq 0.15$ for a given harvest rate resulted in lower values in all of those indicators. These results demonstrated that a small brood-take rate benefitted stock abundance, and importantly, that supplementation did no apparent harm to the stock when the brood-take rate was up to $s = 0.5$, the highest tested. Taken together, these results suggest that the simulated hatchery was working in accordance with its mandate as a conservation hatchery.

However, there are a number of potentially harmful effects of hatcheries that were not represented in the model's processes. Most studies have found negative effects of hatchery-origin upon natural-origin salmon in freshwater, but the interactions during ocean and estuarine residence are relatively unknown because they are rarely studied (Naish et al. 2008). It is also unknown whether hatchery-origin Cowichan Chinook salmon reproduce just as well as their natural-origin counterparts. Waples et al. (2007) found a small number of studies suggesting that some hatchery-origin fish reproduced more poorly in the wild than their natural-origin counterparts, while others reproduced as well. Another study found substantially-reduced reproductive fitness in 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 in sensitivity analyses.

In this study, in almost all combinations of marine survival scenarios and management strategies, the predicted average proportion of hatchery-origin fish among natural spawners was higher than the brood-take rate that produced it, sometimes by a factor of almost 2. This result occurred despite of the poorer marine survival of hatchery-origin fish compared to naturally-spawned fish, and reflects the much higher pre-smolt survival of hatchery-origin fish. The significance of this result is that with all else being equal, it is usually preferable to have a lower proportion of hatchery-origin fish returning to spawn naturally because of some of the potentially adverse effects of hatchery supplementation mentioned above. Also, modelling studies of supportive breeding (i.e., in which natural breeders are taken as brood stock and their offspring released back into the natural environment) suggest that even for these breeding programs, there can be adverse genetic impacts such as genetic drift, inbreeding, change in effective-population size (Wang and Ryman 2001, Duchesne and Bernatchez 2002), and homogenization of locally-adapted stocks (Naish 2008). Even with relatively low gene flow from hatchery fish to the natural stock, the phenotype can change to one that is best adapted to hatchery conditions, and this effect is more pronounced with higher rates of hatchery supplementation (Ford 2002).

In addition to the relatively minor importance of brood-take rate for a given harvest rate, there was a minor interaction effect between harvest and brood-take rates apparent in the sensitivity contour plots (where contours are angled between 0° and 90° in Figures 12 and 13) and in Tables 6 and 7. As a consequence, for most performance indicators, the combined strategy ($r = 0.5$; $s = 0.33$) performed slightly better than either the medium harvest rate ($r = 0.5$; $s = 0.22$) or the high brood-take rate ($r = 0.65$; $s = 0.33$). The response of the cost per hatchery-origin recruit indicator, $C$, at brood-take rates $\leq 0.05$ emerged because at a brood take rate of zero, $C$ necessarily approaches infinity.

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. Regardless, for the Cowichan Chinook salmon, the relative ordering of the highest brood-take-rate strategy compared to the status-quo and other low-ranked strategies was not very robust to uncertainties about the relative marine survival of hatchery and natural fish (Section 3.3.1, Table 10). Therefore, managers would be advised not to use the highest brood-take-rate strategy in an attempt to increase abundance of the Cowichan Chinook stock.

There are two important considerations regarding the choice of the maximum brood number for the Cowichan Chinook supplementation hatchery. First, for a given harvest rate in the good marine survival scenario, the median natural spawners and ocean harvest were very insensitive to the brood-take rate when that rate generated more than the model's maximum of 526 brood fish (contours of those indicators showed an abrupt change to vertical contours at a low brood-take rate - Figures 12 and 13). Although not included in the analysis here, one of the model outputs was the proportion of times that the maximum brood-take number of 526 was reached in 600 Monte Carlo trials. For the highest brood-take rate strategy (*r* =0.65 and *s* = 0.5), this proportion was 0.022, 0.33, and 0.99 for the poor, intermediate, and good marine survival scenarios, respectively. For the status-quo strategy (*r* = 0.65, *s* = 0.22), these values were 0.008, 0.15, and 0.97, respectively. These results suggest that although the choice of maximum brood take was an influential factor for some performance indicators for the good marine survival scenario, this was not the case for the poor and intermediate marine survival scenarios (which were a focus of this study), where performance indicator values were affected much less by the current maximum of 526 hatchery brood fish. Second, a realistic estimate of maximum hatchery output over the next 50 years may be only 0.5

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-recruit model combined with a decision analysis that included rankings of management strategies on the basis of system indicators. Lessard et al. (2008) argue that multi-stage stock-recruitment models can help to develop more robust management policies than models relying on a single stock-recruitment production function, especially in the context of uncertainties. Moussali and Hilborn (1986) developed a multi-stage stock-recruit model in which different Beverton-Holt functions were used for different life stages. Their method has since been expanded and adopted by other modellers (e.g., Sharma et al. 2005, Scheuerell et al. 2006, Honea et al. 2009, McElhaney et al. 2010). Scheuerell et al. (2006) used their model to represent density-dependent population growth at each Chinook life stage while including habitat alteration, system variations over time, and spatial distribution of spawners. They did not focus on marine survival as was done here, but that found that increasing freshwater survival successfully resulted in increased abundance and other improvements. Honea et al. (2009) also used the multi-stage Beverton-Holt model to evaluate the effects of habitat variables on Chinook salmon. McElhaney et al. (2010) conducted tests of the validity of single-species multi-stage Beverton Holt models and emphasized the importance of sensitivity analyses; they suggested that relative indices of abundance were more reliable than predictions of absolute abundance.

Several researchers have also used stochastic life history models to model naturally-spawned and hatchery-origin salmon in a single system as separate cohorts (e.g., Sharma et al. 2005, Scheuerell et al. 2006, Scheuerell and Hilborn 2009, Korman and Grout 2008). Sharma et al. (2005) used their model to assess the negative impact of domestication on natural coho salmon productivity (defined as the maximum survival rate from one life history stage to the next) due to unintended interbreeding with hatchery-origin fish. However, before the cumulative domestication effect occurred, they found that hatchery strays increased natural production, as did hatchery supplementation (the latter just as in the current study). Scheuerell and Hilborn (2009) model two Chinook stocks, including their hatchery operations, harvest rate, and freshwater habitat structure, to estimate how much freshwater habitat is essential to their abundance. Korman and Grout (2008) used a stochastic two-stage model for a population viability analysis, with the Ricker model used to estimate the smolt-to-recruit survival of natural-origin Cultus Lake sockeye salmon. Their emphases were on the effects of harvest rate, hatchery supplementations, and habitat enhancement, and they found that for their optimistic marine survival scenario, continued hatchery supplementation would be unnecessary to promote recovery, whereas under the worst-case marine survival scenario, the captive hatchery brood stock program would need to be extended to improve the long-term viability of the stock.

In addition, one of the chief uncertainties in the Cowichan Chinook system, as in many others, is future ocean marine conditions and their effect upon salmon survival. It is crucial to conduct sensitivity analyses that assess the risks associated with this uncertainty and how the optimal management strategies might change as a result. To model different marine survival regimes, Collie et al. (2012) changed the productivity parameter for the Ricker model (*a*) during the ocean phase of the life cycle. Similarly, in the model here, the density-independent slope at the origin of the Beverton-Holt model, the ratio *a/b*, was modified. Collie et al. (2012) found that time-varying management policies increased abundance and catch, an option that was not assessed in the model here.

## 4.4. Decision support and sensitivity analyses

An advantage of sensitivity analyses in the context of decision analyses is that they identify management actions that are most robust to different management objectives or parameter values (Peterman and Anderson 1999). Here, I used sensitivity analyses to assess robustness of the ranking of management strategies to three sources of uncertainty: overall marine survival, the difference between marine survival of hatchery-origin fish and that of natural-origin fish, and the standard deviation of the variability around the juvenile-to-recruit model, i.e., the ocean production function. The latter proved to be of minor importance.

For all marine survival scenarios, the low and lowest harvest-rate management strategies emerged as consistently favourable across three of four broad management concerns (indicators of conservation, FSC harvest, and hatchery performance). These results can potentially provide managers with a more robust justification for choosing the low or lowest harvest rate choices.

The indicator that most affected the rank-order of management strategies across changes in marine survival conditions was ocean harvest. For example, at poor marine survival, the strategies that ranked highest were the two lowest harvest-rate strategies, whereas for good marine survival, they were ranked lowest, and for intermediate marine survival, they were ranked fourth and second. This response was reflected in the contour plots for this indicator (Figure 13).

There were two other noteworthy changes in the ranks of management strategies across different ocean-survival multipliers. First, for good marine survival, all management strategies were tied in rank for four out of eight indicators, and there were many other ties in rank, which was not seen as much for the other two marine survival multipliers. This situation occurred because during good marine survival, the population abundance increased rapidly and could not do any better in meeting management objectives, even if survival rates increased further. Second, for the comparisons between intermediate and poor marine survival, the management strategies with the low and lowest harvest rates were ranked the two highest, and the medium harvest rate and combined strategies were ranked in the top four, for all indicators except $H_{oce}$ and $Pr_{hat}$. This result indicates that those are the most robust management strategies unless managers are primarily interested in $H_{oce}$ and $Pr_{hat}$.

For differential hatchery- and natural-origin marine survival, the indicators that were the most sensitive were proportion of hatchery-origin spawners and ocean harvest. For proportion hatchery-origin spawners, and for most combinations of marine survival multiplier and hatchery-survival multiplier, increasing brood-take rate was not as effective a strategy for conservation and FSC harvest objectives as reducing harvest rate. However, for the ocean-harvest indicator for different marine survival scenarios and hatchery-survival multipliers, the best strategies varied among higher brood-take-rate verses low to medium harvest-rate strategies. The latter results imply that if managers are primarily interested in ocean harvest for the Cowichan Chinook stock, they should consider investing additional resources into determining relative marine survival of natural and hatchery fish in this system.

In the current study, I have explored some plausible potential management objectives for the Cowichan Chinook system and demonstrated quantitatively what the relative outcomes of particular management decisions might be. One challenge of implementing decision analyses is that management agencies can have difficulty in formulating clear, unambiguous objectives (Peterman and Anderson 1999). Researchers using management advice can help to circumvent this problem, as I do here, by providing some plausible management objectives with possible targets and indicators that operationalize them, and ordering plausible management strategies by the indicator values that the model generates for each strategy. This way, managers can decide later what their management objective(s) are (by choosing among the ones provided). This type of evaluation of a number of potential management options may even help managers to refine what their specific objectives are, which can feed into further analyses.

## 4.5. Recent spawner abundance

In the past two years (2010 - 2011) of data on Cowichan Chinook spawner escapements, which were not included in the model's initialization, there have been substantial increases in abundance, although these increases nevertheless fell far short of the target recovery abundance (Figure 1). Preliminary ocean harvest rate estimates (CWT-based marine survival data from the Salmon Assessment Section of the Salmon and Freshwater Ecology Division, DFO, Nanaimo, B.C.) indicate harvest rates (0.61 in 2010 and 0.44 in 2011) below the mean, but higher than the lowest rate over years 1990-2009 (i.e., 0.4 in 1997 and 0.38 in 2000). FSC harvest has not been especially low during those years, either; it was 301 and 443 adult fish, respectively, which was lower than in 2009 (475 fish), but higher than for the two years prior (238 and 240). However, sea surface temperatures during 2007-2009 were lower than average (Beamish et al. 2012), and may have contributed to better early marine survival for the cohorts returning in 2010-2011. In addition, there was a greater number of older (6-g) hatchery releases in years whose smolts returned in 2010 to 2011 than in previous years, and these fish survive better in the marine environment than younger, smaller releases (Mel Sheng, pers. comm.).

## 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 indicators reflect management objectives, and so ranking of strategies allows managers to examine trade-offs among their different objectives. Sensitivity analyses provide information on the robustness of the order of strategies to uncertainties. Such trade-off analyses help to inform managers of how certain they can be of the relative merits of specific management strategies, and can thus provide them with stronger justification of their management decisions. Also, where there is greater sensitivity to uncertain parameters, this can identify where managers should invest in additional data-gathering efforts. In these ways, a decision tool like the one developed in this study can be valuable to fisheries managers dealing with difficult choices in the presence of uncertainty.

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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 |
|---|---|---|---|---|
| Southeast Alaska | Troll | 0.20 | 1.76 | 0.45 |
| | Net | 0.02 | 0.00 | 0.13 |
| | Sport | 0.00 | 0.00 | 0.12 |
| Northern British Columbia | Troll | 0.19 | 0.00 | 0.44 |
| | Sport | 0.59 | 0.50 | 1.97 |
| West Coast Vancouver Island | Troll | 5.27 | 1.19 | 9.22 |
| | Sport | 0.76 | 1.17 | 5.43 |
| Georgia Strait | Troll | 8.99 | 0.00 | 0.00 |
| | Sport | 49.94 | 34.13 | 27.49 |
| Other Canada | Troll | 0.49 | 0.00 | 0.30 |
| | Net | 5.48 | 0.94 | 0.22 |
| | Sport | 0.00 | 0.00 | 0.00 |
| Washington-Oregon Coast | Troll | 0.42 | 0.00 | 0.87 |
| | Net | 0.00 | 0.00 | 0.00 |
| | Sport | 0.03 | 0.00 | 0.23 |
| Puget Sound | Net | 2.58 | 2.66 | 7.60 |
| | Sport | 1.03 | 2.53 | 2.42 |
| Terminal | Troll | 0.00 | 0.00 | 0.00 |
| | Net | 1.28 | 4.58 | 5.14 |
| | Sport | 1.65 | 4.79 | 2.95 |
| | Esc. | 21.08 | 45.74 | 35.00 |
| Total | | 100 | 100 | 100 |

**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 of which are reproduced in Tompkins et al. (2005). Juvenile hatchery releases were from the Georgia Basin Salmon Stock Assessment Unit, DFO, Nanaimo, B.C. Natural-origin juvenile data and natural-origin recruits were from Appendix 7 of Tompkins et al. (2005). Hatchery-origin recruits were based on data provided by Arlene Tompkins, DFO, Nanaimo B.C. Marine urvival rate data were from CWT-based marine survival estimates from the Salmon and Freshwater Ecology Division, Salmon Assessment Section, DFO, Nanaimo, B.C. Total fishing mortality data were from the Pacific Salmon Commission Chinook Technical Committee (2012). The model was initialized with hatchery brood take and natural spawners from brood years 2005–2009, also shown here. A hatchery failure caused the 2004 brood to be lost after the brood stock was taken.**

| Brood year | Hatchery brood take | Juvenile hatchery releases | Hatchery-origin recruits | Natural spawners | Natural-origin juveniles | Natural-origin recruits | Terminal return | FSC harvest | Survival rate | Total fishing mortality |
|---|---|---|---|---|---|---|---|---|---|---|
| 1979 | 195 | 32,547 | | | | | | | | |
| 1980 | 337 | 65,000 | | | | | | | | |
| 1981 | 282 | 30,373 | | | | | | | | |
| 1982 | 534 | 224,944 | | | | | | | | |
| 1983 | 242 | 101,000 | | | | | | | | |
| 1985 | 175 | 63,886 | 1,680 | 3,500 | 1,001,085 | 24,727 | | | 0.0106 | |
| 1986 | | | | | | | | | | |
| 1987 | 582 | 692,176 | | | | | | | 0.0131 | |
| 1988 | 678 | 855,282 | 10,930 | 6,200 | 1,743,880 | 87,700 | | | 0.0218 | |
| 1989 | 535 | 736,939 | 15,169 | 5,000 | 608,545 | 34,377 | | | 0.0240 | |
| 1990 | 326 | 650,815 | 7,108 | 5,300 | 482,152 | 28,244 | 6,446 | 820 | 0.0260 | 0.86 |
| 1991 | 1408 | 2,566,067 | 11,874 | 6,000 | 763,686 | 17,481 | 7,658 | 250 | 0.0095 | 0.83 |
| 1992 | 1750 | 2,975,343 | 21,695 | 8,500 | 1,238,899 | 29,758 | 10,510 | 260 | 0.0104 | 0.88 |
| 1993 | 1972 | 2,931,614 | 12,793 | 5,058 | 1,610,273 | 24,621 | 7,325 | 295 | 0.0075 | 0.82 |

Table 2 continued

| Brood year | Hatchery brood take | Juvenile hatchery releases | Hatchery-origin recruits | Natural spawners | Natural-origin juveniles | Natural-origin recruits | Terminal return | FSC harvest | Survival rate | Total fishing mortality |
|---|---|---|---|---|---|---|---|---|---|---|
| 1994 | 1357 | 1,663,867 | 8,752 | 5,050 | 1,055,094 | 15,288 | 6,752 | 345 | 0.0067 | 0.67 |
| 1995 | 2149 | 2,581,333 | 3,373 | 14,300 | 1,181,849 | 7,599 | 16,982 | 533 | 0.0038 | 0.53 |
| 1996 | 1616 | 2,878,243 | 6,043 | 12,980 | 1,425,872 | 10,808 | 15,406 | 810 | 0.0035 | 0.61 |
| 1997 | 128 | 262,675 | 910 | 9,845 | 981,079 | 9,850 | 10,164 | 191 | 0.0042 | 0.40 |
| 1998 | 1487 | 2,543,136 | 8,471 | 4,371 | 422,825 | 4,283 | 6,931 | 1,073 | 0.0055 | 0.52 |
| 1999 | 1610 | 2,580,655 | 10,268 | 4,500 | 271,264 | 3,068 | 6,343 | 233 | 0.0042 | 0.62 |
| 2000 | 1529 | 2,409,720 | 2,964 | 5,109 | 3,438,325 | 13,547 | 6,727 | 89 | 0.0017 | 0.38 |
| 2001 | 1732 | 3,228,287 | | | | | 5,932 | 918 | 0.0023 | 0.65 |
| 2002 | 1610 | 1,935,682 | | | | | 5,615 | 1,500 | 0.0014 | 0.70 |
| 2003 | 862 | 1,644,975 | | | | | 4,181 | 825 | 0.0020 | 0.75 |
| 2004 | 0 | | | 2,146 | | | 3,041 | 320 | | 0.75 |
| 2005 | 940 | 1,822,307 | | 1,527 | | | 3,074 | 607 | 0.0022 | 0.74 |
| 2006 | 706 | 939,971 | | 1,069 | | | 2,165 | 390 | 0.0009 | 0.72 |
| 2007 | 315 | 459,841 | | 1,860 | | | 2,413 | 238 | 0.0004 | 0.37 |
| 2008 | 919 | 1,763,345 | | 981 | | | 2,140 | 240 | | 0.67 |
| 2009 | 245 | | | 540 | | | 1,260 | 475 | | 0.60 |

**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 |
| $\sigma_{rr}$ | 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 |
| $\sigma_{ss}$ | 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 |
| $\sigma_{sr}$ | 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-3 adult spawner returns, averaged over 1982-2004 |
| $p_4$ | 0.48 | 7 | Mean proportion of estimated age-4 adult spawner returns, averaged over 1982-2004 |
| $p_5$ | 0.04 | 8 | Mean proportion of estimated age-5 adult spawner returns, averaged over 1982-2004 |
| $L$ | 2,000 | 12 | Break-point of the Food, Social and Ceremonial (FSC) function |
| $c$ | 0.2615 | 12 | Food, Social and Ceremonial (FSC) catch per terminal return |
| $f$ | 523 | 12 | Mean of the FSC catch data for 1990-2009 |
| $\sigma_F$ | 363.6 | 12 | Population standard deviation of residuals for FSC catch data for 1990-2009 |
| $S_{h,max}$ | 526 | 14 | Number of brood fish (male and female) that the hatchery can utilize |
|  | $452,000 |  | Annual Cowichan hatchery budget |

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

| | Density-independent proportion surviving | | Density-dependent mean marine survival rate | | |
|---|---|---|---|---|---|
| *φ* | Hatchery | Natural | Hatchery | Natural | Total |
| 7 | 0.0028 | 0.0043 | 0.0035 | 0.0057 | 0.0044 |
| 4 | 0.0049 | 0.0076 | 0.0053 | 0.0094 | 0.0070 |
| 1 | 0.0196 | 0.0304 | 0.0100 | 0.0215 | 0.0155 |

**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 6.** **Point estimates of indicators showing the performance of management strategies under the poor marine survival scenario ($\varphi = 7$). Ranks were based on the relative ordering of the indicator values, with higher values ranking higher for all indicators except for $Pr_{hat}$ and $C$ (definitions below), which were ranked lowest to highest. Although only point estimates of indicators are shown, tied ranks take into account the 95% confidence interval (see text). Harvest rates ($r$) and brood-take ($s$) rates corresponding to each management strategy are shown in the first two columns of numbers. Bold-face values for $r$ and $s$ indicate the status-quo parameters. $P_{rec}$ is probability of recovery to 6,514 natural spawners by year 15, $Pr_{pers}$ is proportion of years with ≥ 1000 natural spawners , $Pr_{low}$ is proportion of years ≥ 500 natural spawners, and $S_{nat}$ is median annual natural spawners. $H_{fsc}$ is Food, Social and Ceremonial (FSC) harvest and $H_{oce}$ is ocean sport and commercial harvest. $Pr_{hat}$ is proportion hatchery-origin spawners among natural spawners, and $C$ is annual cost per hatchery-origin recruit. Table 2 has more detailed definitions of these indicators.**

| 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 | | | 0.5 | |
| Status quo | Value | **0.65** | **0.22** | 0 | 0.002 | 0.016 | 32 | 14 | 102 | 0.453 | 11,255 |
| | Rank | | | 4 | 6 | 6 | 7 | 7 | 7 | 3 | 7 |
| Lowest harvest rate | Value | 0.3 | **0.22** | 0.150 | 0.775 | 0.919 | 1,517 | 411 | 1,056 | 0.430 | 354 |
| | Rank | | | 1 | 1 | 1 | 1 | 1 | 1 | 3 | 1 |
| Low harvest rate | Value | 0.4 | **0.22** | 0.087 | 0.432 | 2.000 | 779 | 294 | 908 | 0.448 | 551 |
| | Rank | | | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Medium harvest rate | Value | 0.5 | **0.22** | 0.008 | 0.113 | 0.313 | 304 | 134 | 529 | 0.456 | 1,297 |
| | Rank | | | 3 | 4 | 4 | 4 | 4 | 4 | 3 | 5 |
| Combined strategy | Value | 0.5 | 0.33 | 0.017 | 0.2 | 0.4 | 426 | 211 | 861 | 0.561 | 575 |
| | Rank | | | 3 | 3 | 3 | 3 | 3 | 3 | 4 | 3 |
| Low brood-take rate | Value | **0.65** | 0.15 | 0 | 0.001 | 0.013 | 21 | 9 | 62 | 0.346 | 27,077 |
| | Rank | | | 4 | 6 | 6 | 8 | 8 | 8 | 1 | 8 |
| High brood-take rate | Value | **0.65** | 0.33 | 0.002 | 0.004 | 0.025 | 56 | 29 | 209 | 0.578 | 3,773 |
| | Rank | | | 4 | 6 | 5 | 6 | 6 | 6 | 5 | 6 |
| Highest brood-take rate | Value | **0.65** | 0.5 | 0 | 0.007 | 0.034 | 100 | 71 | 505 | 0.719 | 1,103 |
| | Rank | | | 4 | 5 | 5 | 5 | 5 | 5 | 6 | 4 |

**Table 7.** **Same as Table 6, but for intermediate marine survival (*φ* = 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 ($\varphi = 1$).**

| Management strategy | Indicator or parameter | $r$ | $s$ | $P_{rec}$ | $Pr_{pers}$ | $Pr_{low}$ | $S_{nat}$ | $H_{fsc}$ | $H_{oce}$ | $Pr_{hat}$ | $C$ ($) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Status quo | Target | | | 0.80 | 0.90 | 0.95 | 6,514 | 523 | | 0.5 | |
| | Value | **0.65** | **0.22** | 1.0 | 1.0 | 1.0 | 8,174 | 521 | 17,154 | 0.268 | 72.35 |
| | Rank | | | 2 | 1 | 1 | 4 | 1 | 1 | 3 | 1 |
| Lowest harvest rate | Value | 0.3 | **0.22** | 1.0 | 1.0 | 1.0 | 19,827 | 521 | 8,952 | 0.237 | 72.13 |
| | Rank | | | 1 | 1 | 1 | 1 | 1 | 4 | 1 | 1 |
| Low harvest rate | Value | 0.4 | **0.22** | 1.0 | 1.0 | 1.0 | 16,403 | 523 | 11,638 | 0.242 | 72.48 |
| | Rank | | | 1 | 1 | 1 | 2 | 1 | 3 | 1 | 1 |
| Medium harvest rate | Value | 0.5 | **0.22** | 1.0 | 1.0 | 1.0 | 13,265 | 524 | 14,281 | 0.248 | 72.59 |
| | Rank | | | 1 | 1 | 1 | 3 | 1 | 2 | 2 | 1 |
| Combined strategy | Value | 0.5 | 0.33 | 0.998 | 1.0 | 1.0 | 13,198 | 526 | 14,271 | 0.248 | 72.16 |
| | Rank | | | 1 | 1 | 1 | 3 | 1 | 2 | 2 | 1 |
| Low brood-take rate | Value | **0.65** | 0.15 | 1.0 | 1.0 | 1.0 | 8,190 | 528 | 17,225 | 0.266 | 72.88 |
| | Rank | | | 2 | 1 | 1 | 4 | 1 | 1 | 3 | 1 |
| High brood-take rate | Value | **0.65** | 0.33 | 0.968 | 1.0 | 1.0 | 8,237 | 522 | 17,231 | 0.269 | 71.77 |
| | Rank | | | 2 | 1 | 1 | 4 | 1 | 1 | 3 | 1 |
| Highest brood-take rate | Value | **0.65** | 0.5 | 1.0 | 1.0 | 1.0 | 8,164 | 523 | 17,101 | 0.270 | 72.24 |
| | Rank | | | 2 | 1 | 1 | 4 | 1 | 1 | 3 | 1 |

**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 is a 68% decrease in hatchery marine survival compared to natural fish. Italicized numbers represent performance indicator values of zero.**

| | Poor marine survival, $\varphi = 7$ | | | Intermediate marine survival, $\varphi = 4$ | | |
|---|---|---|---|---|---|---|
| | 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 | ***5*** | **5** | 6 | 6 |
| High brood-take rate | **6** | 5 | *5* | **2** | 3 | **5** |
| Highest brood-take rate | 5 | 5 | *5* | 4 | 4 | **7** |

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

| | Poor marine survival, $\varphi = 7$ | | | Intermediate marine survival, $\varphi = 4$ | | |
|---|---|---|---|---|---|---|
| | Survival ratio | | | 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, $\varphi = 7$ | | | Intermediate marine survival, $\varphi = 4$ | | |
|---|---|---|---|---|---|---|
| | Survival ratio | | | 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, $\varphi$ = 7 | | | Intermediate marine survival, $\varphi$ = 4 | | |
|---|---|---|---|---|---|---|
| | Survival ratio | | | 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

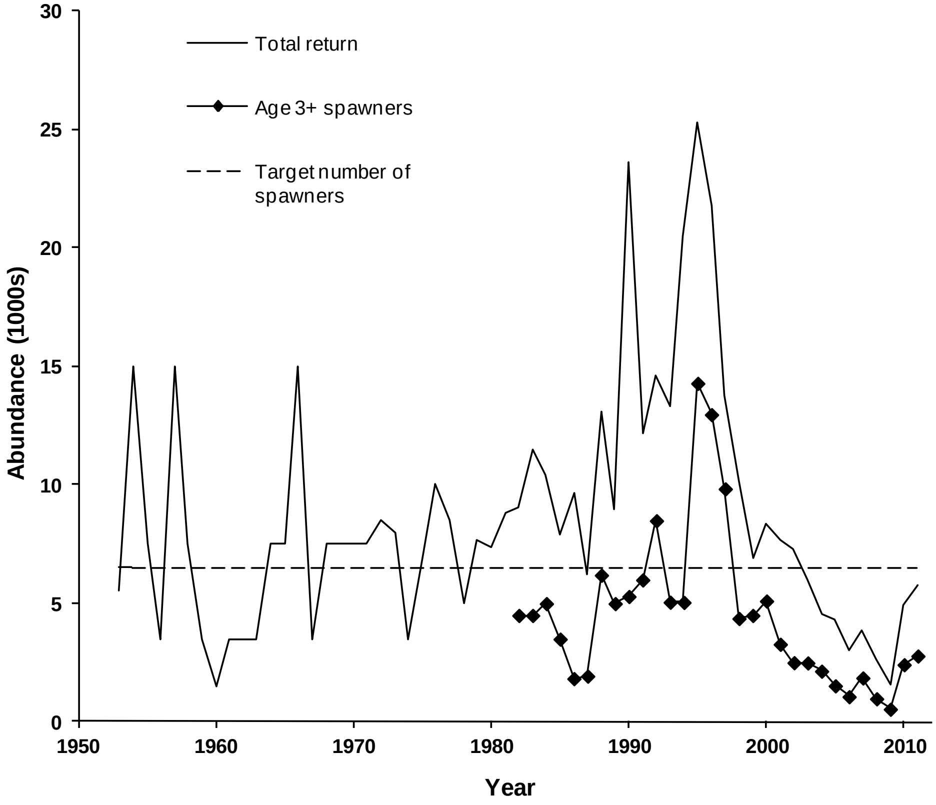

**Figure 1.** **Time series of total Chinook returns to the Cowichan River and age-3+ naturally-spawning fish, showing 2010-2011 as well, although those years were not used in the model because they became available after most analyses were completed. Total return includes fish caught in the First Nations' in-river fishery.**

**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.

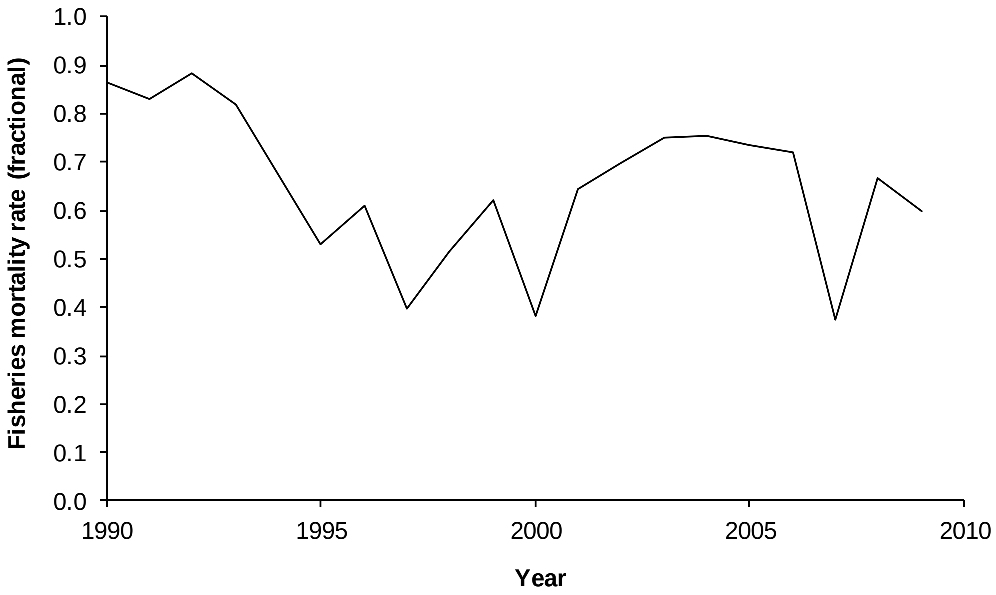

**Figure 3.** Total annual estimated fishing mortality rate for Cowichan Chinook from all sources, including incidental mortality (from data in PSC 2011), but not including in-river First Nations' catches, which are generally low in number (~500 fish or < 28% of the terminal run, according to nuSEDs data (DFO 2011b).

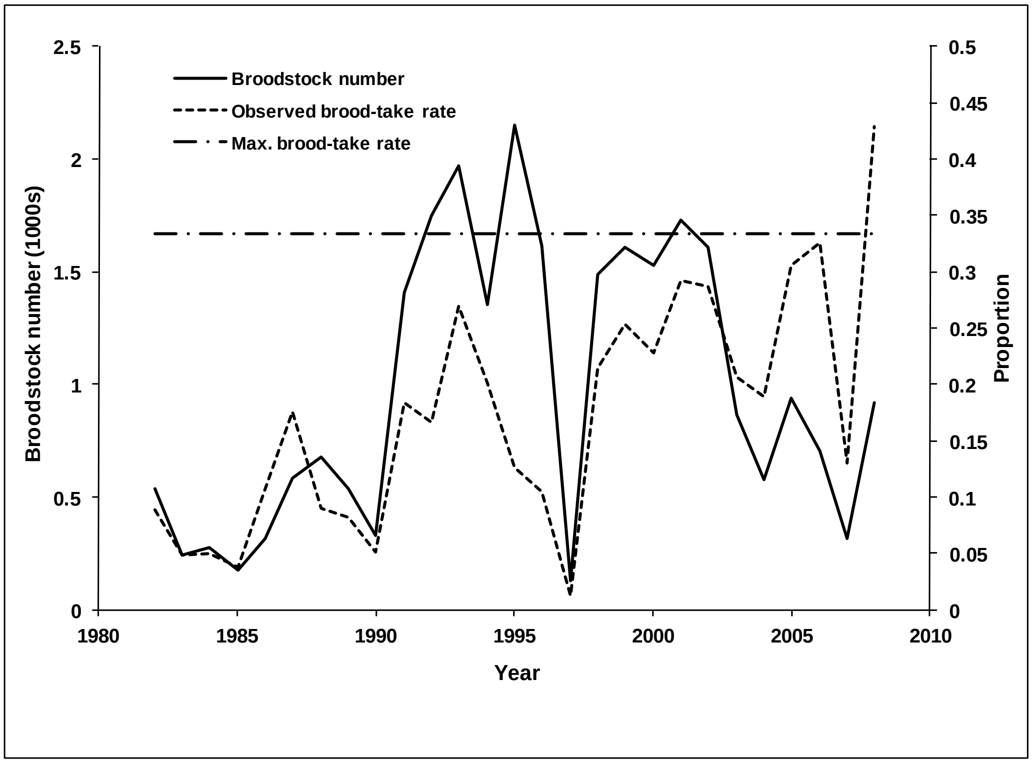

**Figure 4.** Number of Chinook taken as hatchery brood stock and the resulting brood-take rate at the Cowichan River hatchery. The solid line shows the numbers of brood stock (summed male and female) taken. The horizontal dot-dashed line at 0.33 is the maximum allowed proportion of the terminal run of all-ages of fish (minus the Food, Social and Ceremonial (FSC) catch) that can be removed for brood stock, and the short-dashed line indicates the annual proportion of the run minus FSC catch that was taken as brood stock. Source of the data is nuSEDs (DFO 2011b).

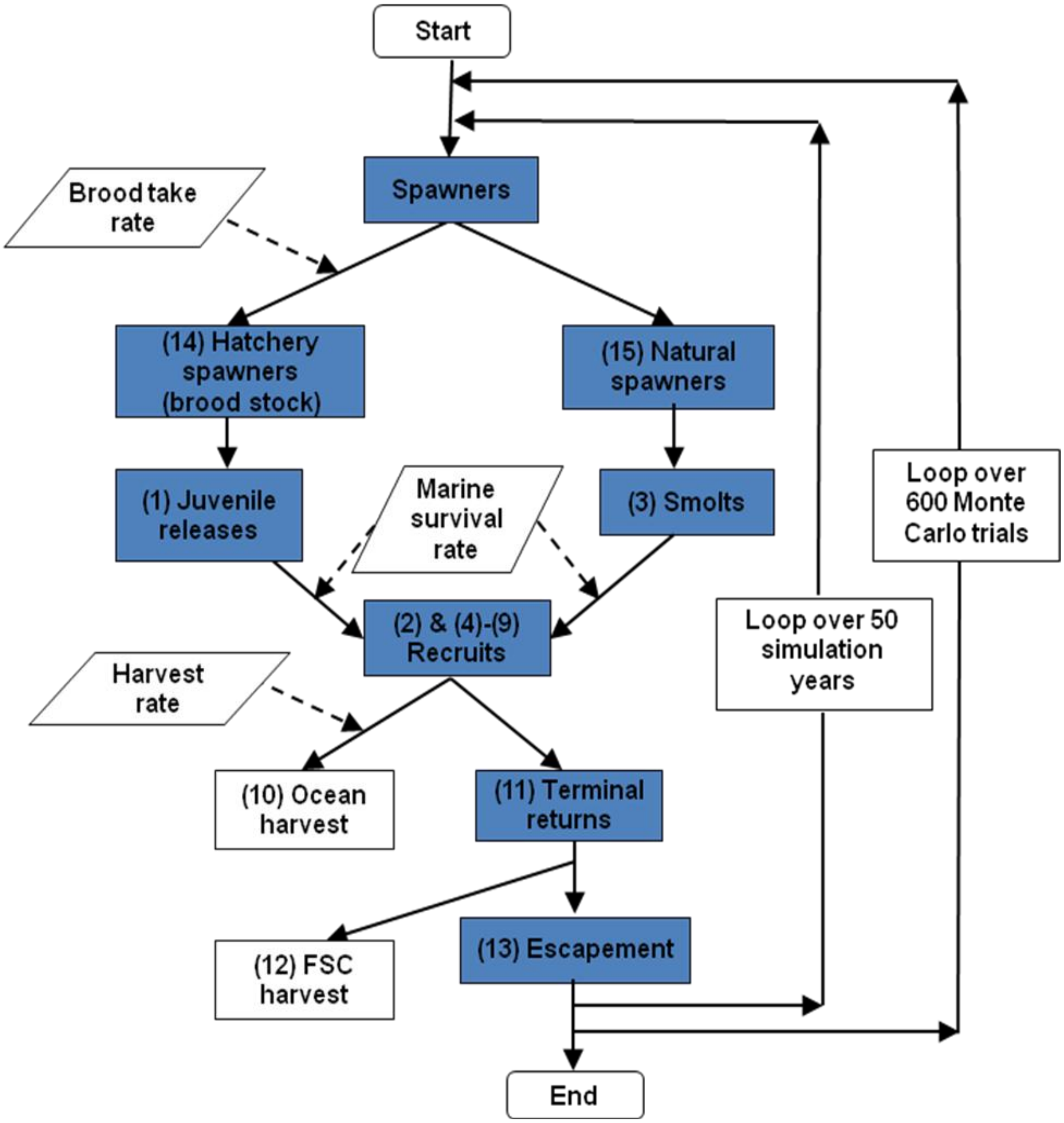

*Figure 5.* ***Flow chart of the Cowichan River fall Chinook salmon simulation model, indicating life-history components (shaded) and variables that changed according to different management strategies and marine survival rates (parallelograms). Numbers in parentheses indicate corresponding equation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

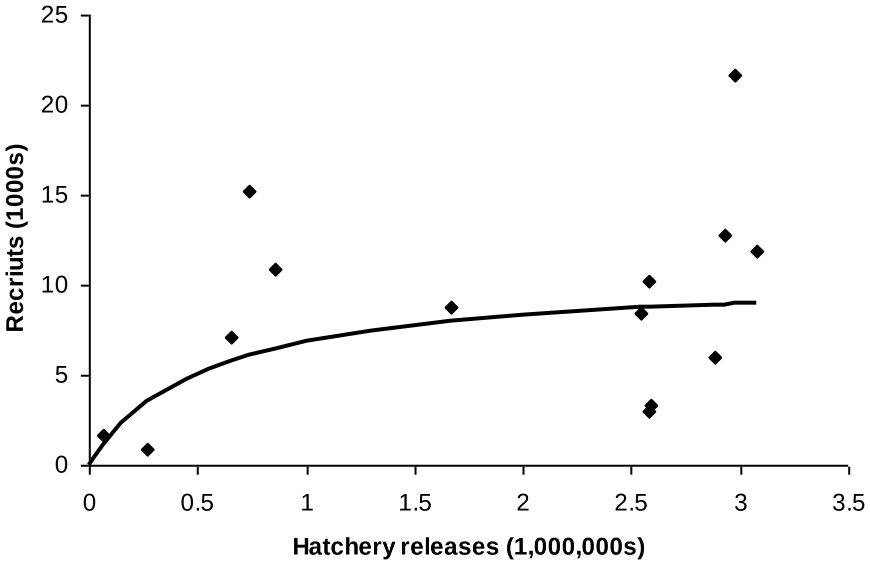

**Figure 7.** Hatchery-origin recruits as a function of numbers of hatchery releases (brood years 1985 and 1988-2000). The curve is the best-fit Beverton-Holt curve (Equation 2), with parameter values $a_{rr}$ = 10,573, $b_{rr}$ = 538,703, and $\sigma_{rr}$ = 0.676.

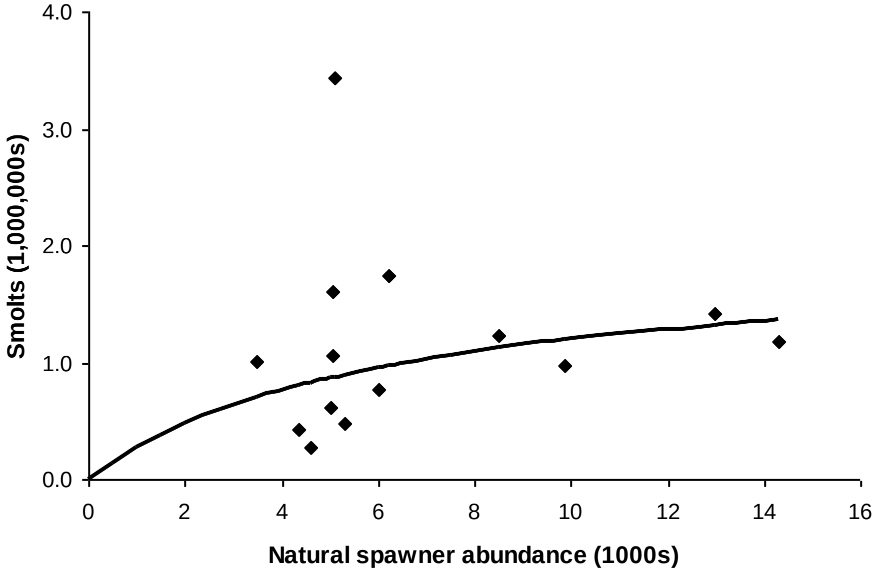

**Figure 8.** **Natural-origin smolts as a function of naturally-spawning age-3+ fish (brood years 1985 and 1988-2000). Best-fit Beverton-Holt parameter values (Equation 3) were $a_{ss}$ = 1,977,843, $b_{ss}$ = 6410, $\sigma_{ss}$ = 0.598.**

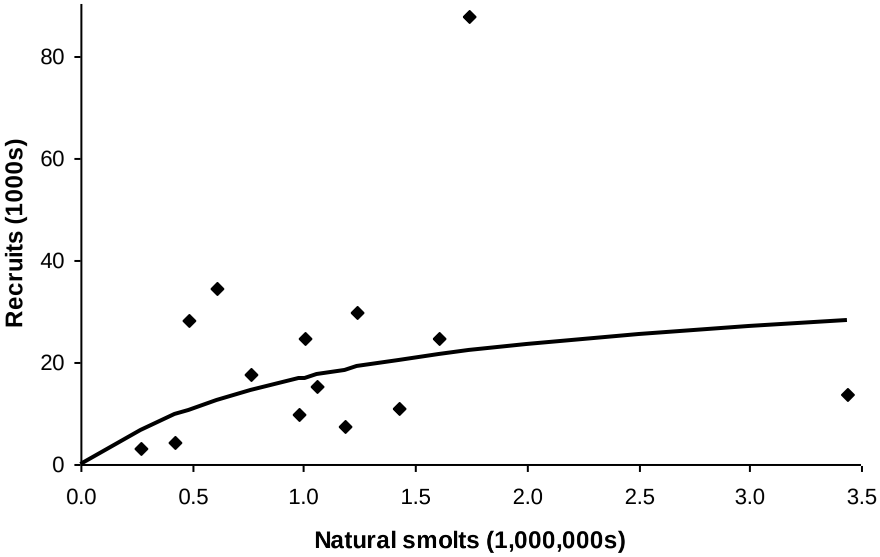

**Figure 9.** Natural-origin recruits as a function of natural-origin smolts (brood years 1985 and 1988-2000). The curve is the best-fit Beverton-Holt curve (Equation 4), with parameter values $a_{sr}$ = 38,260, and $b_{sr}$ = 1,257,591, and $\sigma_{sr}$ = 0.736.

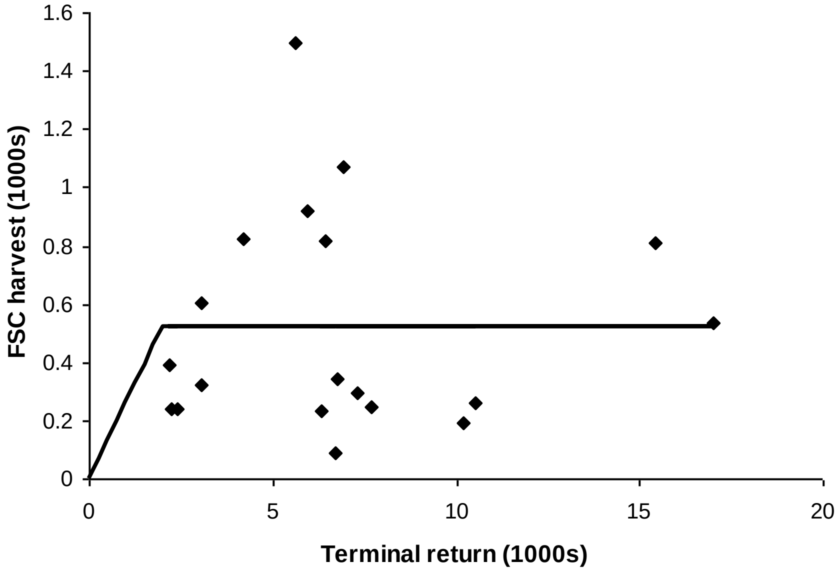

**Figure 10.** **Food, social and ceremonial (FSC) harvest function for age-3+ Chinook (return years 1990-2009), as a function of terminal returns, i.e., all age-3+ Chinook returning to the river. The function break point is $L$ = 2,000, and other parameters are $f$ = 523 (average catch), and $\sigma_F$ = 364 (Equation 12).**

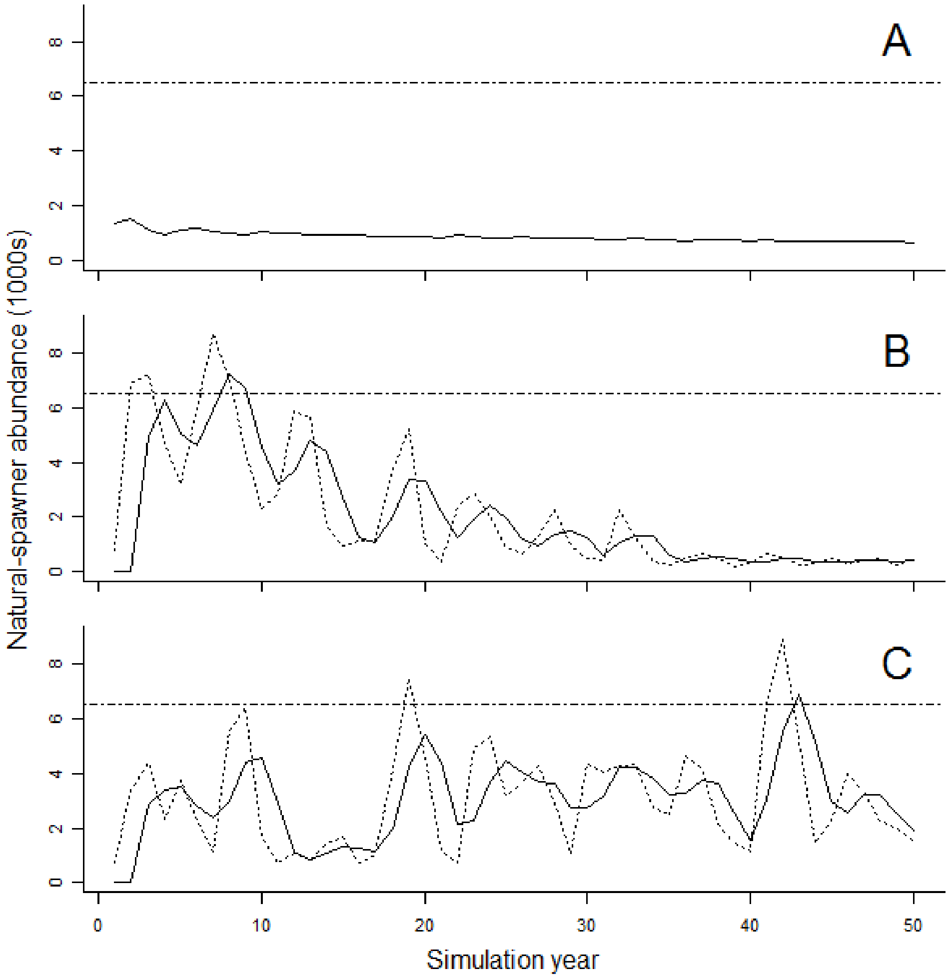

**Figure 11.** **Example model simulations for the low harvest-rate management strategy (*r* = 0.4; *s* = 0.22) under poor ocean survival (*φ* = 7). The horizontal line indicates target natural spawner abundance, 6,514. (A) Median natural-spawner abundance over 600 Monte Carlo trials; 95% confidence 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 (C), the dotted line indicates yearly abundance, and the solid line indicates the 3-year running average.**

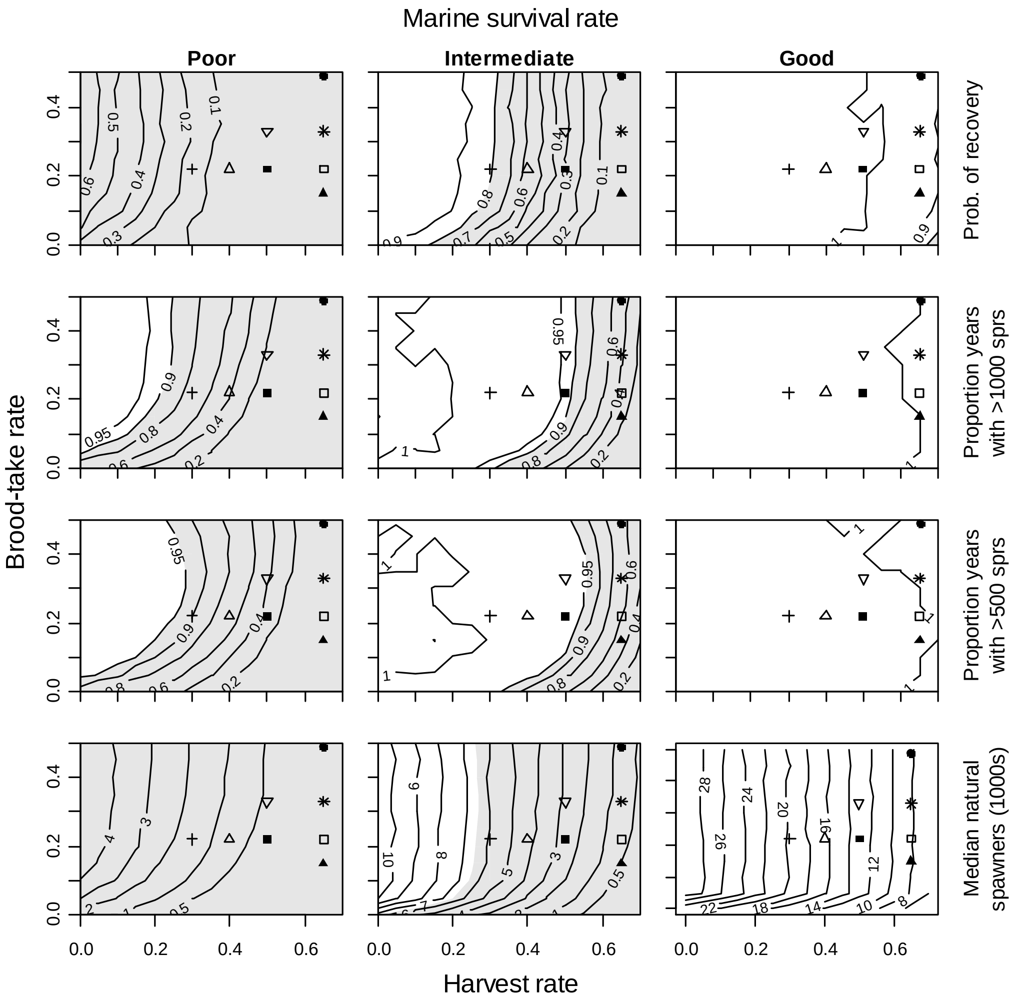

**Figure 12.** **Contour lines show values for the four performance indicators for conservation management objectives (rows) as a function of the harvest rate and brood-take rate (the latter provides brood stock for the supplementation hatchery). Marine survival rate scenarios are poor ($\varphi$ = 7), intermediate ($\varphi$ = 4), and good ($\varphi$ = 1). Shaded regions of the plot surface indicate values below proposed indicator targets, i.e., unacceptable management options. Symbols represent combinations of harvest and brood-take rate used for specifically labelled management strategies in Table 6: ‘■’ is status quo, ‘+’ is the lowest harvest rate, ‘▲’ is the low harvest rate, ‘□’ is the medium harvest rate, ‘▽’ is combined, ‘△’ is low brood-take rate, ‘✱’ is high brood-take, and ‘●’ is highest brood-take rate.**

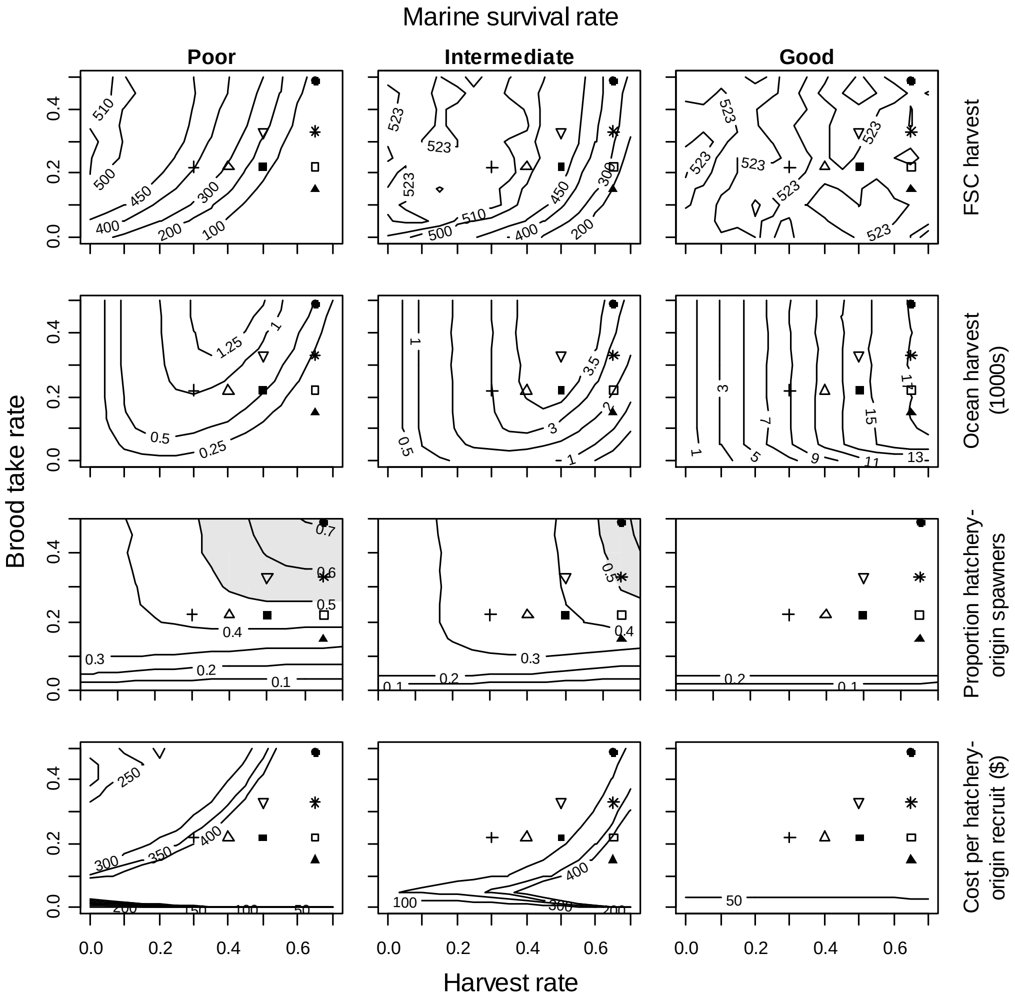

**Figure 13.** **Same as for Figure 12, but for the four performance indicators for harvest and hatchery objectives (rows). FSC harvest,ocean harvest, and cost per hatchery-origin recruit indicators are unshaded because they had no proposed targets.**