AN EVALUATION OF PREDATOR CO

APPROVAL

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ABSTRACT

The Cultus lake sockeye salmon (*Oncorhynchus nerka*) population has declined dramatically over the past few decades, and was classified as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2003. There are currently three major initiatives underway for assisting the recovery of this population (harvest management, predator control, and hatchery operations). I use a stochastic simulation model within a decision analysis framework to evaluate management strategies associated with these three initiatives. I estimate the probability of meeting pre-specified survival and recovery objectives for four alternative management strategies. My results suggest that the probability of recovery for Cultus Lake sockeye salmon is low under current marine survival rates. I also describe trade-offs between probability of achieving the conservation objectives and reductions in the commercial sockeye salmon fishery to help evaluate the relative merits of these initiatives.

Keywords: recovery planning, predator control, hatchery supplementation, decision analysis

Subject Terms: conservation biology, simulation modelling, predator-prey dynamics, decision analysis

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Figure 7	Simulated northern pikeminnow abundance under alternative	
-	levels of control, with (A) low recruitment compensation, and (B)	
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- Figure 9 Same as Figure 8 except results are based on using harvest rule 2 ($H_{min} = 0.30$, H_{max}

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1.0 INTRODUCTION

the same time as Cultus sockeye. Closure or reductions in these fisheries would reduce impacts on Cultus sockeye, but would also reduce catches for the more abundant sockeye populations, resulting in social and economic impacts (Irvine et al. 2005, GSGislason & Associates Ltd. 2004, Gross et al. 2004, Pestes et al. 2008).

For work on species at risk, the decision-making process can be assisted by the combined use of population viability analysis (PVA) and decision analysis (DA). These techniques have been recognized as useful partners and are methods that have been widely accepted and used in conservation biology (Drechsler 2000, Harwood 2000, Drechsler and Burgman 2004, Peters et al. 2001, VanderWerf et al. 2006). PVA involves constructing models that are used to assess the persistence of populations. PVA was initially developed to estimate long-term extinction probabilities in small populations while taking into account genetic, demographic, and environmental stochasticity (Shaffer 1981). DA is a framework used to synthesize expert knowledge and assist in the decision making process. One common use of DA methodology is to determine the rank order, from best to worst, of management actions based on forecasted outcomes and specified management objectives. The main benefit of using DA is that it provides a transparent protocol for assessing and comparing management options while explicitly taking various sources of uncertainty into account.

Currently there are three main management strategies that are being used

hatchery releases. Unfortunately, the benefits from reductions in harvest rates since 1998 have been reduced by higher-than-normal pre-spawning mortality (PSM), and more recently by lower-than-average marine survival (Ann-Marie Huang, Fisheries and Oceans Canada, Delta, B.C., personal communication). The reduction in commercial fishery harvest rates on the adult Cultus sockeye population in recent years is substantial (Figure 1) and undoubtedly this will help in population recovery. However, this carries a considerable cost in foregone harvest of other, more abundant and commercially valuable, co-migrating sockeye populations.

A current predator control program targets adult northern pikeminnow (*Ptychocheilus oregonensis*), a large piscivorous cyprinid native to Cultus Lake (Bradford et. al. 2007). Northern pikeminnow control programs have previously been shown to increase freshwater survival of juvenile sockeye at Cultus Lake (Foerster and Ricker 1941) and other salmonids in the Columbia River system (Friesen and Ward 1999). However, in both of these cases, increases in freshwater survival of salmon occurred at times when juvenile salmon abundance was high. The benefits at low abundances (as is the current situation at Cultus Lake) are uncertain. It is unclear whether removals of northern pikeminnow will cause a concurrent increase in sockeye freshwater survival for two main reasons. First, there is no practical way to directly measure northern pikeminnow predation rates on juvenile sockeye, so it is unclear whether pikeminnow predation is even a limiting factor at such low sockeye abundances. Second, there is a large amount of uncertainty about the potential for a compensatory



response in the predator population (i

et al. (2008) in several ways. First, I evaluated three different recovery activities (predator control, hatchery operations, and alternative harvest rates), whereas Pestes et al. (2008) only evaluated different harvest rates as a recovery action. Second, they explicitly included uncertainty in the implementation of harvest rates and uncertainty in prespawning mortality (PSM) of Cultus sockeye, whereas I did not. Instead, I explicitly included uncertainty in predator/prey dynamics and in marine survival of hatchery fish.

1.1 A brief history of Cultus Lake

Cultus Lake is small, with a surface area of 6.3 km² and a mean depth of 31 m. Only 6% of the lake area is considered littoral (Schubert et al. 2002). The

The long-standing role of Cultus sockeye salmon as a subject of scientific study means that the population has special interest for naturalists and for the scientific community. The population is also important to First Nations, especially the Soowahlie Band of the Sto:lo Nation. Historic colonization of the area by humans was strongly influenced by the presence of sockeye in the lake and Sweltzer Creek (Schubert et al. 2002).

In 1925, R.E. Foerster and W.E. Ricker began a program at Cultus Lake to help understand the factors limiting the production of sockeye salmon. They found that the losses of juvenile salmon in the lake (egg-to-smolt stage) amounted to over 95% of each brood, and hypothesized that these losses were largely due to predation. Consequently, they subjected the Cultus sockeye salmon population to two large-scale manipulations over the next 15 years. The first was the use of a hatchery to evaluate the potential benefits of artificial production, and the second was a predator removal program targeting the large piscivorous fish inhabiting the lake (Foerster and Ricker 1941).

Although the hatchery efforts were not considered worthwhile and were terminated after a few years, the predator control program continued. Between 1932 and 1942 nearly 22,000 northern pikeminnow and over 7,000 trout (*Oncorhynchus mykiss, O. clarki*) and char (*Salvelinus confluentus*) were removed from the lake. Increased returns of sockeye salmon from the experiment were strong enough for Foerster and Ricker to consider the approach a cost-effective means to increase salmon abundance. The result of this program was an increase in average egg-to-smolt survival rate of sockeye from 3.13% for

the 8-year period prior to predator removal to 9.95% for the 3-year period after predator removal (Foerster and Ricker 1941). It was estimated that the cost of predator control amounted to 20 cents for each additional returning adult, which was worth \$6 in the commercial fishery at the time (Foerster and Ricker 1941).

The number of Cultus sockeye salmon that have returned to spawn has steadily declined since the 1960's (Figure 1), and has resulted in the current spawner population being less than 4% of there was likely an abundant predator population in Cultus Lake and it was likely having an impact on the population's ability to recover.

Ultimately, the Cultus sockeye population was not listed under SARA. The Minister of Environment, who is responsible for SARA listings, proposed in January 2005 that the Cultus and Sakinaw populations of Pacific sockeye salmon not be listed because of the unacceptably high social and economic costs. Extensive closures in the mixed-stock commercial fisheries would be required to ensure the protection of the small Cultus Lake population if it had been listed under SARA (Irvine et al. 2005). Thus, the Cultus Lake sockeye population has received no protection under SARA, but Fisheries and Oceans Canada (FOC) has committed to its protection and rebuilding.

Efforts to protect and rebuild t

B.C., personal communication). The hatchery was scheduled to take its last broodstock in late 2007 with final smolt releases in 2014, but this may be extended for at least one more sockeye generation (four years).

The Cultus Sockeye Recovery Team (2004) identified the need for a better understanding of the potential impact of northern pikeminnow on sockeye production. A series of northern pikeminnow mark-recapture studies were conducted by FOC during 2004-2005. This work revealed that the northern pikeminnow population is much larger (approximately 60,000 adult fish) than

management actions based on performance indicators of how well objectives are met, and (8) conduct sensitivity analyses.

2.2 Management Objectives

The management objectives used in this study are loosely based on objectives developed for the National Recovery Strategy (Cultus Lake Recovery Team 2004). The goal is to halt the decline of the Cultus sockeye population and return it to the status of a viable, self-sustaining, and genetically robust wild population that will contribute to its ecosystems and have the potential to support sustainable use. Four quantitative objectives that are sequential steps toward the recovery of the population are identified in the National Recovery Strategy and I used two of them as the first two objectives in my analysis.

The three management objectives I used are best described as survival, recovery, and harvest objectives. The survival objective is designed to ensure the genetic integrity of the population and therefore its survival. It requires that the four-year arithmetic mean number of spawners in the year 2022 be greater than 1000, and that there be no fewer than 500 spawners in any one year. The recovery objective is related to deciding when the population is "recovered". Meeting this objective requires that the four-year arithmetic mean number of spawners in the year 2022 be greater than 500 spawners in the year 2022 be greater than 500 spawners in the year 2022 be greater. The recovery objective requires that the four-year arithmetic mean number of spawners in the year 2022 be greater than 8000, and that there be no fewer than 500 spawners in any one year. This objective was determined based on the observation that the Cultus Lake population shows less potential for rebuilding, or sustaining harvest, when abundance is below the threshold of about 7000

model, the calculation of performance measures did not include those fish collected at the fence that were to be used for hatchery broodstock, nor did it include fish that were released from the hatchery and have returned to spawn (see section 2.5.2 for description)

Since reductions in harvest for the protection of Cultus sockeye might result in significant losses of fishing opportunities (commercial, recreational, and aboriginal), I also included a third management objective in my analysis. The third objective was to minimize the number of years with a low (H_{min} , see section 2.5.2) harvest rate for Cultus sockeye, which would affect opportunities to exploit other, more abundant salmon populations.

2.3 Alternative Management Strategies

I evaluated recovery actions (strategies) that either closely approximated strategies currently being used or that are likely to be used within realistic time with continued predator control efforts for 2008 through to the end of 2022. Specific parameter values and time frames are given in Table 1.

I simulated two scenarios of hatchery production using the current schedule of releases (A. Stobbart, personal communication) and the most recent estimates for freshwater survival of hatchery fish (J. Hume, personal communication). The status quo hatchery strategy had a capacity to produce 450,000 fed fry to be released in the lake and 50,000 yearling smolts to be released in Sweltzer Creek annually for 2006 through 2014. The extended program was assumed to be able to produce 1,000,000 fry and 100,000 smolts annually for 2006 through 2018. Hatchery facilities are limited for this population and the extended hatchery strategy would likely require construction of new facilities. In the model, both hatchery strategies collect spawners annually at the Sweltzer Creek fence for the maintenance of broodstock, ending in 2007 for the status quo hatchery strategy and in 2011 for the extended strategy.

The terminated predator control strategy assumed no pikeminnow removals after 2007 and simulated approximately 25% reduction up through that year in the adult population of 60,000 fish based on the 2004 estimate. For the continued predator control strategy the removal of pikeminnow occurred annually to the final simulation year (2022).

Parameter/ Scenario	Description	Estimate/Statistic		
	Sockeye			
	Log _e (smolts/spawner) at low spawner abundance when influence of pikeminnow in sockeye smolts/spawner relationship is high/low	5.05/4.45		
	Density dependence in smolt production	7.4 x 10 ⁻⁶		
k	Reduction in Log _e (smolts/spawner) per pikeminnow when influence of pikeminnow in sockeye smolts/spawner relationship is high/low	0.000015/0.000005		
	Standard deviation of Log _e (smolts/spawner)	0.62		

Table 1Description of parameters used in the simulation model and
definition of scenarios and terms.

	Northern pikeminn	ow
PM _{init}	60,000	Initial abundance of age 5+ pikeminnow in 2004
М	Natural mortality rate of age 5+ pikeminnow	0.36
b	Density dependence in pikeminnow recruitment (high/low)	Calculated by rearranging

2.5 Model to determine consequences

2.5.1 Model Initialization

The total simulation period in each Monte Carlo run was 24 years from 1999 through 2022. The first nine years (1999 through 2007) were the initialization years where the model used observed data from the Cultus Lake program. Thus, each simulation began with the same Cultus sockeye spawner numbers, smolt numbers, hatchery releases and northern pikeminnow removals for the first nine years. The remaining 15 years (2008 through 2022) represent the simulation period over which performance measures were computed, and where stochasticity was applied to the model.

2.5.2 Sockeye sub-model

The operation of a counting fence at the lake outlet, which counts the number of returning sockeye spawners each fall and emigrating smolts each spring, has provided Cultus smolts per spawner (Sm/Sp) and marine survival data for many years between 1925 and 2006, allowing for the modelling of this population using spawner-to-smolt and smolt-to-adult recruit relationships. These data are summarized in Cultus Lake Recovery Team (2004). Many years were likely affected by predator control programs, hatchery operations, or high prespawning mortality (PSM), producing data not representative of natural production, and they were not included in the data set used in this study. I used 26 years (1951-1952, 1954-1961, 1965-1972, 1974-1976, 1988-1990, and 2002-2003) of Sm/Sp (Figure 3) and marine survival (Figure 4) data to parameterize the sockeye component of my model.



Figure 3 (A) Cultus sockeye smolt and spawner data for years that were not likely affected by either predator control efforts, hatchery operations, or high pre-spawning mortality (solid circles). Years that followed predator control are indicated by open circles. (B) $Log_e(Sm/Sp)$ for standard Ricker model (k = 0) and the two alternative models used in this study. (C) Resulting spawner-tosmolt relationships from assuming low k (low consumption rate of sockeye smolts per pikeminnow) at three different northern pikeminnow abundances. (D) Spawner-to-smolt relationships assuming high k (high consumption rate of sockeye smolts per pikeminnow) at three different northern pikeminnow abundances.



Figure 4 Frequency distributions of marine survival rates for observed Cultus Lake sockeye data (A) and Beta distribution used in Monte Carlo trials for generating annual marine survival rate (B). Bars represent a sample frequency distribution of simulated values with parameters estimated from the historical data; lines represent alternative distributions. Within the sockeye sub-model, the annual number of smolts emigrating from Cultus Lake and the annual number of returning adults was simulated based on a two-stage life history model. The first stage used a spawner-to-smolt model to predict the number of smolts emigrating each year from the lake based on the number of spawners reaching the spawning grounds one and a half years previous.

The model assumed that all juveniles migrate to the ocean in the spring after spending 1.5 years in the lake after egg fertilization. It also assumed that all adult sockeye return at age 4 to spawn after spending 2.5 years in the Pacific Ocean. These assumptions are based on the observations that spawners are >95% age-4 fish and emigrating smolts are >95% age-1 (Cultus Sockeye Recovery Team 2004). My model did not include any pre-spawning mortality (PSM) of adults after they pass the fence, and did not include any outcome uncertainty in harvest (difference between target and achieved harvest rates).

The second stage of the sockeye sub-model predicted the number of spawners each year in three sequential steps: (1) the number of pre-fishery recruits based on density-independent marine survival of smolts (Equation 3); (2) adult escapement at the Sweltzer Creek counting fence derived from a statedependent fishery harvest rule (Equation 4, Figure 5); and (3) the number of spawners reaching the spawning grounds based on number of fish taken as broodstock (Equation 6).

The sockeye sub-model tracked the abundance of 3 "stock types" (wild, naturalized hatchery fish, and hatchery fish). Wild fish were those that met the



requirements for wild fish as defined in the Wild Salmon Policy (DFO 2004), where they must be the progeny of parents that spent their entire life cycle in the wild. Hatchery fish were fish that were released from the hatchery. Naturalized hatchery fish (NHF) were the progeny of hatchery released fry or smolts that returned and spawned naturally. It was necessary to track the abundance of hatchery fish and NHF because, although neither is considered wild under the Wild Salmon Policy, the progeny of NHF are considered wild. Keeping track of the contribution of each stock type to the total population size may be important to managers as they consider the potential deleterious effects of an increasing contribution of hatchery fish to the total population. In this model wild fish and NHF had the same freshwater and marine survival rates (Figure 4), whereas the freshwater survival rate of hatchery-released fry and smolts was assumed to follow recent empirical data from the Cultus Lake program (J. Hume personal Communication; Table 1). Marine survival of hatchery fish was simulated as a fraction of the survival rate of wild fish each year (Table 1).

I assumed that predation on sockeye by northern pikeminnow is proportional to adult northern pikeminnow abundance. A linear functional response was used, where northern pikeminnow encounter fry or smolts at random and the per capita encounter rate increases with smolt density (Ricker 1941). This linear relation, rather than the more traditional nonlinear one, is based on the observation that Cultus sockeye smolt abundances are so low that encounter rates are also likely low.

The total number of wild and naturalized hatchery smolts produced for a given number of wild and hatchery spawners (wild and hatchery spawners were assumed to have equal reproductive success), was predicted as,

(1)
$$Sm_{i,t}$$
 * $Sp_{i,t-2}$ * $e^{*Sp_{i,t-2} k*PM_{t-t}}$,

where $Sm_{i,t}$ is the number of smolts of stock type i

affected the abundance estimates (Bradford et al. 2007). If northern pikeminnow are significant predators of sockeye, then sockeye Sm/Sp should have declined over the past 70 years. However, a regression of Sm/Sp on year (using all available data) showed no significant trend ($R^2 = 0.0005$, p = 0.91). I therefore assumed the northern pikeminnow population has remained relatively stable over the years, and that the Sm/Sp time series represents sockeye productivity in Cultus Lake with an adult northern pikeminnow abundance of 60,000 individuals.

I fit a Ricker-type model (Equation 1) to the 26 years of smolt and spawner data, and estimated the parameters and via least squares regression of Sm/Sp on Sp, assuming that k = 0 for this first fit. I then fixed the k value in Equation 1 at one of two values representing high ($k= 15 \times 10^{-6}$) and low ($k= 5\times 10^{-6}$) predation rates, assumed 60 000 adult northern pikeminnow, and estimated the respective Ricker parameters holding constant. Figure 3 illustrates the modified Ricker model in the context of observed data and how a decrease in northern pikeminnow abundance increases sockeye spawner-to-smolt productivity. This is how predator control results in increased sockeye production in the model.

The current Cultus sockeye hatchery program is a complex operation and I made some simplifying assumptions for my analysis but captured its essential features. In the model, eggs and milt are taken from broodstock collected at the Sweltzer Creek fence. A small portion of eggs are raised to adults (captive broodstock) in the hatchery. Surplus eggs are used in the hatchery to produce a variable number of fry released into the lake in their first summer, and smolts

which are released directly into Sweltzer Creek after spending one and a half years in the hatchery. The mature captive broodstock population is used to produce additional fry, which are released along with those mentioned above to meet the annual total fry release target.

I have no reliable estimates of the relative success of hatchery origin fish in either the freshwater or the ocean environment. Recent estimates available from the Cultus Lake hatchery program have been confounded because of the complicated release strategies used by hatchery operators. The model assumed that freshwater survival of smolts released is 100%, as these fish are assumed to migrate immediately to the ocean following release released below the Sweltzer Creek counting fence. The model assumed a freshwater survival rate for hatchery fry that are released in the lake were a function of *k* and abundance of adult northern pikeminnow (Equation 2; a variant of equation 1 used to simulate hatchery smolt production). Based on recent experience, this survival rate is 9%

m thelviv,a

future marine survival rates because it confined the marine survival rate to be between zero and one and it can be parameterized to have a similar shape as a

(5) $Sp_t \quad Esc_t \quad Broodtake_{t_s}$

where Sp_t is the number of spawners in year *t* and *Broodtake*_t is the number of fish collected

fully vulnerable age classes, and q is the age-specific catchability that scales F according to the selectivity of the fishing gear used in the predator control program.

The parameterization of the northern pikeminnow sub-model was based on work conducted during 1989-1991 (Hall 1992) and 2004-2005 (Bradford et al. 2007). Length and age data were used to estimate natural mortality rate for the age 5+ population, as well as Von Bertalanffy growth parameters and age specific catchabilities (Figure 6, Table 1). Length (cm) at age was determined using Von Bertalanffy's equation (Ricker 1975),

(8)
$$L_a = L^{*}(1 - e^{-k_{VB}^{*}(a - t_{OVB})})$$

where L_a the length for age class a, L is the asymptotic length, k_{VB} is the Brody growth coefficient, and t_{OVB} is the hypothetical length at *t*=0. From the lengths determined in Equation 8, the weight at age was determined as,

(9)
$$W_a = a_w * (L_a * 0.1)^{b_w}$$
,

where W_a is the weight for age class a, a_w is a scalar, L_a is the length (cm) at age a, and b_w is the allometric growth coefficient. Note here that the parameters in the formula convert length from cm to mm for use in the weight-at-age calculation.



Figure 6 Length-at-age, weight-at-age, and catchability-at-age models (lines) fit to data (circles) and used to simulate the northern pikeminnow population (see text). Parameter values are given in Table 1.

The age-specific catchability was determined by fitting a two-parameter ogive function to data contained in Bradford et al. (2007),

(10)
$$q_p = \frac{p^c}{p^c d^c}$$
,

where

populations, so I used two values that resulted in high (a = 7) and low (a = 2) compensation (Figure 7). For each value of a, a corresponding value of b that resulted in 18 000 pikeminnow recruits being produced by a spawning biomass of 14 000 kg was found (Table 1) by r





Figure 7 Simulated northern pikeminnow abundance under alternative levels of control, with (A) low recruitment compensation, and (B) high recruitment compensation. Notice that all four trajectories begin with the same abundance up to 2007, which represents predator control efforts to date.

3.0 RESULTS

3.1 Survival Objective

The probability of meeting the survival objective by 2022 for the Cultus sockeye population under the proposed actions and harvest rule 1 was high, even for relatively low marine survival scenarios (Figure 8). When the mean marine survival rate (MMS) was expected to be at least 4%, all 4 combinations of management strategies produced probabilities of meeting the survival objective >90% (i.e., >450/500 Monte Carlo simulations). If MMS was less than 4%, then more aggressive strategies (C and D) are required. With a MMS rate of 1%, and status quo hatchery operations, the model predicted a 20% increase (from 20% to 40%) in the probability of meeting the survival objective by continuing the predator control program (strategy B) versus the termination of predator control (strategy A). This difference diminished with increasing MMS rates.

Extended hatchery operations were more effective than predator control at low marine survival rates. With a MMS rate of 1%, and terminated predator control, the extended hatchery program (strategy C) increased the probability of meeting the survival objective by 36% (from 20% to 56%) over strategy A.



Figure 8 Simulation results based on Harvest rule 1 ($H_{min} = 0.12$, $H_{max} = 0.50$). Top panel shows survival (mean spawners/year 1000) and recovery (mean spawners/year 8000) probabilities for four alternative management strategies (A = status quo hatchery operations combined with terminated predator control; B = status quo hatchery operations combined with continued predator control; C = extended hatchery operations combined with terminated predator control; C = extended hatchery operations combined with terminated predator control; D = extended hatchery operations combined with terminated predator control), at four alternative mean marine survival rates (MMS). Bottom panel shows the proportion of simulated years where the harvest rate was set at H_{min} as a result of low Cultus Lake sockeye abundance. Error bars represent two standard deviations.

in number of years with low harvest rates among the four strategies at the



Figure 9 Same as Figure 8 except results are based on using harvest rule 2 ($H_{min} = 0.30$, $H_{max} = 0.60$) as opposed to harvest rule 1.

probabilities (from 90% belief in the low value of the uncertain parameter to 90% belief in the high value) of alternative states of the parameter in question. For example, if one is confident that the RHMS is most likely 0.8 instead of 0.2, then the focus would be in the final row of Figure 10. Information in the cells of this row represents 90% belief that the true value of RHMS is 0.8 and only 10% belief that the true value of RHMS is 0.8 and only 10% belief that the true value of RHMS is 0.2. Of the two uncertainties considered, my results were most sensitive to the RHMS parameter.

Changes in the degree of belief in *RHMS* (Figures 10 and 11) had a moderate effect in determining the optimal management strategy. Using harvest rule 1 (Figure 10), the level of uncertainty in RHMS was large enough to create a range of strategies that achieved the survival objective with 90% probability, particularly under MMS rates of 2% and above. My results also show that when there was a 90% degree of belief in *RHMS* being high (0.8), strategy D met the survival objective with a MMS of only 1%. Results for the recovery objective were much less sensitive to changes in *RHMS*, with changes in strategies occurring only under a MMS 4% (right side of Figure 10). When harvest rule 2 was used (Figure 11), results for the survival objective were most sensitive to changes in the degree of belief in RHMS while using the more aggressive harvest rule 2 because none of the strategies achieved the objective with 90% probability under any of the MMS rates evaluated.

Changes in the degree of belief in the *k* parameter, which relates predation losses of sockeye to pikeminnow abundance, did not affect the optimal

action (Figures 12 and 13). Using harvest rule 1 (Figure 12), the level of uncertainty in k was not large enough to change the optimal management strategy for either the survival or the recovery objective. The model results for the survival objective were only slightly sensitive to changes in k

k

А	sq hatchery and terminate predator control
В	sq hatchery and continued predator control
С	extend hatchery and terminate predator control
D	extend hatchery and continue predator control

		Mean	marin	e surviva	al rate		Mean	marine	surviva	l rate
e	P1_RHMS (0.8)	1%	2%	4%	6%	P1_RHMS (0.8)	1%	2%	4%	6%
lief	0.1	None	None	B/C/D	All	0.1	None	None	None	B/C/D
be	0.2	None	None	B/C/D	All	0.2	None	None	None	B/C/D
of	0.3	None	None	B/C/D	All	0.3	None	None	None	B/C/D
ree	0.4	None	D	B/C/D	All	0.4	None	None	None	B/C/D
legi	0.5	None	D	All	All	0.5	None	None	None	B/C/D
Д	0.6	None	D	All	All	0.6	None	None	None	B/C/D
	0.7	None	C/D	All	All	0.7	None	None	None	B/C/D
	0.8	None	C/D	All	All	0.8	None	None	None	All
	0.9	D	C/D	All	All	0.9	None	None	D	All

Survival

Recovery

Figure 10 Prescription tables showing which management strategies (A-D) meet the survival (left) and recovery (right) objectives with at least 90% probability across a range of mean marine survival rates and different degrees of belief for the RHMS of sockeye. Moving down each column mean that greater belief (from 10% to 90%) is placed on high RHMS (0.8) as the true state of nature, rather than RHMS being only 0.2. These results are based on using harvest rule 1 (H_{min}=0.12, H_{max}=0.5).

A	sq hatchery and terminate predator control
В	sq hatchery and continued predator control
С	extend hatchery and terminate predator control
D	extend hatchery and continue predator control

	1%	2%	4%	6%
0.1	None	None	D	B/C/D
0.2	None	None	D	B/C/D
0.3	None	None	D	B/C/D
0.4	None	None	D	B/C/D
0.5	None	None	D	All
0.6	None	None	D	All
0.7	None	None	C/D	All
0.8	None	None	C/D	All
0.9	None	None	B/C/D	All

Degree of belief

Survival

Recovery

А	sq hatchery and terminate predator control
В	sq hatchery and continued predator control
С	extend hatchery and terminate predator control
D	extend hatchery and continue predator control

		Mean	marin	e surviva	al rate		Mean	marine	surviva	l rate
<u>د</u>	P1_k (15x10^-6)	1%	2%	4%	6%	P1_k (15x10^-6)	1%	2%	4%	6%
lief	0.1	None	D	All	All	0.1	None	None	None	B/C/D
be	0.2	None	D	All	All	0.2	None	None	None	B/C/D
of	0.3	None	D	All	All	0.3	None	None	None	B/C/D
ree	0.4	None	D	All	All	0.4	None	None	None	B/C/D
legi	0.5	None	D	All	All	0.5	None	None	None	B/C/D
Д	0.6	None	D	All	All	0.6	None	None	None	B/C/D
	0.7	None	D	All	All	0.7	None	None	None	B/C/D
	0.8	None	D	All	All	0.8	None	None	None	B/C/D
	0.9	None	D	All	All	0.9	None	None	None	B/C/D

Survival

Figure 12 Prescription tables showing which management strategies meet the survival (left) and recovery (right) objectives with at least 90% probability across a range of mean marine survival rates and different degrees of belief for the impact of Northern pikeminnow on the sockeye Sm/Sp relationship. Moving down each column means that greater belief (from 10% to 90%) is placed on the high *k* value (15 x 10⁻⁰⁶) as the true state of nature. These results are based on using harvest rule 1 (H_{min} = 0.12, H_{max} = 0.50).

Recovery

Α	sq hatchery and terminate predator control
В	sq hatchery and continued predator control
С	extend hatchery and terminate predator control
D	extend hatchery and continue predator control



Survival

Recovery

4.0 DISCUSSION

I have demonstrated that large increases in probability of achieving survival and recovery objectives are possible through predator control and hatchery operations, but ultimately the survival/recovery of this population is highly dependent on factors that are not controllable (i.e. marine survival). The model predicts that achieving the survival objective with at least 90% probability is possible under poor (2%) mean marine survival using harvest rule 1, but achieving the recovery objective will be unlikely unless marine survival rates average 6%. The observed long-term average marine survival is 6.8%, but the average marine survival for the period 1999 through 2006 has been <3% (J. Hume, personal communication). My results suggest that the Cultus sockeye population will never recover under the current harvest rule and any of the management strategies evaluated. This conclusion is consistent with recent returns, which continue to decline despite the ongoing recovery efforts. However, recovery of the population is possible if marine survival rates average 4% or greater when the most intensive strategy (continued predator control and extended hatchery operations) is adopted under harvest rule 1.

from the predator control and hatchery operations. Pestes et al. (2008) also demonstrated the importance of maintaining conservative harvest rates, particularly when considering uncertainty in future pre-spawning mortality (PSM) rates. Although I did not include PSM in my simulations of Cultus sockeye, its effect can be seen as one mechanism by which MMS rates would decline to levels as low as the ones I simulated (e.g. 1%).

The sensitivity of results to alternative management strategies, as well as uncertainty in model parameters, was inconsequential compared with sensitivity to uncertainty in future marine survival rates. It is important to remember, however, that the range of MMS rates evaluated here represents a 6-fold increase from lowest (1%) to highest (6%). The difference in survival/recovery probabilities is small among the alternative management strategies at high marine survival rates; this therefore may make the more intensive strategies not

4.1 Management Implications

4.1.1 Predator control

Predator control has a long history in natural resource management, but efforts have not always resulted in the desired effect. Past failures of predator control programs are mainly related to the lack of understanding of the complexities of ecological systems and a lack of monitoring of results of management strategies and subsequently learning from them (Lessard et al. 2005, Meacham and Clark 1979). At Cultus Lake, continued active control of northern pikeminnow may have unpredictable consequences in the lake ecosystem, such as an increase in abundance of a sockeye competitor that would otherwise be maintained by northern pikeminnow presence in the lake. For instance, past predator control programs at Cultus Lake likely led to an increase in the threespine stickleback (*Gasterosteus aculeatus*) population, a competitor of juvenile sockeye salmon (Foerster 1968). Thus, an important component of the recovery efforts at Cultus Lake should be the monitoring of other fish species in order to identify and document if an undesirable ecosystem response occurs.

There is a general lack of knowledge about the nature of the relationship between juvenile sockeye salmon survival and northern pikeminnow predation rates. For Cultus Lake the problem lies in the reliability of predator abundance estimates over the past 70 years and in limited knowledge of predator diet. It has been suggested that northern pikeminnow predation may be a source of

depensatory mortality in juvenile Cultus sockeye (Steigenberger 1972, COSEWIC 2003) and that this likely happens during smolt out-migration when northern pikeminnow may aggregate at the lake outlet. However, there is no conclusive evidence for such a relationship and recent investigations (Bradford et al. 2007) into movements of northern pikeminnow within Cultus Lake revealed that an aggregation of northern pikeminnow at the lake outlet does not seem to occur during years with very low sockeye abundance. This leads one to believe that encounters between northern pikeminnow and juvenile sockeye occur randomly during years of low sockeye abundance and that northern pikeminnow likely switch to other, more abundant, prey such as redside shiner (*Richardsonius balteatus*) and threespine stickleback during these times. This line of thinking is supported by Ricker (1941) at Cultus Lake, where it was observed that in years of small sockeye populations, consumption of alternative prey by northern pikeminnow increases.

It is important to recognize that the assumptions made here about northern pikeminnow predation represent a conservative approach, from the standpoint of sockeye recovery, in that the simulated predation rates are relatively small and do not represent a source of depensatory mortality on sockeye. The benefits of predator control would be even greater if northern pikeminnow are a source of depensatory mortality in sockeye. The model simulates a relationship where predation occurs randomly and increases with predator abundance. The nature of this relationship is largely unknown, and

better methods of collecting data for northern pikeminnow diets are necessary so that the real impacts of predation can be illuminated.

The effects of the pikeminnow removal on the survival of juvenile sockeye salmon in Cultus Lake is being assessed by DFO and results from the current program will be available in the next few years by comparing the freshwater survival index (fall fry or smolts per spawner) in years with and without predator removal. However, due to the highly variable nature of freshwater and marine survival, many years of northern pikeminnow removal may be necessary to increase confidence in effectiveness of the predator removal program.

Ricker and Foerster (1941) noticed that after predator removals, freshwater survival of sockeye juveniles increased and that the average size of sockeye smolt migrants increased. They hypothesized that this was a result of less competition because fewer newly hatched fry were required to produce a given number of migrants. However, in light of newer hypotheses about species interactions between predators and their prey (foraging arena theory; Walters and Martell 2004), it seems that a likely cause of this phenomenon would be that there is reduced predator avoidance and therefore increased feeding and growth among sockeye fry in the lake. This type of interaction has been demonstrated for other sockeye lakes (Eggers 1978).

To achieve the recovery objective, I recommend that FOC continue with predator control efforts and monitor not only the northern pikeminnow population but the whole lake system. Monitoring the whole system will help to determine if undesired changes in the ecosystem, resulting from predator control, have

occurred. To achieve the survival objective (i.e. maintaining a persistent low abundance of Cultus Lake sockeye), extended hatchery operations appear to be more effective than predator control.

In his review of the theory, Soule (1985) identifies that conservation biology is a crisis-oriented discipline where sometimes action must be taken before knowing all the facts. At Cultus Lake northern pikeminnow removals are ongoing, but the long term consequences of removing so many large fish from the lake are difficult to predict. Likewise, the hatchery program designed to aid in the recovery of Cultus sockeye has significant momentum and will likely continue for at least the next ten years. However, the long-term effects of the program are uncertain.

4.1.2 Hatchery operations

There are many potential benefits of broodstock/supplementation programs, such as reducing short-term extinction probability through increased recruitment, maintaining a reserve of genetic material, and maintaining the population until causes of the decline are addressed. My results suggest that extending the hatchery program results in the highest probability of all management strategies for meeting the objectives (survival and recovery) and allows for more harvest. However, extending the hatchery program may pose other problems associated with the increase of hatchery origin fish in the population. Thus, it is important to consider the potential negative consequences. Waples and Drake (2004) summarize the major problems associated with supplementation programs, such as loss of genetic diversity, increased disease

In my analysis, I have identified management options and have quantified their potential effects on the recovery of the Cultus sockeye salmon. I evaluated the major uncertainties in sockeye life history and used best available knowledge to simulate likely outcomes of alternative management strategies. Accounting for the uncertainties brings greater transparency and also facilitates logical systemscale thinking (management choices).

When there are competing goals, in this case between maximizing survival and recovery probabilities and minimizing harvest restrictions, the task is to find a solution that provides a best compromise. This involves making decisions about the preferences of society which are usually undertaken by managers. The major difficulty in determining the best compromise for the Cultus situation is that the tradeoffs are so large. Maintaining the population has significant cultural and biological importance, but the competing economic tradeoffs involved are substantial. Pestes et al. (2008) showed that, by using alternative harvest rules, probability of recovery of the Cultus Lake sockeye salmon population could be increased from 60% to 90%, but in one of their scenarios this resulted in a reduction in expected annual gross revenue of at least \$6.7 million per year (13%) for the commercial fleet that targets all late-run Fraser River sockeye salmon.

Ultimately only time will tell if our actions result in the recovery of the Cultus sockeye population, but continued monitoring is necessary to ensure that we can recognize whether the management actions or some other factors enable rebuilding of the population. Our ability to control the situation is limited and it is

not easy to identify an optimal policy, mainly because the system is driven by the uncertainty in marine survival.

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