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Supplement A: Precision of Estimates of Winter Chinook Salmon Spawning Abundance in the Sacramento River

The best estimates of the number of winter Chinook Salmon spawning in the Sacramento River come from carcass surveys conducted by California Department of Fish and Game (CDFG) and the U.S. Fish and Wildlife Service (USFWS) (Killam 2009; USFWS 2010). The number of spawners is estimated using mark–recapture methodology. In the early years of these surveys, estimates were derived using a Petersen model (Snider et al. 2001). The reported CVs of these estimates (standard error as a proportion of the estimate) ranged from 0.13 to 0.24 in the first 4 years (1996–1999), but the CV was much lower in 2000 (0.04). The tag recovery rate was much higher in 2000 (42%) than from 1996–1999 (12–18%), as was the number of carcasses examined as a proportion of the estimated population size. These factors likely contributed to the higher precision of the estimate in 2000. In more recent years the number of "adult" female spawners in the carcass survey area whose adipose fin was not clipped (i.e., of natural origin) was estimated using a Jolly–Seber superpopulation approach (Schwarz et al. 1993), and the numbers of clipped females, age-2 females, males, and spawners outside of the carcass survey area were estimated using expansion factors based on sample proportions (Killam 2009). The precision of these estimates has not been reported.

We derive here estimates of the uncertainty (CVs) associated with the estimates of the number of unclipped, adult female winter Chinook Salmon spawners in the carcass survey area from 2003 to 2010. These spawner estimates are similar to the estimates of the total number of natural-origin female spawners because only a small proportion of females return to spawn at age 2 or spawn outside of the carcass survey area. Thus, we applied the estimated CVs for these spawner estimates to the spawner data to which our model was fitted.

METHODS

Data.—A description of the carcass survey methods can be found in Killam (2005). D. Killam (California Department of Fish and Wildlife, personal communication) provided us with the raw data and spreadsheets used to calculate the spawner abundance estimates from 2003 to 2010. Our analysis focused on the mark–recapture component of the abundance estimates. This component was based on unclipped adult female carcasses in the carcass survey area. The specific data that we used in this part of our analysis were the number of new unclipped adult female carcasses that were tagged (i.e., marked by attaching a tag to the carcass) in each survey period (or group of survey periods), the number of these tagged carcasses that were subsequently recovered and chopped in each survey period, and the number of new unclipped adult female carcasses examined and chopped (i.e., not tagged) in each survey period. The number of unique unclipped adult female carcasses examined ranged from a high of 5,263 in 2005 to a low of 556 in 2010 (Supplementary Table SA.1). The proportion of these carcasses that was tagged varied from 0.63 to 0.81, and of these tagged carcasses between 0.37 and 0.70 were recaptured. It is important to note that some of the data in some years were estimates (i.e., calculated numbers). For example, it was not possible to determine whether the adipose fins of fish whose remains were skeletons or badly decayed carcasses had been clipped. These estimates were sometimes decimal numbers.

Mark–recapture estimates.—A Jolly–Seber superpopulation approach (Schwarz et al. 1993) was previously used to estimate the numbers of unclipped adult female spawners in the carcass survey area (Killam 2005, personal communication). Most of the calculations (and our notation) followed the equations presented in Table 2 of Schwarz et al. (1993) for the "less-biased estimators" of the "unconfounded parameters." Note that the parameters defined here do not correspond to the parameters represented by the same symbols in the main text.

The total number of unclipped adult female spawners in the carcass survey area in a given year, $\hat{F}$, was calculated as

$$\hat{F} = \sum_{i=0}^{s-1} \tilde{B}_i^* , \tag{SA.1}$$

where s is the number of survey periods and $\tilde{B}_i^*$ is the estimated number of new female carcasses entering the system between survey periods i and $i + 1$, which was calculated as

$$\tilde{B}_i^* = \begin{cases} \dfrac{\tilde{B}_i}{\sqrt{\tilde{\phi}_i}} & \text{for } i = 2,\ 3, \ldots, s-2 \quad \text{(SA.2a)} \\ n_1 + \dfrac{\tilde{N}_2 - \tilde{\phi}_1 R_1}{\sqrt{\tilde{\phi}_1}} & \text{for } i = 0 \quad \text{(SA.2b)} \\ \dfrac{\tilde{N}_{i+1} - \tilde{\phi}_i \left(\tilde{N}_i - n_i + R_i \right)}{\sqrt{\tilde{\phi}_i}} & \text{for } i = 1,\ s-1, \quad \text{(SA.2c)} \end{cases}$$

where

$$\tilde{N}_1 = \tilde{N}_2 \frac{n_1}{n_2}, \quad \text{(SA.3)}$$

$$\tilde{N}_s = \frac{\left(n_s + 1\right) \tilde{M}_s}{m_s + 1}, \quad \text{(SA.4)}$$

$$\tilde{\phi}_{s-1} = \frac{\tilde{M}_s}{\tilde{M}_{s-1} - m_{s-1} + R_{s-1}}, \quad \text{(SA.5)}$$

and

$$\tilde{M}_s = \frac{\tilde{M}_{s-1} m_s}{m_{s-1}}. \quad \text{(SA.6)}$$

All variables ($\tilde{B}_i$, $\tilde{M}_i$, $\tilde{N}_i$, R_i, n_i, m_i, and $\tilde{\phi}_i$) are defined and were calculated from the data as presented by Schwarz et al. (1993). In particular, $\tilde{\phi}_i$ is the "survival" rate of carcasses during the interval between *i* and *i* + 1 (Schwarz et al. 1993). Equation SA.2a accounts for new carcasses that left the system before having a chance to be captured by assuming that all new carcasses recruited to the population at the midpoint between survey periods (Schwarz et al. 1993). Equations SA.2b and SA.2c represent additional calculations not presented by Schwarz et al. (1993).

The presence of zeroes in the data and certain data combinations sometimes resulted in infinite parameter estimates. Previous investigators dealt with this situation by adding a small number to the problematic zero data. However, the approach that we took to estimating uncertainty involved resampling the data (see the section on uncertainty in mark–recapture estimates). Identifying and adjusting the problematic data each time the data were resampled would have required a complex algorithm. Instead, we designed systematic fixes to the parameter estimates themselves when infinite values arose. First, survival rates $(\tilde{\phi}_i)$ of zero and infinity were set to 1×10^{-6} and 1, respectively. Second, $\tilde{N}_1$ was set equal to $\tilde{N}_2$ when $n_2 = 0$ (equation SA.3). Third, $\tilde{M}_s$ was set equal to $\tilde{M}_{s-1}$ when $m_{s-1} = 0$ (equation SA.6).

The estimates of the total number of unclipped adult female spawners in the carcass survey area between 2003 and 2010 ranged from a high of 7,494 in 2006 to a low of 722 in 2010 (Table SA.2). The number of unique carcasses examined each year represented 0.47–0.77 of the respective estimates (Table SA.2).

Uncertainty in mark-recapture estimates.—Several approaches can be used to estimate the uncertainty associated with mark–recapture estimates of abundance. Schwarz et al. (1993) presented formulae for an estimate of the variance of population size estimated using a Jolly–Seber superpopulation approach. Buckland and Garthwaite (1991) discuss alternative parametric and nonparametric boostrapping approaches. Given that the calculation of escapement by CDFG involved calculations not presented by Schwarz et al. (1993), we decided to use a nonparametric bootstrap approach to estimate uncertainty.

First, the data were reformatted into capture histories for each individual unclipped adult female carcass. In each survey period a carcass was assigned one of four event codes: 0 = not seen, 1 = first capture and tagged, 2 = recaptured and chopped (or effectively chopped), and 3 = first capture, not tagged, and chopped. In each bootstrap iteration, these individual capture histories were randomly sampled with replacement to obtain a new data set with the same number of individuals as the original data set. This new data set of capture histories was then back-formatted for input into the equations for calculating the abundance estimate. We conducted 10,000 bootstrap iterations to obtain a sample of 10,000 estimates of the number of unclipped adult female carcasses in the carcass survey area. Summary statistics were then calculated from this bootstrap sample.

It should be noted that our bootstrapping algorithm required integer numbers of carcasses; thus, the decimal data referred to in the data section were rounded before bootstrapping. This rounding resulted in slightly different estimates of abundance than when decimal data were used, even when the data were not resampled.

RESULTS AND DISCUSSION

The CVs of the estimated numbers of unclipped adult females spawning in the carcass survey area $(\hat{F})$ were relatively small, indicating relatively precise estimates (Table SA.2). The CVs ranged from 0.01 to 0.07 and seemed to partially reflect the size of the estimate itself (larger CVs for smaller estimates) and possibly the proportion of carcasses sampled (the largest CV was in the year with the lowest proportion), although this was not always the case (e.g., compare 2007 and 2008).

The bootstrap 95% confidence intervals were asymmetrical, indicating a positively skewed distribution of estimates (Table SA.2). Thus, the mean bootstrap estimates were slightly higher than the median estimates. Both the mean and median bootstrap estimates were higher than the estimates for the original data, with as much as a 5% difference in the mean estimate (Table SA.2).

Supplementary Table SA.1.—Number of unclipped adult female carcasses sampled by year. Captured carcasses were either tagged and returned to the river or not tagged and subsequently ignored. Recaptured carcasses were ignored after the first recapture, so the number of recaptures represents unique carcasses. (Source: Killam, personal communication.)

Year	Tagged	Not tagged	Recaptured	Recapture rate
2003	2,884	687	1,896	0.66
2004	1,436	541	828	0.58
2005	3,476	1,787	2,318	0.67
2006	2,939	1,712	1,630	0.55
2007	811	251	565	0.70
2008	610	336	362	0.59
2009	760	362	283	0.37
2010	452	104	318	0.70

Supplementary Table SA.2.—Estimated number of unclipped adult female carcasses in the carcass survey area, $\hat{F}$, by year (Killam, personal communication) and bootstrapped estimates from this study. The sampled proportions represent the number of unique carcasses captured each year as a proportion of these estimates. Bootstrap statistics were calculated from a sample of 10,000 estimates. The CV represents the standard deviation of the bootstrap sample of estimates as a proportion of the mean bootstrap estimate. Three quantiles of the bootstrap sample of estimates are also presented, corresponding to the 2.5th, 50th, and 97.5th percentiles of the distribution.

			Bootstrap statistics				
Year	$\hat{F}$	Sampled proportion	Mean	CV	0.025	0.5	0.975
2003	4,903	0.73	4,946	0.01	4,822	4,942	5,092
2004	3,025	0.65	3,076	0.03	2,929	3,068	3,267
2005	7,205	0.73	7,235	0.01	7,073	7,234	7,409
2006	7,494	0.62	7,622	0.02	7,330	7,609	7,984
2007	1,383	0.77	1,422	0.05	1,323	1,410	1,589
2008	1,368	0.69	1,401	0.04	1,307	1,396	1,517
2009	2,399	0.47	2,517	0.07	2,238	2,499	2,914
2010	722	0.77	740	0.06	679	733	839

SUPPLEMENTAL REFERENCES

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