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Evaluation of two release operations at Bonneville Dam on the smolt-to-adult survival of Spring Creek National Fish Hatchery fall Chinook salmon

By

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Abstract

In March 2004, two groups of coded wire tagged subyearling fall Chinook were released from Spring Creek National Fish Hatchery to directly evaluate the effects of alternative operations at Bonneville Dam on smolt-to-adult survival (*SAR*). The first group, released on March 1st, passed Bonneville Dam during a four-day, 25 kcfs spill operation with the corner collector closed. The second group, released on March 10th, passed Bonneville Dam during a four-day, 5 kcfs corner collector operation with the spillways closed. Tagged adults were subsequently recaptured in ocean fisheries, Columbia River fisheries, and at the hatchery during 2005-2007. The overall *SAR* was 0.118% for the fish released during the spill operation and 0.100% for fish released during the corner collector operation. The overall *SAR* for fish released during the spill operation was 18% higher than the *SAR* for fish released during the corner collector operation, however this difference was not statistically significant. Using Bayesian statistical methods, we estimated an 80% probability that the *SAR* for the spill operation release was higher than the *SAR* for the corner collector operation release. Applying the results from the 2004 March release operations to the March releases over 2005-2007, we estimate that a foregone loss of 15,200 adults (range 2,400-38,900) may have occurred due to corner collector-only operations during 2005-2007. Additional years of comparative study would be useful to quantify the degree of evidence that these results are consistent across years or not.

Introduction

Spring Creek National Fish Hatchery (SCNFH), located upstream of Bonneville Dam on the Columbia River, annually produces tule fall Chinook (*Oncorhynchus tshawytscha*) that are released in the spring of each year as subyearlings. Half of the total production of 15 million fish is released in March, prior to the onset of the Biological Opinion spill program for ESA-listed salmonids. Although SCNFH Chinook salmon are listed under the Endangered Species Act (ESA) as part of the Lower Columbia River Chinook ESU, they are deemed not necessary for recovery and therefore are available for harvest.

The 7.5 million fish that are released in March are very important to United States/Canada treaty and domestic West Coast fisheries because these fish make up a significant portion of the Chinook caught in West Coast Vancouver Island (WCVI) fisheries, near shore fisheries off the Washington and northern Oregon coast, and local fisheries in the Columbia River. Historically, Spring Creek NFH fish contributed up to 9% of the Chinook catch in the WCVI fisheries and 27% of the Chinook catch off of the Washington and northern Oregon coasts. Spring Creek NFH has contributed as many as 65,600 fish to treaty Indian fisheries (1976) and 41,500 fish to non-treaty commercial fisheries (1977) in the Columbia River (PFMC, 1996). More recently, the 2002-2004 average catch of Spring Creek NFH origin fall Chinook in the fall season treaty Indian fisheries above Bonneville Dam was 54,900 Chinook, while non-treaty in-river commercial and sports fisheries averaged another 12,600 Chinook (PFMC, 2006).

In addition to supplying large numbers of fish for harvest, the high abundance of tule fall Chinook stocks has likely provided some level of stock protection for other depressed stocks of concern in mixed-stock fisheries. Under the Chinook harvest ceiling management regime implemented by the Pacific Salmon Treaty in 1985, abundant Columbia River tule and upriver bright fall Chinook stocks had the effect of buffering impacts on other Chinook stocks of concern in certain Canadian and south east Alaskan ocean fisheries. With the adoption of an aggregate abundance-based management (AABM) regime for these ocean fisheries under the renegotiation of the Pacific Salmon Treaty in 1999, the buffering effect of these Columbia River stocks only occurs when harvest for a particular fishery is constrained to a level substantially less than allowed under the AABM regime for that particular fishery. This management scenario has, in fact, been the case for the WCVI Canadian troll fishery in several recent years where Columbia River tule fall Chinook stocks are a significant contributor to the overall stock mix of this fishery. Up until 2003, the WCVI troll fishery has been managed by Canada to harvest a much lower number of Chinook than allowed under the AABM regime, primarily to address domestic concerns for depressed WCVI naturally spawning stocks and the need to rebuild this stock group. Beginning in 2003, the WCVI troll fishery again expanded up to AABM quota limits as the fishery ostensibly found ways to maximize total catch, including significant numbers of Columbia River stocks, while minimizing impacts on their depressed local wild stocks through intensive time and area management actions.

However, even when AABM fisheries are harvested at their full allowable levels, harvest rate ceilings for particular stocks of concern (e.g., threatened Snake River fall Chinook and lower Columbia River Chinook) are now in place under ESA management constraints to provide an appropriate level of protection for these stocks while providing the opportunity to shape coastal and in-river fisheries to optimize the harvest of co-mingled healthy stocks when abundance levels for these stocks are high. For example, in addition to the AABM framework of the Pacific Salmon Treaty in Canadian and southeast Alaskan ocean fisheries, Washington, Oregon, and California ocean fisheries are managed under an ESA constraint that limits the annual allowable ocean fisheries impact on Snake River fall Chinook (including Canadian and Alaskan impacts) to 70% of the 1988-1993 base period average impacts. A similar 30% base period reduction in impacts for this stock in Columbia River fisheries is also required to provide an appropriate level of protection while allowing for management flexibility for other stocks. These impact rates are currently being reviewed by NOAA Fisheries relative to Snake River fall Chinook stock status and fisheries impacts.

As fisheries are increasingly constrained to protect ESA-listed and other stocks of concern, the fishery management agencies are continually seeking ways to maintain a reasonable level of harvest opportunity for stocks with harvestable surpluses. Mark-selective fisheries are now in place for nearly all non-Indian steelhead sport fisheries, many non-Indian marine and freshwater sport and commercial coho fisheries, and most non-Indian Columbia River spring and summer Chinook fisheries. Although, mark-selective ocean Chinook fisheries and in-river fall Chinook fisheries have not yet been broadly implemented, they are clearly a likely management strategy on the horizon as the States of Washington and Oregon begin to mass mark their federally funded fall Chinook hatchery production consistent with Congressional mandates. Spring Creek NFH hatchery production has been mass marked for several years (beginning with the 2003 brood year) and these fish are now available for mark-selective harvest as these types of management strategies are implemented. Maintaining high survival rates for mass marked hatchery fish production is critical to the success of any mark-selective fishery management program since all unmarked (naturally produced fish) must be released and the abundance of the targeted stocks must be large in relation to the cost (incidental mortality impact) on the stocks of concern.

Preseason planning for 2007 ocean and Columbia River fisheries used 21,300 Spring Creek tule fall Chinook as an expectation for river mouth run size after accounting for modeled ocean fishery impacts. This is a very sharp reduction from the 2001-2005 average in-river run size abundance of 148,500 Spring Creek stock adult fish. As a result, the 2007 PFMC area ocean Chinook fisheries north of Cape Falcon and Columbia River fall Chinook fisheries were severely constrained (low quotas and short seasons) because of low tule fall Chinook abundance and the need to protect the co-mingled stocks of concern. Preliminary post-season estimates for the 2007 adult return of Spring Creek fall Chinook to the Columbia River indicate a run size of approximately 17,000 fish and Spring Creek NFH barely made its broodstock egg take goal in 2007. The 2008 return is, however, expected to be improved from the very low run in 2007 based on an improved jack return in 2007.

Over the past 13 years, fish hatchery programs for Columbia River production have been reduced significantly due to Congressional reduction or flat funding for Mitchell Act programs. These funding cuts have resulted in a very substantial reduction in the production of tule fall Chinook salmon (approximately 25.0 million since 1995) at both state and federal fish hatcheries and have caused the closure of some facilities. The State of Oregon has drastically reduced its production of tule fall Chinook salmon in the Columbia River system. Spring Creek NFH is now the only facility producing tule fall Chinook above Bonneville Dam. Nearly all of the remaining Columbia River tule production is released from hatcheries in the State of Washington below Bonneville Dam. These reductions and hatchery closures make maximizing survival and production at Spring Creek NFH even more important for maintaining and improving fisheries opportunity in the Pacific Ocean and Columbia River, especially in years of low ocean productivity.

Spill is generally accepted as the safest route for fish passage at Federal Columbia River Power System (FCRPS) facilities in terms of both immediate and delayed survival effects. However, neither route-specific nor comparative life-cycle survival studies have been conducted on March releases from Spring Creek NFH due to the size limitations of telemetry and PIT-tag approaches. Various survival studies have been cited for indirectly examining these questions based on different species groups and different times of the year using direct survival estimates (no estimates of delayed survival or life-cycle survival), with unknown applicability for making inferences on the March release from SCNFH.

Historically, the March release of juvenile fish at Spring Creek NFH has produced 44% of the returning adults (based on a recent 5-year average). The Service has released juvenile fall Chinook in March, April, and May to maximize the rearing capacity of the facility by splitting the April and May releases into available empty pond space after the March release has occurred. Along with maximizing rearing capacity, this release strategy also balances the risks associated with the possibility of low survival from a particular release month. As described in the paragraphs above, maximizing the survival of the March release fish is important for international and domestic fisheries operating both in the ocean and in-river.

Historically, the Bonneville Power Administration (BPA) allowed spill at Bonneville Dam, coinciding with the timing of the SCNFH releases in March to provide a non-turbine/non-bypass passage route and to improve their survival past Bonneville Dam. The duration and volume of spill that BPA has allowed at Bonneville Dam for the Spring Creek March releases has varied over time. Since 1992, there have been three general categories of the duration and volume of spill allowed at Bonneville Dam during the March releases (Figure A3). During 1992-2000, spill duration and volume averaged 178 hours (7.4 days) and 1100 KAF. During 2001-2004, average spill duration and volume were reduced to 59 hours (2.5 days) and 177 KAF. During 2005, 2006, and 2007, BPA did not allow spill for the March releases. However, beginning in 2004, the Bonneville Dam corner collector was operated during the March releases, providing a non-turbine/non-bypass passage route through the dam. During the 2004-2007 March releases, the corner collector was operated for 85 hours using 35 KAF on average during the March releases. These recent volumes using the corner collector are 3.2% of the volumes allowed using spill during 1992-2000.

The provision of spill at Bonneville Dam for the SCNFH March releases has been an important issue among the FWS, other fishery management agencies, commercial and sport fishing groups, and the Action Agencies. In 2004, the FWS developed and distributed a research proposal to directly evaluate the effects of Bonneville Dam operations on the life-cycle survival of SCNFH March releases (USFWS 2004). Because this study design utilized coded wire tags (CWT) that could be applied to March-released fish, the study could directly measure the life-cycle survival rates for groups of March-released fish. This proposed study consisted of three years of CWT marking and releases under three operations at Bonneville Dam: a spill-only operation, a spill plus corner collector operation, and a corner collector-only operation. Partitioning the March release into three groups was intended to balance the risks caused by uncertainty about the newly-constructed corner collector route, and this balanced design would aid in understanding the additive and/or multiplicative effects of the components of spill and corner collector operation on efficiency (through hydroacoustics) and life-cycle survival (through coded wire tag recovery rates). To achieve this balanced design, FWS requested that the treatment operations be: 75 kcfs spill-only, 75 kcfs spill with the corner collector, and the corner collector-only. Spill levels for the spill and spill with the corner collector needed to be similar in this study design to assess whether the effect of the corner collector was additive or not. FWS believed that spill levels at 75 kcfs would provide adequate survival conditions and would provide a level of precaution against the unknown survival rates associated with the other passage routes. The proposal to conduct the study over three years was made to ensure confidence and reliability in the results.

Following the distribution of this proposal, discussions between the FWS and the Action Agencies resulted in a single year of CWT-marking, only two operations being evaluated (spill versus corner collector), reduced levels of spill (50 kcfs instead of the proposed 75 kcfs), and no spill requests for two years. For the most part, this is what occurred. A major exception was that calibration errors in spill rates resulted in actual spill rates of 25 kcfs instead of the agreed-to level of 50 kcfs in 2004. Adults with CWTs were captured in ocean fisheries, in-river fisheries, and at the hatchery during 2005-2007. The following analyses summarize the return data from the 2004 releases.

The objectives of this research paper are therefore to: 1) summarize the life-cycle survival rates (*SARs*) for the two release groups derived from the CWT recaptures, 2) calculate the percent difference in the *SARs* for the two release groups to quantify relative survival of the two release operations, and 3) quantify the uncertainty in these estimates. An additional objective was to provide context for the results by examining the potential implications of this study on the releases that occurred in 2005-2007 without spill or a comparative evaluation. In addition to traditional frequentist statistical approaches, we used Bayesian statistical methods to quantify uncertainties through posterior probability distributions, reflecting easily-interpreted probabilities for the unknown quantities of interest conditioned on the observed data.

Methods

Sample size calculations

Prior to the releases, we conducted sample size calculations to quantify the differences that could be detected for various release sizes, at specified levels for type-I and type-II error rates (Snedecor and Cochran 1967). We determined that a release of 220,000 fish could detect a 27% reduction in the *SAR* of fish released during corner collector operation with 80% power ($\beta = 0.2$) and $\alpha = 0.1$, assuming the *SAR* for fish released during spill was 0.16% (the average *SAR* for March-released fish over brood years 1990-1997 during spill operations). These levels of precision and detectable differences were determined to be acceptable, and the study proceeded using a total release of roughly 220,000 CWT fish.

Tagging and releases

Spring Creek NFH staff randomly selected nine rearing ponds and tagged approximately 25,000 fingerlings with CWT from each pond. Four ponds were randomly assigned for release during the spill operation and the remaining five were assigned to release during corner collector operation. Mean fish weight at tagging was 2.2 grams for the spill release group fish and 2.3 grams for the corner collector release group fish. The spill release group fish were released from the hatchery in the early afternoon of March 1 and had a mean weight of 2.7 grams. The corner collector release group fish were released from the hatchery in the morning of March 10 and had a mean weight of 3.2 grams. After accounting for tags that were shed, there were 98,932 CWT fish in the spill release group and 122,853 CWT fish in the corner collector release group. In total, 221,785 CWT fish were released.

Bonneville Dam operations

Following the March 1 release, spill began at Bonneville Dam at 20:00 hours on March 2 with a spill target of 50 kcfs (actual spill rate was 25 kcfs, after accounting for spillgate mis-calibration). After 96 hours, spill was terminated at 20:00 hours on March 6. Following the March 10 release, corner collector operation began in the afternoon of March 11 and continued for 96 hours, until the afternoon of March 15. Flow in the corner collector was approximately 5-6 kcfs.

Estimating SARs

Tagged adults from the 2004 releases (2003 brood year) were subsequently recaptured in ocean fisheries, Columbia River fisheries, and at the hatchery during 2005-2007 (Table 1). In all years, adults returning to the hatchery were randomly selected across the duration of the run for examination of CWT presence. Similarly, the coast-wide CWT monitoring program randomly sampled commercial and recreational fisheries for CWT presence. When these sampling programs examine a subset of the total catch or return, the observed CWTs are expanded for the proportion sampled to estimate the total number of CWT fish that were present. For example, if 50% of the catch in a fishery is sampled for CWT and five CWT fish were observed, the expansion factor would be 2.0 and the resulting estimate for the total number of CWT fish in that fishery would be 10.

To calculate overall *SARs*, we divided the sum of the expanded CWT recaptures in fisheries and at the hatchery by the number of CWT fish released for each release group:

$$SAR_i = \frac{R_i}{N_i},$$

where *i* refers to releases during the spill operation or the corner collector operation, R_i is the number of expanded recoveries for group *i*, and N_i is the number of CWT fish released in group *i*. We calculated an estimate of the ratio of the *SARs* (SAR_{Spill}:SAR_{CC}) as:

$$SAR \text{ ratio} = SAR_{Spill} / SAR_{CC}.$$

As described above, the overall number of recoveries is the sum of the expanded fishery recoveries and hatchery recoveries across years 2005-2007. The observed recoveries can be modeled using a binomial distribution for calculating the variance of the observed recovery rates. However, the expansion factors need to be accounted-for when calculating the variances of the overall *SARs*. To calculate the variances of the *SARs*, we applied three statistical properties. First, for a random variable (X) multiplied by a constant (c), the variance of cX is $c^2\text{var}(X)$. Second, for a binomial proportion p (in this application p = (number of observed recoveries) / (number of CWT fish released)), the variance of p is $p(1-p)/n$. Third, for independent random variables X_i, the $\text{var}(\sum_i X_i) = \sum_i \text{var}(X_i)$. Combining these statistical properties, we calculated the variances of the *SARs* as

$$\text{var}(SAR_i) = \sum_j \sum_k c_{j,k}^2 p_{j,k}(1-p_{j,k}) / N_i$$

where $c_{j,k}$ is the expansion factor and $p_{j,k}$ is the observed recovery proportion ($p_{j,k} = n_{obs.,j,k} / N_i$) for observed fishery or hatchery (k = fisheries or hatchery) recoveries in year j. To quantify the relative magnitude of the SARs for the two releases, we calculated the percent difference in the SARs as

$$\text{Percent difference} = \frac{SAR_{Spill} - SAR_{CC}}{SAR_{CC}} \cdot 100\%.$$

We conducted a two-tailed test of the null hypothesis $H_0 : SAR_{Spill} = SAR_{CC}$, versus the alternative hypothesis $H_A : SAR_{Spill} \neq SAR_{CC}$, using a test statistic based on the standard normal deviate z:

$$z = \frac{SAR_{Spill} - SAR_{CC}}{\sqrt{\mathrm{var}(SAR_{Spill}) + \mathrm{var}(SAR_{CC})}},$$

estimating the *SARs* and their associated variances as defined above.

Quantifying uncertainty

We applied Bayesian statistical methods for quantifying uncertainty in the *SARs* and a ratio of the *SARs*. Bayesian statistical methods quantify the probability of observable and unobservable quantities in a problem through posterior probability distributions that are conditioned on the observed data (Gelman et al. 1995). A key advantage of a Bayesian approach is that it allows for common-sense interpretation of statistical conclusions that are reflected by the posterior probability distributions. These distributions quantify the probability that a parameter of interest, or a function of those parameters, takes on a particular value (Gelman et al. 1995, p. 23). In contrast, traditional frequentist confidence intervals strictly reflect the sequence of similar inferences that might be made under repeated sampling of the same process and sampling in the same manner. Because our primary focus was on quantifying the degree of evidence for quantities of interest based on the observed data, rather than bounding a quantity of interest as defined under repeated sampling, we applied Bayesian statistical methods in this evaluation.

The three quantities of interest were the *SARs* for the spill and corner collector release groups and the ratio of these two *SARs*. We were interested in the ratio of the *SARs* (SAR_{Spill}:SAR_{CC}) because values less than one reflect the probability that the corner collector release group had a higher *SAR* and values greater than one reflect the probability that the spill release group had a higher *SAR*. Additionally, the magnitude of the ratios and their associated probabilities reflect the probabilities of differences in life-cycle survival between the release groups.

A Bayesian analysis involves combining prior information with a likelihood function for the observed data to arrive at a posterior distribution. This posterior distribution summarizes the probability that a parameter of interest, or a function of that parameter, takes on a particular value, after conditioning on the observed data. In this application, we used three "uninformative" prior distributions in conjunction with the observed return data to calculate posterior distributions for the *SARs* as well as the ratio of those *SARs*.

We assumed a binomial likelihood for the observed return data and used a beta distribution for specifying the prior. The beta prior distribution is a conjugate family for the binomial likelihood (Gelman et al. 1995, p. 36), and through application of Bayes rule, the posterior has a beta distribution:

$$p(\theta \mid n, y) \propto \mathrm{Beta}(y + \alpha, n - y + \beta),$$

where $p(\theta \mid n, y)$ is the posterior distribution for the return rate θ, n is the number of CWT fish released, y is the number of observed returns. The parameters α and β define the prior distribution. Three "uninformative" prior distributions have been suggested for modeling binomial data, and each is defined by different values for α and β (Lee 1997, p. 83-86). A uniform prior distribution is obtained by setting $\alpha = \beta = 1$, a Haldane prior distribution is obtained by setting $\alpha = \beta = 0$, and a Jeffreys prior distribution is obtained by setting $\alpha = \beta = 0.5$. Consistent with the conclusions of Lee (1997), the selection of the different priors had little effect on the posterior distributions (see Appendix Figures A1, A2). However, both the uniform prior and the Jeffreys prior tended to shift the mean of the posterior in a positive direction compared to the Haldane prior. Due to the consistency between the maximum likelihood estimate and the mean of the posterior distribution when using a Haldane prior (Lee 1997, p. 84), we selected Haldane priors for all subsequent analyses.

The posterior distributions for the *SARs* are functions of the posterior distributions for the observed location- and year-specific returns, accounting for the expansion factors. We generated 500,000 simulated values for defining the posterior distributions for the *SARs* as:

$p(SAR_{Spill} \mid n, \mathbf{y}) \propto$ 3.51*Beta(6, 98926) + 1.00*Beta(4, 98928) + 1.12*Beta(31, 98901) + 3.31*Beta(16, 98916) + 1.00*Beta(4, 98928), and

$p(SAR_{CC} \mid n, \mathbf{y}) \propto$ 1.17*Beta(6, 122847) + 1.12*Beta(34, 122819) + 2.62*Beta(27, 122826) + 1.00*Beta(7, 122846).

The 2.5% and 97.5% percentiles of the simulated values were used to define 95% credibility intervals for the *SARs*. To quantify the uncertainty in the SAR ratio, we calculated the ratio of the *SARs* (SAR_{Spill}:SAR_{CC}) by dividing the posterior distribution values for the SAR_{Spill} by the posterior distribution values for SAR_{CC} and calculated the proportion of values greater than 1.

Implications for March releases during 2005-2007

The *SAR* ratio calculated from the 2004 releases is the *only* estimate of comparative life-cycle survival for March releases under two operations at Bonneville Dam. March releases during 2005-2007 were provided no spill operations and the *SARs* for these releases are uncertain, as adult returns will not be complete until 2010. To quantify the potential effects of these operations, relative to effects that may have occurred if spill operations had been provided, we estimated the number of adults that may have returned, given a range of observed values for *SARs* and the estimated *SAR* ratio from the 2004 releases. We determined the minimum, average, and maximum *SAR* over brood years 1989-2001 (all brood years where spill operations were provided) and multiplied these by the number of fish released each year in March, 2005-2007. These were used to estimate the range of the expected number of adults that could have returned if spill operations had been provided, as the minimum, average, and maximum *SARs* observed during brood years 1989-2001 were all provided spill operations. Then we applied the estimated *SAR* ratio to these calculated adults to estimate the number of adult returns that may have occurred under corner collector operations. The differences between the two estimates across years and the range of SARs were used to quantify the potential gains or losses of adults that may have occurred due to corner collector-only operations during 2005-2007.

Results

Fisheries/Hatchery Returns and SARs

The number of observed CWT recoveries, expanded CWT recoveries and expansion factors in the fisheries and at the hatchery are provided in Table 1. The 2007 ocean and in-river fisheries information for age-4 fish is not yet available.

Table 1. Number of observed CWT recoveries, expanded recoveries, and expansion factors for fisheries and hatchery returns, by age, for the spill operation and the corner collector operation release groups. Data from fisheries was downloaded from RMIS on January 31, 2008 and may be subject to change.

		Age-2		Age-3		Age-4	
		Hatchery	Fisheries	Hatchery	Fisheries	Hatchery	Total
Spill Group	Observed	6	4	31	16	4	61
N_{sp} = 98,932	Expanded	21	4	35	53	4	117
	Expansion	3.5098	1.0000	1.1187	3.3125	1.0000	
CC Group	Observed	0	6	34	27	7	74
N_{cc} = 122,853	Expanded	0	7	38	71	7	123
	Expansion	3.5098	1.1667	1.1187	2.6296	1.0000	

The estimated *SARs* for the two release groups were therefore:

$$SAR_{Spill} = \frac{117}{98{,}932} = 0.118\%\text{, and}$$

$$SAR_{CC} = \frac{123}{122{,}853} = 0.100\%.$$

The estimated *SAR* ratio and the *SAR* percent difference were:

$$SAR_{Ratio} = \frac{117\,/\,98932}{123\,/\,122853} = 1.18$$

$$\text{Percent difference} = \frac{0.118 - 0.100}{0.100} \cdot 100\% = 18\%$$

In addition to the overall *SAR* ratio calculated above, we also calculated that *SAR* ratio for various subsets of the data to investigate whether the life-cycle survival differences were consistent across other groups of interest. Considering hatchery-only returns, the *SAR* ratio was 1.33. Considering fisheries-only returns, the *SAR* ratio was 0.91. Considering full term adults-only returns (excluding the age-2 jack returns), the *SAR* ratio was 0.98. These results indicate that the overall differences in life-cycle survival that were observed (overall *SAR* ratio = 1.18) were partially due to a large jack return to the hatchery in 2005 for the spill release group and an absence of jacks for the corner collector release group.

The test statistic z was 0.825, with a resulting p-value = 0.41. As the p-value was greater than the type-I error rate used in the study design ($\alpha = 0.10$), we conclude that the difference between the *SARs* were not statistically significant based on this test.

The posterior credibility intervals were (0.087%, 0.155%) for the SAR_{Spill} and (0.077%, 0.127%) for the SAR_{CC} (Figure 1). Using the posterior distribution for the *SAR* ratio, we calculated a 80% probability that the SAR_{Spill} was higher than the SAR_{CC} , as indicated by SAR ratios ≥ 1.0 (Table 2, Figure 2). We also summarized the posterior probabilities for other values of the *SAR* ratio, and calculated a 63% probability that the SAR_{Spill} was at least 10% higher than the SAR_{CC}, a 46% probability of the ratio being at least 20% higher, a 30% probability of the ratio being at least 30% higher, and an 18% probability of the ratio being at least 40% higher (Table 2).

Table 2. Posterior probabilities for the ratio of the SAR_{Spill}:SAR_{CC} exceeding various threshold values.

Ratio	Probability
≥ 1.0	80%
≥ 1.1	63%
≥ 1.2	46%
≥ 1.3	30%
≥ 1.4	18%
≥ 1.5	10%

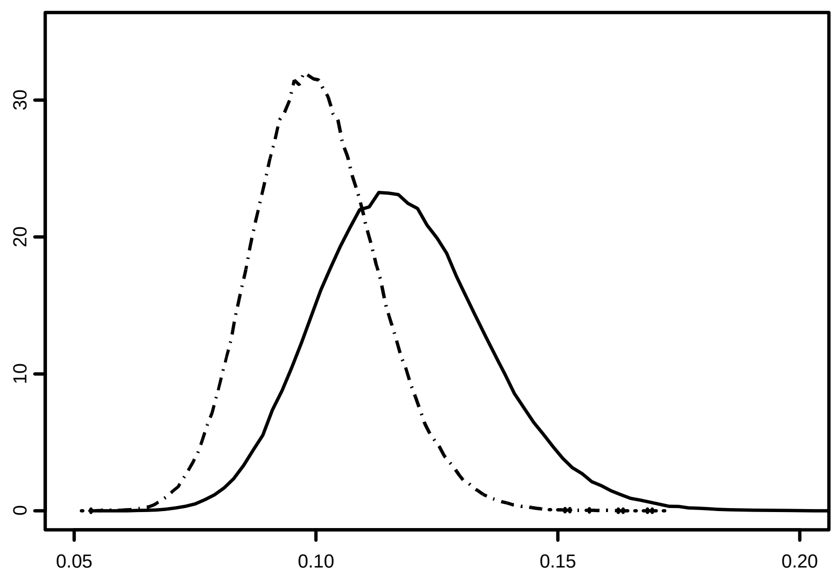

Figure 1. Posterior probability distributions for the SAR_{Spill} (solid line) and the SAR_{CC} (dashed line).

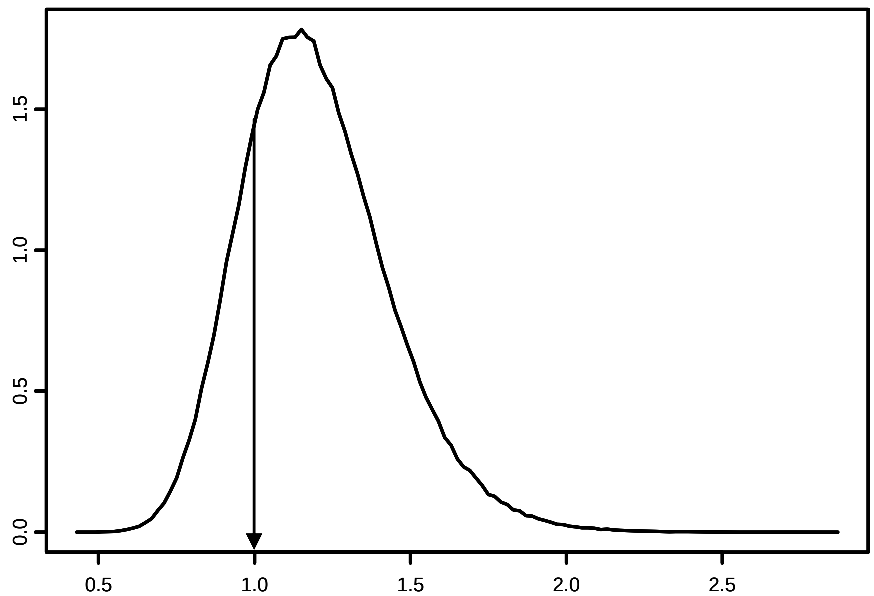

Figure 2. Posterior probability distribution for the SAR_{Spill}: SAR_{CC} ratio. The arrow denotes the location of ratios equal to 1.0. The probability mass to the left of the arrow describes the evidence that the SAR_{CC} was greater than the SAR_{Spill}, while the probability mass to the right of the arrow describes the evidence that the SAR_{Spill} was greater than the SAR_{CC}.

Across brood years 1989-2001 of March releases with spill, the minimum, average, and maximum *SARs* were 0.07%, 0.44%, and 1.12%, respectively (Table 3). During March releases 2005-2007 with corner collector operations, approximately 7.5 million fish were released each year. By applying the range of *SARs* observed during spill conditions in the past to these releases, we estimate that spill operations may have resulted in 5,100-87,100 adults each year from the March releases. By dividing these estimated adults by the observed *SAR* ratio (1.18), we estimate that corner collector operations may have resulted in 4,300-73,800 adults each year from the March releases. Taking the annual differences between the two operational estimates and summing across years, we estimate that a foregone loss of 15,200 adults (range 2,400-38,900 adults) may have resulted from corner collector-only operations during 2005-2007 (Table 3).

Table 3. Minimum, average, and maximum *SARs* for the March releases during brood years 1989-2001 under spill operations, the number of fish released in March 2005-2007, and forecasts of the expected number of total adult returns (fisheries and hatchery) for spill operations and corner collector operations using the observed *SAR* ratio (1.18). The differences between the forecasts and the sum of these differences across years is also presented.

			Expected Adult Returns		
Release Year	Number Released (Mar.)	Group	Min. *SAR* 0.07%	Avg. *SAR* 0.44%	Max. *SAR* 1.12%
2005	7,348,976	Expected with Spill	5,071	32,328	82,441
		Expected with CC	4,297	27,397	69,865
		difference	774	4,931	12,576
2006	7,591,028	Expected with Spill	5,238	33,393	85,156
		Expected with CC	4,439	28,299	72,166
		difference	799	5,094	12,990
2007	7,767,253	Expected with Spill	5,359	34,168	87,133
		Expected with CC	4,542	28,956	73,842
		difference	818	5,212	13,291
		Total across years:	2,390	15,237	38,857

Discussion

These results provide some evidence that the fish released during the spill operations had higher life-cycle survival than fish released during the corner collector operations in 2004. However, the lack of strong contrast in the operations provided at Bonneville Dam (5 kcfs corner collector versus 25 kcfs spill) likely hindered the ability to detect biologically significant differences between the *SARs* of the release groups. Still, applying these results to the March releases that occurred in 2005-2007, a large number of adults may have been lost that otherwise could have been available to ocean fisheries, in-river fisheries, and back to the hatchery. As discussed in the introduction, in addition to possible foregone losses of harvest opportunities in fisheries, other detrimental effects to ESA-listed and other stocks of concern may have resulted. Due to the lag between release and adult return, the effects of those operations, whatever they in fact were, will continue to be manifest as the adults from these releases continue to return.

While the evidence for the 2004 releases suggests that there may be a difference in life-cycle survival, and the resulting estimate of the *SAR* ratio is the *only* estimate of comparative life-cycle survival, additional years of data are necessary to evaluate whether these results are consistent across years or not. The Bayesian methods presented in this analysis provide a convenient framework for augmenting the results from this experiment with those that may be obtained from future experiments. We envision that the observed *SAR* ratio could be used as a prior distribution for *SAR* ratios from subsequent experiments to quantify the evidence that these differences are consistent or not across years.

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Appendix:

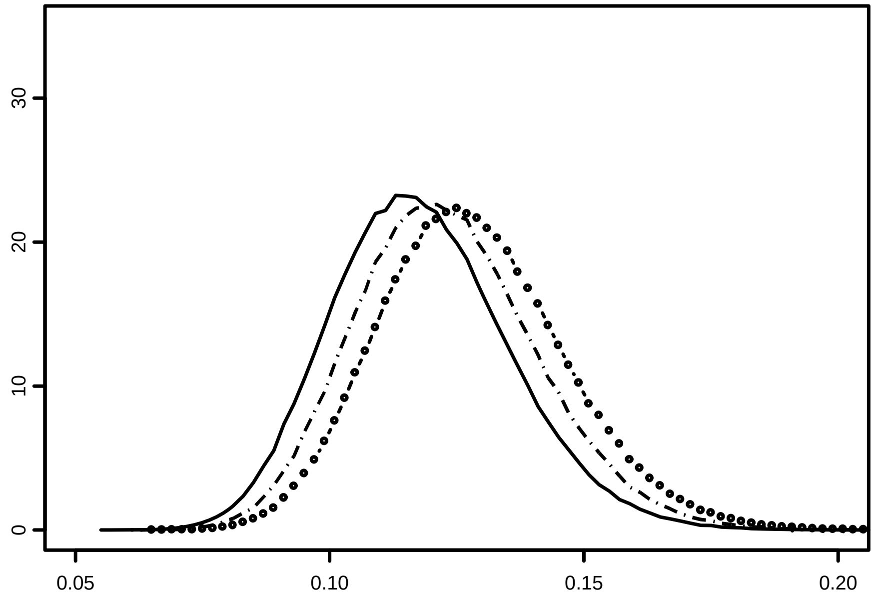

Figure A1. Posterior probability distributions for the SAR_{Spill} using a Haldane prior (solid line), Jeffreys prior (dashed line), and a uniform prior (line with open circles).

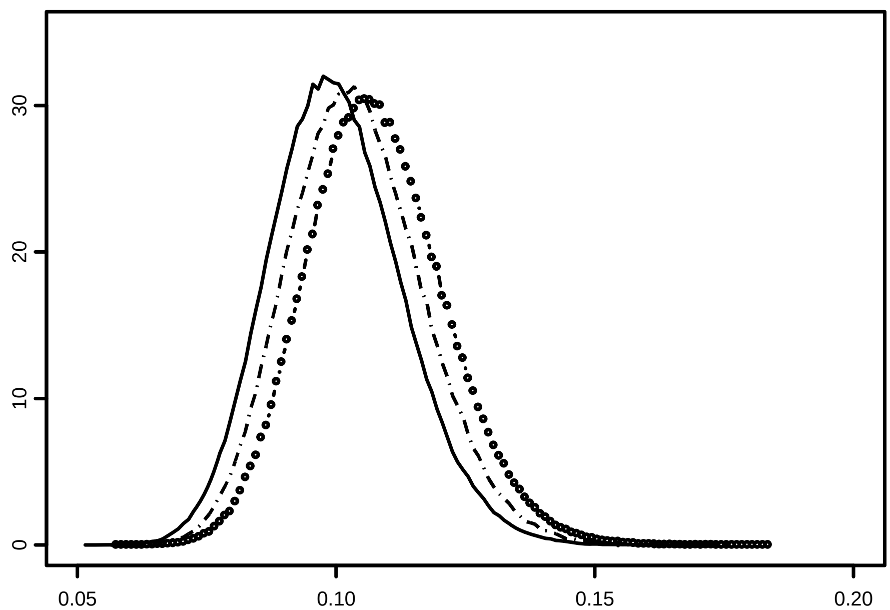

Figure A2. Posterior probability distributions for the SAR_{CC} using a Haldane prior (solid line), Jeffreys prior (dashed line), and a uniform prior (line with open circles).

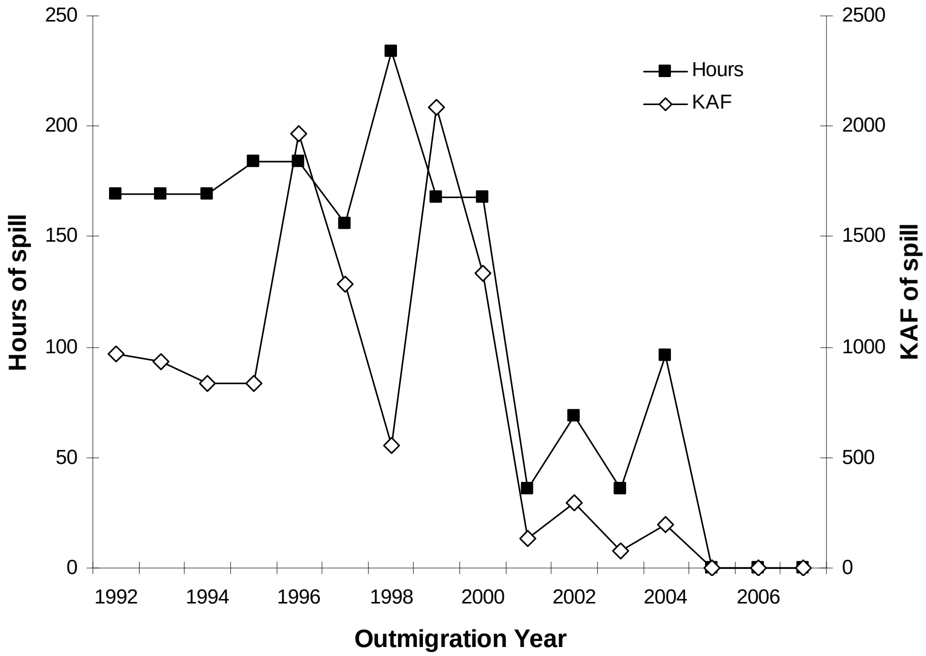

Figure A3. Hours of spill and KAF of spill at Bonneville Dam during the March release of Spring Creek NFH tule fall Chinook, 1992-2007.