

U.S. Fish & Wildlife Service

Arcata Fisheries Technical Report TR 2014-20

Evaluation of Reductions in Sampling and Mark-Recapture Effort on the Bias and Precision of Juvenile Chinook Salmon Outmigrant Estimates on the Trinity River, California.

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July 2014



Funding for this study was provided by the Arcata Fish and Wildlife Office of the U. S. Fish and Wildlife Service at the request of the Trinity River Restoration Program.

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key words: Rotary Screw Trap, Mark-Recapture, Simulation, Chinook Salmon

The correct citation for this report is:

Som, NA and WD Pinnix. 2014. Evaluation of Reductions in Sampling and Mark-Recapture Effort on the Bias and Precision of Juvenile Chinook Salmon Outmigrant Estimates on the Trinity River, California. U.S. Fish and Wildlife Service. Arcata Fish and Wildlife Office, Arcata Fisheries Technical Report Number TR 2014-20, Arcata, California.

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Evaluation of Reductions in Sampling and Mark-Recapture Effort on the Bias and Precision of Juvenile Chinook Salmon Outmigrant Estimates on the Trinity River, California.

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Abstract. We evaluate the effects of reduced sampling and mark-recapture effort on abundance estimates generated from two rotary screw trap sites currently employed on the Trinity River, California. Under current protocols, the programs sample 7 days of most weeks, and implement mark-recapture experiments during the majority of the trapping season. We consider scenarios that reduce sampling to 5 days-per-week, and mark-recapture experiment reductions that halve the current effort, in either the middle portion of the season or every-other week of the trapping season. We first describe a simulator created to mimic the weekly abundance pattern of migrating juvenile Chinook Salmon (*Oncorhynchus tshawytscha*), and the weekly trapping efficiencies of the rotary screw traps. We then apply this simulator to generate rotary screw trap data sets under the considered effort scenarios that are then used to generate annual estimates of abundance. Compared to the currently employed effort, reductions in mark-recapture effort generally increase the bias and sampling variability of abundance and standard error estimates. Reductions in sampling effort increase the sampling variability of estimates, but in general lead to unbiased estimates of abundance. We employ these results to evaluate the consequences of increased sampling variability on the ability to detect population trends. We find relatively small differences in time to detect population trends between protocols sampling 5 or 7 days of each week. We conclude by evaluating the relative standard errors of the estimates under reduced sampling effort, and find they are sufficient for monitoring purposes.

Introduction

The Trinity River Restoration Program (TRRP, a table of all acronyms referenced within this report can be found in Appendix A) inquired about the statistical consequences of reduced effort in their rotary screw trap (RST) monitoring program. The RST program estimates the abundance, size, and timing of outmigrating juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) every year. The results are used to track population trends, and in particular, to potentially measure the effects of the restoration efforts conducted in upper 40 miles of the mainstem Trinity River, California. Outmigrant monitoring occurs at two sites on the mainstem Trinity River. The upper site at Pear Tree bar (PT) is at the downstream end of the restoration reach, and the lower site at Willow Creek (WC) is near the confluence of the Trinity and Klamath rivers. The PT monitoring site is primarily intended to estimate the abundance of juvenile Chinook Salmon and investigate population trend across years. The WC monitoring site is primarily operated to estimate emigration timing of juvenile Chinook Salmon, in relation to water temperature objectives, and to estimate the basin wide juvenile Chinook Salmon abundance.

In recent years, abundance estimates have been created by applying the Bayesian time-stratified Peterson analysis system (BTSPAS) that was developed for the TRRP (Bonner and Schwarz 2011). The BTSPAS uses Bayesian p-splines to smooth the temporal pattern in abundances among sampling strata (i.e., weeks), and has the advantage of correcting for poor or missing data. These abundance estimates also incorporate a mark-recapture component to expand the actual catch numbers by the estimated RST efficiency. Following the recommendations in North State Resources et al. (2008), RST efforts were substantially increased by incorporating a large-scale mark-recapture program that utilizes hatchery reared Chinook Salmon, and by increasing the sampling period of the PT trap. An additional recommendation of North State Resources et al. (2008) was to evaluate the precision of the abundance estimator and use these results to evaluate the impact of changing monitoring strategies and effort on the ability to detect changes in abundances. A similar recommendation had also been made by the TRRP's Science Advisory Board (SAB) in their evaluation of the draft Integrated Assessment Plan (Science Advisory Board 2006). The work presented in this report formally addresses these recommendations.

The RST monitoring efforts that this work aims to evaluate are the number of days per week that the RST is fished (i.e., trapping fish in a collection box for counting and measurement via field staff), and the number and arrangement of weeks per trapping year that mark-recapture experiments are conducted. Currently, the two TRRP RST sites generally collect fish in all seven days of each week, and continuously apply mark-recapture experiments for the majority of the monitoring season (with the exception of several weeks at the beginning and end of the season, depending on the RST location). A noted exception, is that effort is reduced to 5 days per week for the last two months of the WC site sampling season.

Simulation Methods

To evaluate the statistical implications of the various effort reductions, a function to simulate daily numbers of juveniles passing a RST was constructed. Though the overall structure of the simulator does not change with location, the simulator was parameterized separately for the PT and WC RST sites. The simulator requires the following inputs:

- **Abundance(s):** The true abundance of juveniles that pass by and into the simulated RST site. This can be more than one population (e.g., hatchery and natural).
- **Mean weekly discharge:** Weekly mean discharge values are needed for each week of the monitoring season.
- **Arrivals:** A weekly-stratified temporal distribution of the proportion, for each week, of the arriving population(s) to the RST site. Values summed across weeks must sum to 1. An arrival proportion distribution is required for each abundance that is provided.
- **Release schedule:** A vector of numbers, with length equal to the number of RST season weeks, representing the number of marked fish released each week. In this simulator, all marked fish are assumed to have been released on the first day of the week.
- **Discharge vs. trap efficiency parameters:** The intercept, slope, and random error from estimating the relationship between weekly discharge and trap efficiency. This simulator assumes a linear relationship between the logit of trap efficiency and discharge (see more detailed explanation below).
- **Daily recapture proportions:** A series of 6 proportions (that all sum to one) representing the proportion of a week's total of recaptured fish caught each day after release. The consequence and assumption here is that all recaptures occur within the week of release.
- **Adipose fin-clip (Ad-clip) rate:** If a population of hatchery fish is included in the simulation, this is used to turn a simulated, and combined, population of hatchery and naturally produced fish into a population of adipose fin-clipped and un-clipped fish.

Data and analyses for parameterizing the simulating function

Examples, and the tabular and figure evidence provided below, generally reflect the data from the PT RST. WC-specific data were used to parameterize the WC RST simulations, but because the methods were identical, we have omitted some of their presentation here.

Discharge vs. trap efficiency analysis

We used data collected between 2009 and 2012 to estimate the relationship between mean weekly discharge and weekly trap efficiency. For the analysis, the observed trap efficiencies were transformed via the logistic function ($\log(p/(1-p))$), where p is the trap efficiency). This transformation was useful for several reasons. First, it resulted in a linear relationship with discharge. Additionally, the logistic distribution guarantees that the simulated trap efficiencies remain in the proper parameter space of probabilities (strictly between 0 and 1 when back-transformed). A statistically significant relationship between discharge and trap efficiency was estimated, with an R-squared value of almost 50% (Figure 1). To prevent random trap efficiency draws from being too small (such as simulating that less than a single fish was recaptured), a minimum value of a single recaptured fish, or the lowest non-zero recapture rate recorded between 2009 and 2012 (0.002) was imposed.

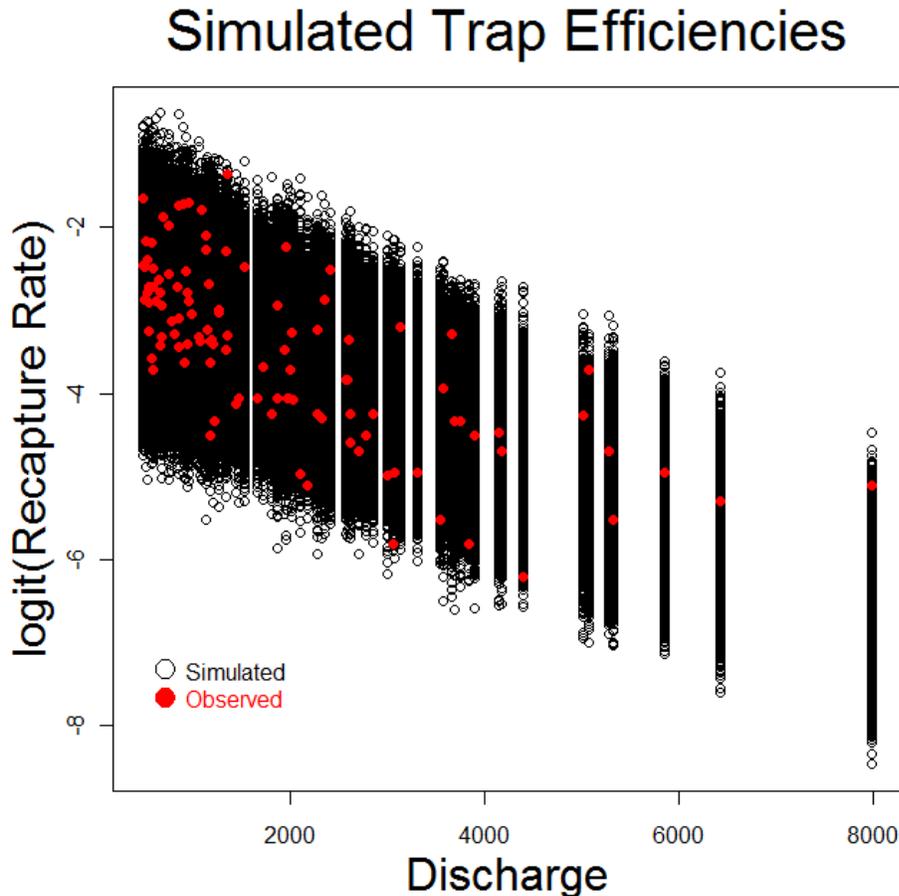


Figure 1. Estimated linear relationship between discharge and the logit of rotary screw trap efficiencies. Open black circles represent 10,000 simulated trap efficiencies based on the function estimated using the observed data (filled red circles) between 2009 and 2012 with data from the Pear Tree rotary screw trap site. The estimated slope parameter is -0.0005 (95% CI: -0.0006 to -0.0004).

Release schedule

To assign the numbers of marked fish released in each week, we used the actual 2012 pre-season release schedules (Table 1). Though in-season deviations from these schedules are common, the relative numbers of released fish amongst the weeks remains similar.

Table 1. An example of a release schedule for marked juvenile Chinook Salmon. This example is from the 2012 rotary screw trap season at the Pear Tree location, and was applied for the Pear Tree based simulations.

Week	Released	Week	Released
2	0	20	4000
3	0	21	4000
4	0	22	3000
5	0	23	2500
6	1000	24	2000
7	1500	25	2000
8	1500	26	2000
9	1500	27	2000
10	1500	28	2000
11	1500	29	1500
12	1500	30	1500
13	2000	31	1000
14	2000	32	1000
15	4000	33	500
16	4000	34	0
17	4000	35	0
18	4500	36	0
19	4000	37	0

Numbers of recapped fish per week

Each weekly number of recaptured fish was generated by drawing a binomial random variable with the randomly drawn trap efficiency value, and the numbers of marked fish released, as the parameters.

Distribute recaptured fish amongst days post-release

To parameterize the function that distributes recaptured fish among the days after release, we first gathered all the weekly data from 2009-2012 where a single day of release was employed. Next, over all weeks and years, we computed the average proportion of fish that were recaptured on each subsequent day of the week. For days 1 – 6 post release, those averages were: 0.8722, 0.0996, 0.0462, 0.0331, 0.0275, 0.0050, respectively. To ensure summation to 1 we employed the following multinomial probabilities of daily recapture post release: 0.8, 0.1, 0.045, 0.03, 0.02,

and 0.005. For each week, the number of fish recaptured on each of the post-release days was drawn from a multinomial distribution with these post release probabilities and the number of recaptured fish generated in the section above as parameters. It is important to note that our simulator assumes a diagonal recapture experiment (Schwarz et al. 2009), in which all recaptures are made in the same week as release. Though it is possible that fish are recaptured from previous week releases, the occurrence is rare for the two TRRP RST sites, and therefore previous analyses evaluating the TRRP RST programs have assumed a diagonal recapture experiment (Schwarz et al. 2009). We also note that while recaptures are only tabulated on days after release, we allow for fish to arrive at the RST on the day of release. Given the protocols employed at each RST site, released fish that happen to arrive on the day of release are held overnight in the holding tank and counted with those having arrived by the morning on the first post-release day.

Proportion of total population arriving every week

For each year, and for Ad-clipped and unclipped separately, we divided each week's total number of trapped fish by that annual total to estimate the proportion of that year's population arriving during each week. We then averaged across years to find each week's average proportion of trapped fish (Table 2), after making some very minor adjustments to force a summation to 1. Numbers of the population arriving in each week were selected by taking a set of multinomial random variables with the user-defined total abundance and these multinomial probabilities as parameters.

Numbers of arriving population trapped per week

We made the common assumption (also assumed by the Schwarz et al. 2009 abundance estimation method) that the RST catches marked and unmarked migrating fish at the same efficiency. This assumption also carries to the efficiency of catching natural and hatchery fish. The numbers of non-marked fish trapped per week were generated by drawing a binomial random variable with the number of total fish passing the RST site generated in the section above, and the randomly generated trap efficiency value for each week as parameters.

Table 2. Multinomial probabilities for simulating the proportion of the total abundance passing the Pear Tree rotary screw trap location in each week of the season.

Week	Hatchery	Natural	Week	Hatchery	Natural
2	0	0.0007	20	0	0.0147
3	0	0.0020	21	0	0.0107
4	0	0.0180	22	0.0400	0.0092
5	0	0.0297	23	0.1350	0.0300
6	0	0.0579	24	0.1200	0.0267
7	0	0.0503	25	0.0890	0.0250
8	0	0.0523	26	0.0600	0.0185
9	0	0.0748	27	0.0500	0.0148
10	0	0.0635	28	0.1200	0.0356
11	0	0.0676	29	0.1100	0.0319
12	0	0.0298	30	0.0880	0.0207
13	0	0.0140	31	0.0730	0.0137
14	0	0.0257	32	0.0630	0.0100
15	0	0.0505	33	0.0330	0.0055
16	0	0.0858	34	0.0170	0.0040
17	0	0.0892	35	0.0020	0.0008
18	0	0.0084	36	0	0.0001
19	0	0.0078	37	0	0.0001

Distribute a week’s worth of trapped fish to individual days in each week

We first drew and sorted 7 random variables from a uniform(0, 1) distribution. This partitioned the total weekly probability into bins with cut-off points. Next, we concatenated this vector with 1 and computed the lag-1 differences. Finally, we divided this vector by its sum to normalize the sum of all probabilities for each week to 1. Numbers of trapped fish were assigned to each day by randomly drawing from a multinomial distribution with the total weekly number of trapped fish assigned to that week and the probability vector created here as parameters. This method allows the potential for substantial variation in the numbers of trapped fish across the days within each week (Table 3).

Apply adipose fin-clips

When the hatchery population begins to arrive at each RST, a certain proportion of the hatchery fish are Ad-clipped. Given the user defined Ad-clip rate, on each day we drew a random value from a binomial distribution to assign Ad-clips to the daily arrival of hatchery fish. The index parameter of this binomial distribution is the

Table 3. Five examples of the assignment of a weekly total number of trapped fish to each day in the week. For all 5 simulations, 2,550 fish were to be caught by the RST.

Day	Sim1	Sim2	Sim3	Sim4	Sim5
Monday	106	67	251	31	125
Tuesday	474	519	751	411	444
Wednesday	237	294	59	85	496
Thursday	858	202	706	486	554
Friday	50	842	121	400	149
Saturday	33	252	374	930	382
Sunday	792	374	288	207	400
Total	2550	2550	2550	2550	2550

number of hatchery fish simulated to be arriving on that day, and the Ad-clip rate defines the other binomial parameter (the probability of being ad-clipped, given hatchery origin).

Unplanned unmonitored days

During the course of a RST season, it is not uncommon for weather or flow conditions to prevent RST operations. We accounted for these unmonitored days in our simulations by reducing the total number of monitored days, summed for each week, to match those during the 2012 RST season. We started with the number of unmonitored days for each week. We then selected the same number of missing days for each week of the simulation. To inject some randomness to the distribution of missing days in each week, we randomly assigned missed days in each week according to how many occurred in 2012. The assignment of missing days was done before the reductions of effort (described below). The 2012 RST season saw a larger amount of unmonitored days than usual (William Pinnix and Paul Petros, Pers. Comm.), and likely reflects a worst-case scenario in regards to the number of unplanned unmonitored days.

Historically, RST crews have had the flexibility to release marked fish later in the week should missed days occur at the beginning, or on a planned release day. To approximate this in our simulations, we did not allow release days to be missed, and allowed the missed days later in the week to shorten the period of time available for recapture.

Procedural flow of simulator

1. Mark-recapture experiment

1.1. Weekly trap-efficiency values

1.1.1. Using the user-defined “Mean Weekly Discharge” and the “Discharge vs. Trap Efficiency Parameters” data, draw the logit of trap efficiency values for each week. Use the anti-logit function to transform these values into probabilities between 0 and 1.

1.1.2. Ensure that simulated trap efficiencies are not less than the smallest observed value from 2009 – 2012 (0.002).

1.2. Number of recaptured fish for each week

1.2.1. Randomly draw a value for each week from a binomial distribution with the user-defined “Release Schedule” number of fish tagged and released, and the simulated trap efficiency values created in step 1.1 as parameters.

1.3. Distribute each weekly’s total number of recaptured fish among the 6 days post release.

1.3.1. Draw random values from a multinomial distribution with the number of recaptured fish from Step 1.2 and the user defined “Daily Recapture Probabilities” as parameters.

2. Population

2.1. Arrivals of fish per week

2.1.1. Randomly draw a sample from a multinomial distribution with user defined “Abundance” and proportions from the user-defined “Arrivals” dataset as parameters. This is computed separately for each population (e.g. natural and hatchery).

2.2. Trapped fish per week

2.2.1. Randomly draw values for each week from a binomial distribution using the number of arriving fish from Step 2.1 and the trap efficiency values from Step 1.1 as parameters. This is computed separately for each population (e.g. natural and hatchery).

2.3. Distribute a week’s total of trapped fish to days in that week

2.3.1. Begin with the number of trapped fish from Step 2.2

- 2.3.2. Draw seven uniform random variables between 0 and 1 to select bin cut-off values.
 - 2.3.3. Concatenate this vector with 1, and then take the lag-1 differences of the set of cut-off values.
 - 2.3.4. Divide the lagged differences by their sum to achieve a set of 7 multinomial probabilities.
 - 2.3.5. Draw random values from a multinomial distribution using the number of arriving fish from 2.2.1 and the multinomial probabilities from 2.3.4.
 - 2.3.6. This is computed independently for each population (e.g. natural and hatchery) within each week, though the same multinomial probabilities are employed.
- 2.4. Apply Ad- clips to fish when hatchery population begins to arrive at RST locations
- 2.4.1. Randomly assign Ad- clips to the trapped hatchery population by drawing values from a binomial distribution using the user defined " Adipose-fin clip rate" and the numbers of trapped fish from Step 2.3
- 2.5. Convert hatchery-origin and natural-origin populations into the two forms of juveniles entering the RST: those with adipose fins (all natural-origin and the majority of hatchery-origin fish) and those without adipose fins (a proportion of hatchery-origin fish).

Effort Reduction Scenarios and Analysis

We initially considered the following combinations of effort reductions according to RST sampling per week and mark-recapture experimentation during the season:

- 7 days of trapping with current mark-recapture schedule (28 weeks for PT, 24 weeks for WC).
- 7 days of trapping with half of current mark-recapture effort (14 weeks for PT, 12 weeks for WC)
 - Simulate M/R Every-other week
 - Simulate M/R during the middle weeks of trap season
- 5 days of trapping with same mark-recapture scenarios described above
 - Remove trapping and recapture effort from last two days of each week

For the 5 days of trapping scenario, on each of the 5 days trapped fish are counted, and marked fish are either released (1st day of the week) or tallied with the unmarked fish (2nd-5th days of the week). After initial results were provided to RST program agencies, an additional scenario for the PT RST site was requested for evaluation. For this scenario, the full sampling and mark-recapture efforts were applied for the first 28 weeks of the RST season. For the final 8 weeks, sampling effort was reduced to a plan similar to the 5 days effort described above. It differs from the above scenario in that only marked fish are released on day 1 of each week. On days 2 – 5 of each week, all trapped fish are counted and those fish bearing marks or Ad-clips are additionally tallied. There was no sampling or mark-recapture effort on the 6th and 7th days of each week. Weather and flow based missing days were applied to this scenario as in the above scenarios. We also note that the WC RST currently employs this reduced within-week schedule, and therefore we did not evaluate this scenario for the WC site.

To evaluate the effort reductions, we first simulated 1,000 complete (complete in the sense that arriving fish from the river and mark-recapture experiment were distributed to every day in the monitoring calendar) datasets for each RST location. The simulated abundances were 5,500,000 (5,000,000 naturally produced fish and 500,000 hatchery produced fish) at PT and 3,800,000 (3,400,000 naturally produced and 400,000 hatchery fish) at WC. These simulated abundances were selected based on the BTSPAS derived estimates of those populations from the data collected at each site in 2012. We then subset each simulated dataset by deleting data according to the prescribed effort reductions listed above. Finally, we summarized the data subsets by week and obtained abundance estimates via the BTSPAS. Given the Bayesian implementation, the whole-season abundance estimates were derived from the posterior distribution (for natural, hatchery, and total). For point estimates, we used the mean of each posterior distribution as our abundance estimate, and the standard deviation of each posterior distribution as our estimate of the standard error. We tracked the hatchery and natural abundance estimates, as well as their estimated standard errors, from each of the 1,000 simulations. The BTSPAS was applied as is currently done by TRRP partners, with one addition: we observed that reduced data sets showed poorer Markov chain Monte Carlo (MCMC) coverage of the posterior distribution parameter space and inadequate multiple MCMC chain mixing. To account for these differences, we increased the number of MCMC burn-in samples, the thinning rate, and the total number of MCMC samples for datasets generated from effort reductions. More information on how these aspects of the MCMC sampling effect goodness-of-fit can be found in Schwarz et al. (2009).

Methods for Presentation of Results

We present the results of this analysis in three ways, with each described more thoroughly below. First, we provide graphical and numeric summaries of the abundance and standard error estimates. We then present a power-type analysis, where we evaluate the efficiency of detecting abundance trends given several of the

effort scenarios. Finally, we compare the relative standard errors for each effort scenario.

For the abundance and standard error estimates, we display their distributions using violin plots, and other numerical summaries. A violin plot is a vertical mirror image of the kernel density plot (akin to what a smoothed histogram would look like) for a sample that gives slightly more information on distributional shape than a boxplot. The box and bar in the middle of the plot are standard boxplots, with the white circle representing the median of the distribution. The box is drawn to the quartiles, and the whiskers are drawn to the last datum within the median ± 1.5 times the interquartile range. These plots display the bias and sampling variation associated with estimates derived from the suite of effort scenarios. For presentation ease, we adopted a label abbreviation scheme, where the number (either 7 days per week, 5 days per week, or 7/5 for the scenario when the sample week was reduced to 5 days for the last two months of the season) on the left side of the colon references the number of days per week that RST sampling took place, and the adjacent letters (“Full”, “E/O”, or “MID”) represent full season mark-recapture effort, half-effort distributed every other week, or half-effort occurring in the middle of the RST season, respectively.

For the power-type analysis, we focused on estimates of the naturally produced populations passing each RST, and restricted the analysis to the 7, 5, and 7/5 days (at the PT site) of sampling per week scenarios, each with full mark-recapture effort. We assumed two levels of continuous population growth: 1.5% and 6.5% annual growth in the abundances. The 6.5% rate of increase was gleaned from an analysis conducted by William Pinnix (USFWS, pers. comm.) of WC abundance estimate data, though that analysis included data from years before and after the Record of Decision (U.S. Department of the Interior, 2000) flows, after which a noticeable population increase has been observed. The latter value of 1.5% represents a very modest population increase that may align with increases in habitat availability within the restoration reach of the Trinity River (Science Advisory Board 2014). Given the continuous rates of population growth, estimation error observed from our simulation experiment, and postulated process error in the natural cycle of annual juvenile productivity, we then calculated how many years it might take to detect a trend in the abundances according to the 7:Full, 5:Full, and 7/5:Full scenarios.

Generating baseline future abundance increases

For each RST location, we started with the natural stock abundances that we used for our effort reduction analyses, which were 5,000,000 juveniles for PT and 3,400,000 for WC. We then grew the abundances by annually adding either 1.5% or 6.5% growth, and continued this for 30 years.

Population process error

Even if the abundance of juveniles is increasing over a length of time, the annual abundances will not increase in a smooth continuous fashion. Instead, due to many factors that control abundances (hereafter: process error; which includes annual spawner abundance, egg survival, rearing survival, etc.) the abundance values will

ebb and flow over time. The process error would be realized in abundances even without increasing or decreasing trends.

To obtain estimates of process error, we began with the available BTSPAS-generated natural-origin abundance estimates from each RST location. We note here that there was one questionable abundance estimate from the PT site, both relative to other Pear Tree abundance estimates and also the general pattern among the abundance estimates between the two RST sites. For interested readers, we provide a brief description of how we dealt with this estimate for process error in Appendix B. There were six years of available estimates from the WC site, and five available estimates from the PT site. We fit a simple linear regression to de-trend the abundance estimates, independently for each RST site, and used the residual errors from each to approximate potential process error at each RST site. We acknowledge that these estimates include sampling error, and that the available data are limited, but we believe this the best option for an approximation to what process error might look like on the Trinity River.

We also acknowledge, if the population abundances truly are increasing over time, that the amount of process error could increase as well. These increases could lead to longer times for trends to be detected, but would most likely lead to decreases in the differences among effort scenarios at each location.

Generating future abundance values

For each RST location, we started with the baseline future abundance values generated above. For each of the 30 years and each RST site, we drew a normally distributed random variable with the baseline future abundance value as the mean, and each RST site's population process error value as the standard deviation. This created a 30 year time series of abundance values that increased according to the population growth rates, but ebbed and flowed in the trending direction with the process error for each RST site.

Bias and standard errors of future estimates

As described below for both RST locations, our results demonstrate that the abundance estimates are relatively unbiased for the 7 and 5 days per week sampling scenarios when coupled with full mark-recapture effort. As such, we assumed the estimators would remain unbiased moving forward. We calculated the standard deviation of the 1,000 natural-stock abundance estimates for each RST from the 7 and 5 days per week effort scenarios. Historic data from both locations reveals a positive association (estimated slope = 0.030, 95% CI: 0.001 – 0.006) between the annual abundance estimates and the estimated standard errors that accompany them (Figure 2), which is not surprising given the count nature of these data. We incorporated this relationship in our calculations by fitting a simple linear regression model to the estimated abundances and standard errors, and by imposing future standard error increases according to the population growth and the estimated parameters of this linear regression model.

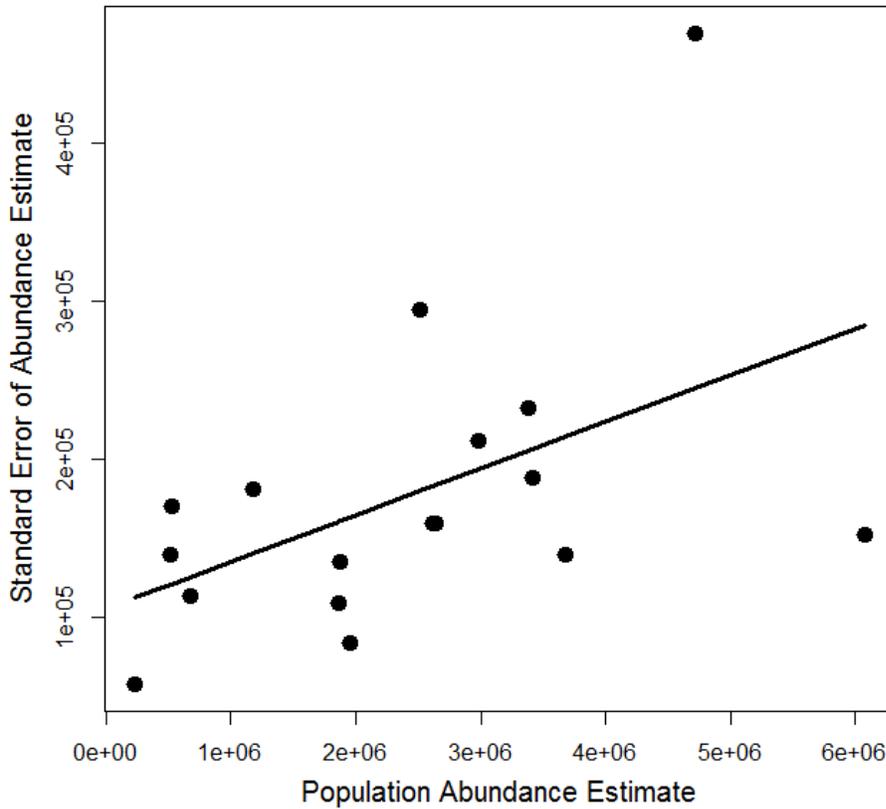


Figure 2. The standard errors (SE) of abundance estimates as a function of the population abundance estimate (A), for pooled data from Pear Tree and Willow Creek rotary screw trap sites. The solid line is the estimated simple linear regression line, $SE = 105,400 + 0.02955 * A + e$, $e \sim N(0, 84,400)$; the 95% confidence interval for the slope parameter is (0.01, 0.06).

Generating simulated estimates of abundance

To simulate what future estimates might look like under each of the population growth scenarios, for each year we drew a normally distributed random variable with the mean parameter set to the generated abundance in that year (i.e., we assumed unbiased estimation) and the standard deviation parameter set to the value calculated from the section directly above (i.e., adjusted for population growth).

Detecting trend

Given the sizes of the counts generated from the abundance estimates, and the non-linear population growth, a potential method for estimating trend in future years could be to log-transform the abundance estimates from each year, and fit a linear regression model with time as the explanatory variable (Shea and Mangel, 2001). The detection of a trend would amount to evaluating the statistical significance of the estimated coefficient for the time explanatory variable. We adopted a similar approach herein, and focused only on the ability to detect a positive population trend given the population growth rates we imposed. After generating the abundances for the subsequent 30 years, and turning these into simulated estimates of abundance, we applied the following procedure:

1. Take the first 3 years of the time series.
2. Fit a simple linear regression model with the log-transformed simulated abundance estimates as the response variable, and the numbers 1,2, and 3 as the explanatory variable.
3. Obtain the 95% confidence interval for the estimated trend coefficient (time), and find its lower bound.
4. If the lower bound of the 95% confidence interval was greater than zero, we declared that a trend had been detected.
5. Repeat Steps 1 – 4 using the first 4 years, the first 5 years, . . . , all 30 years.

We repeated this process 5,000 times for each combination of RST location and sampling effort. After 5,000 iterations, we calculated, for each year into the future, the percentage of the 5,000 iterations that a trend had been detected. We focus on differences among effort scenarios in regards to the time it takes to have an 80% chance of detecting a trend, a level commonly evaluated in power analyses (Murphy et al. 2011).

Prior inquiries to the TRRP RST program have suggested the program consider the relative standard errors ($rse = \text{estimated standard error} / \text{estimated abundance}$) of the abundance estimates, and cited 0.12 and below as appropriate *rse* values for informed management work (North State Resources et al. 2008). We explore the distribution of *rse* values via violin plots, and assess differences among the effort scenarios.

Results

Distribution of abundance estimates: Pear Tree RST

For the estimates of total and natural abundance (given the size of our simulated total population, the total estimate is driven predominantly by the natural population) at PT RST, the bias and variance of abundance estimates is more impacted by reductions in mark-recapture effort than the number of sampled days per week (Figures 3 - 4, Tables 4 - 5). Moving from the “7:Full” scenario to the “5:Full” results in a very minor increase in bias and a standard error roughly 1.5 times higher (Table 5). For both the 7-day and 5-day sampling scenarios, the every-other-week

mark recapture experiment leads to stronger increases in both bias and variance, and conducting mark-recapture experiments only during the middle of the season leads to severe increases in both the bias and variance of abundance estimates.

For estimates of hatchery abundance at PT RST, the effects in bias and variance due to changes in effort are different than for estimates of the total (and natural) abundances (Figure 5, Tables 4-5). The relative increases in variance are greater in moving from 7 days to 5 days of sampling. Reductions in mark-recapture effort lead to negative bias, and while they also lead to increases in the variance of estimates, they do so less drastically than for the natural estimates.

Distribution of abundance estimates: Willow Creek RST

All abundance estimates from the WC RST were more sensitive to the with-in week sampling effort than reductions in mark-recapture effort (Figures 6 – 8, Tables 4 – 5). Within-week reductions caused larger increases to the variance of estimates (around 2 times greater, Table 5) than mark-recapture reductions; however, the change to 5 days per week has little effect on the bias of estimates. All other effort reductions led to negative biases in estimates.

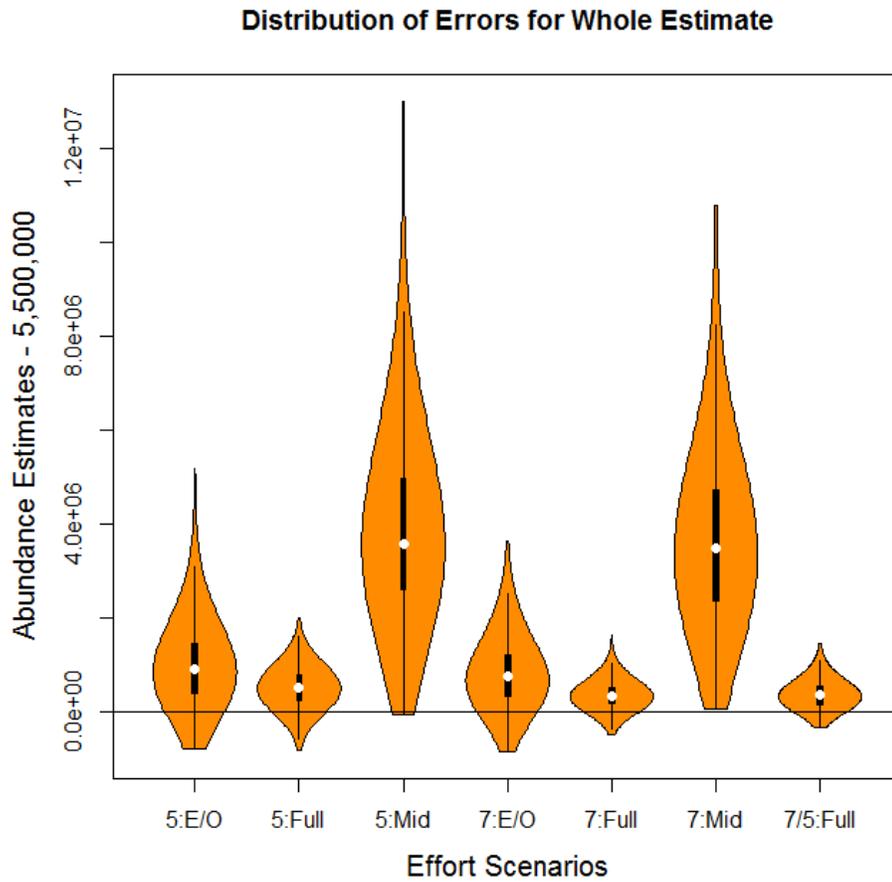


Figure 3. Distribution of errors (abundance estimates – 5,500,000) of total juvenile Chinook Salmon passing the Pear Tree rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations.

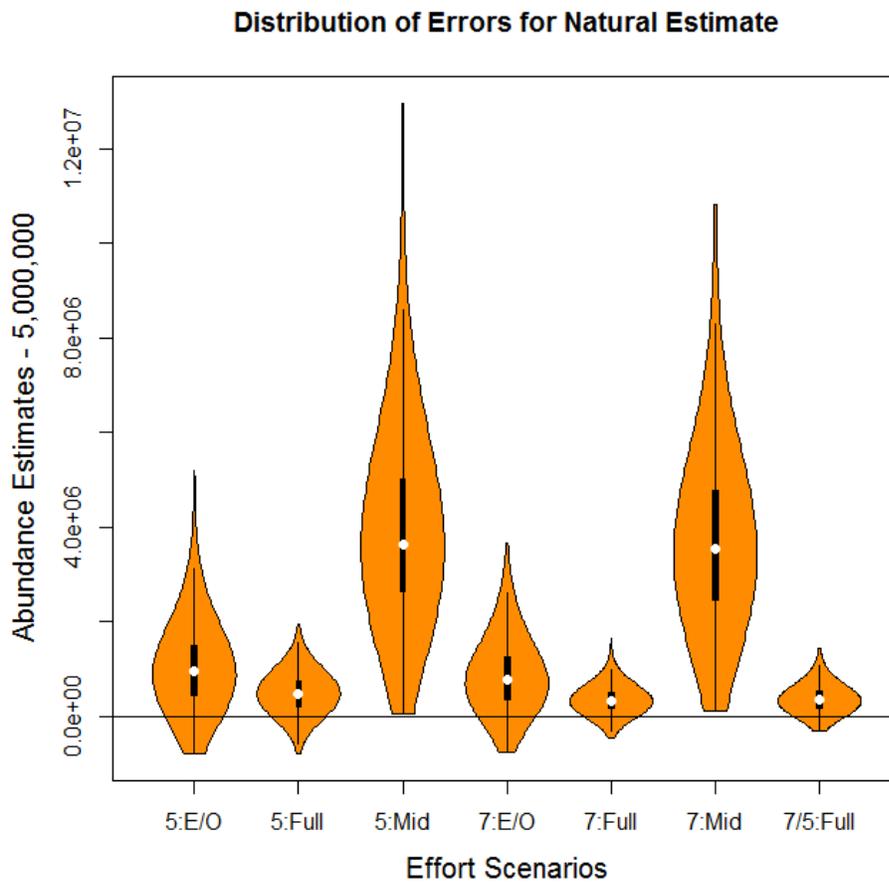


Figure 4. Distribution of errors (abundance estimates – 5,000,000) of natural juvenile Chinook Salmon passing the Pear Tree rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations.

Table 4. Ratios of abundance estimates to the true simulated abundances. For the abundance estimates, we took the average over 1,000 simulations for each effort scenario. For Pear Tree, the true simulated abundances were 5,500,000 (Whole), 5,000,000 (Natural), and 500,000 (Hatchery). For Willow Creek, the true simulated abundances were 3,800,000 (Whole), 3,400,000 (Natural), and 400,000 (Hatchery). In table headers, numbers on the left side of the colon reflect the number of days per week sampling occurred, and text on the right side of the colon reflect mark-recapture effort (Full: weekly as currently occurs, E/O: every other week, Middle: only during the middle of the season).

Pear Tree	7: Full	7: E/O	7: Middle	5: Full	5: E/O	5: Middle	7/5:Full
Whole Estimate	1.07	1.15	1.66	1.09	1.18	1.70	1.07
Natural Estimate	1.07	1.17	1.74	1.10	1.21	1.79	1.07
Hatchery Estimate	1.03	0.94	0.86	1.05	0.95	0.89	1.03
Willow Creek							
Whole Estimate	1.00	0.92	0.94	1.01	0.91	0.94	
Natural Estimate	1.00	0.92	0.94	1.00	0.91	0.94	
Hatchery Estimate	1.02	0.91	0.93	1.02	0.91	0.95	

Table 5. Ratios of reduced-effort standard errors of the abundance estimates to the reference scenario of 7 days-per-week sampling and full mark-recapture effort. Standard errors were computed by taking the standard deviation of the abundance estimates over the 1,000 simulations for each effort scenario. In table headers, numbers on the left side of the colon reflect the number of days per week sampling occurred, and text on the right side of the colon reflect mark-recapture effort (Full: weekly as currently occurs, E/O: every other week, Middle: only during the middle of the season).

Pear Tree	7: Full	7: E/O	7: Middle	5: Full	5: E/O	5: Middle	7/5:Full
Whole Estimate	1	2.69	6.36	1.46	3.09	6.52	1.04
Natural Estimate	1	2.77	6.57	1.47	3.19	6.75	1.05
Hatchery Estimate	1	1.22	1.54	1.65	1.69	1.90	1.30
Willow Creek							
Whole Estimate	1	1.44	1.52	1.88	2.08	2.06	
Natural Estimate	1	1.44	1.46	1.99	2.16	2.12	
Hatchery Estimate	1	1.41	1.77	2.32	2.51	2.61	

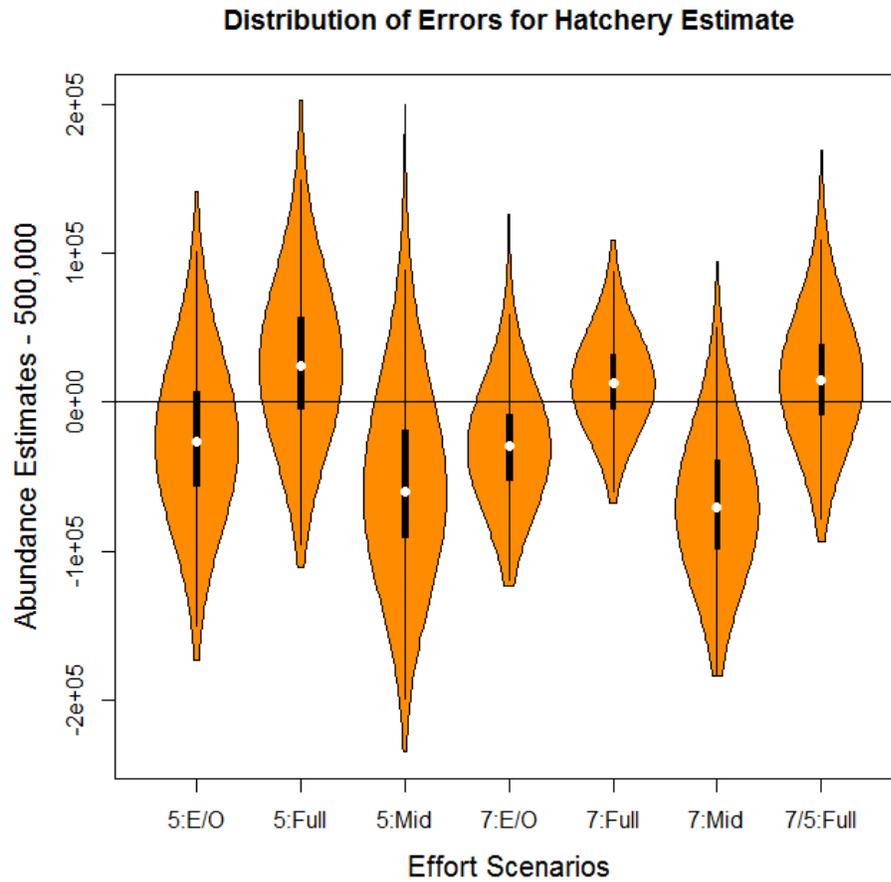


Figure 5. Distribution of errors (abundance estimates – 500,000) of hatchery juvenile Chinook Salmon passing the Pear Tree rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations.

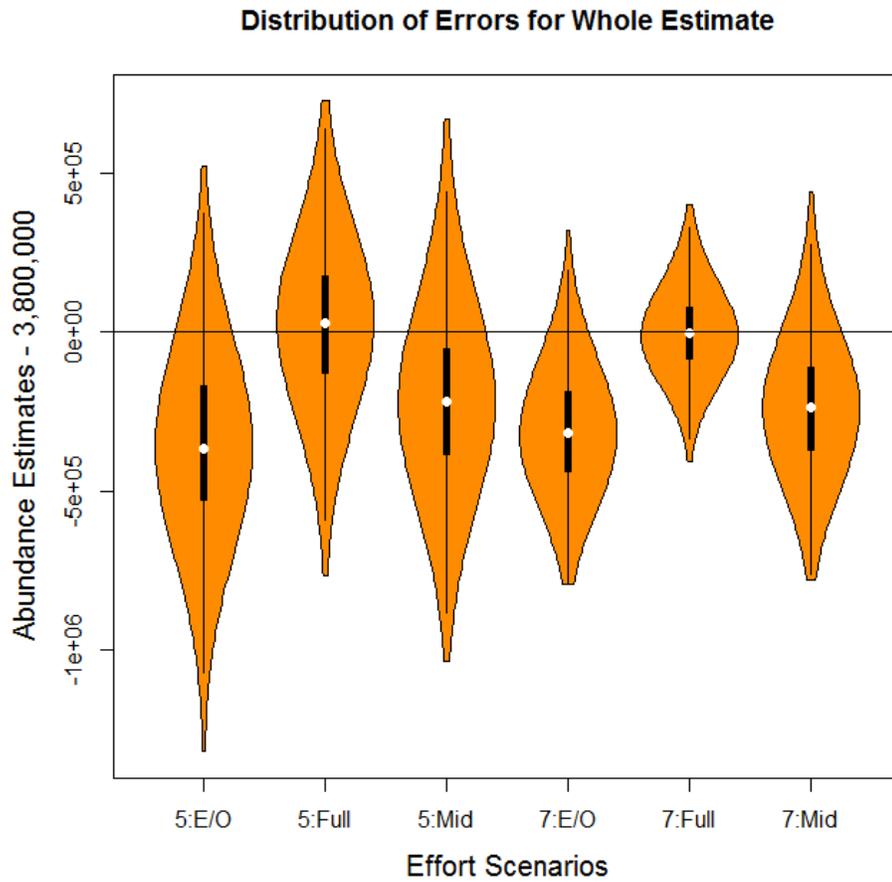


Figure 6. Distribution of errors (abundance estimates – 3,800,000) of total juvenile Chinook Salmon passing the Willow Creek rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations.

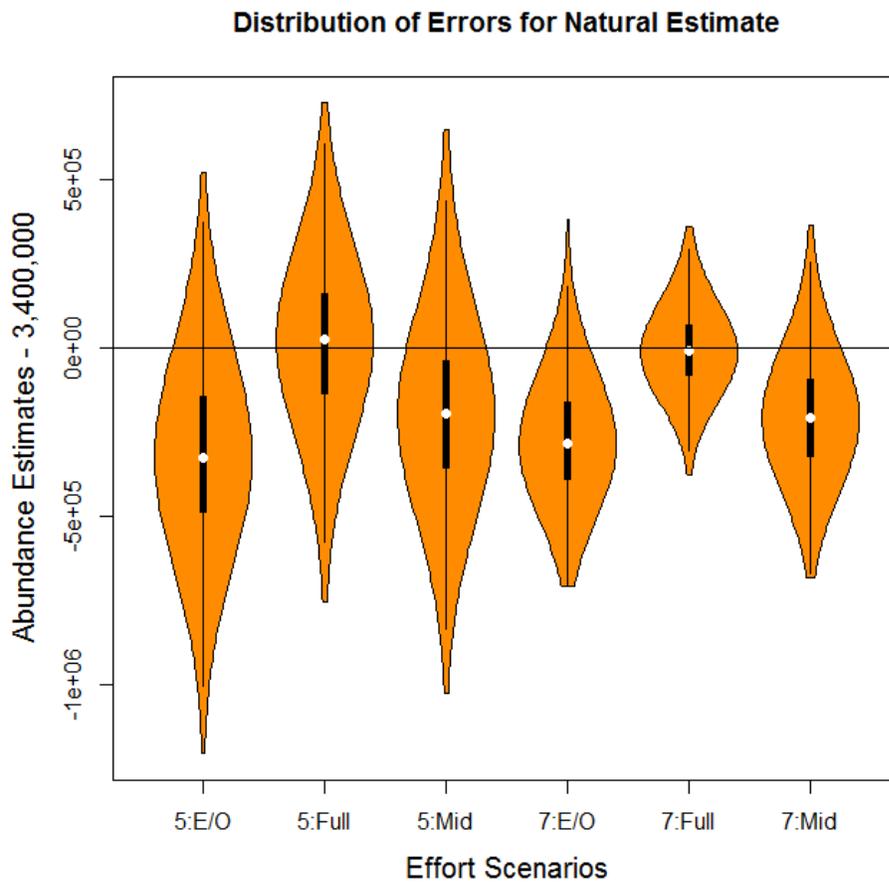


Figure 7. Distribution of errors (abundance estimates – 3,400,000) of natural juvenile Chinook Salmon passing the Willow Creek rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations.

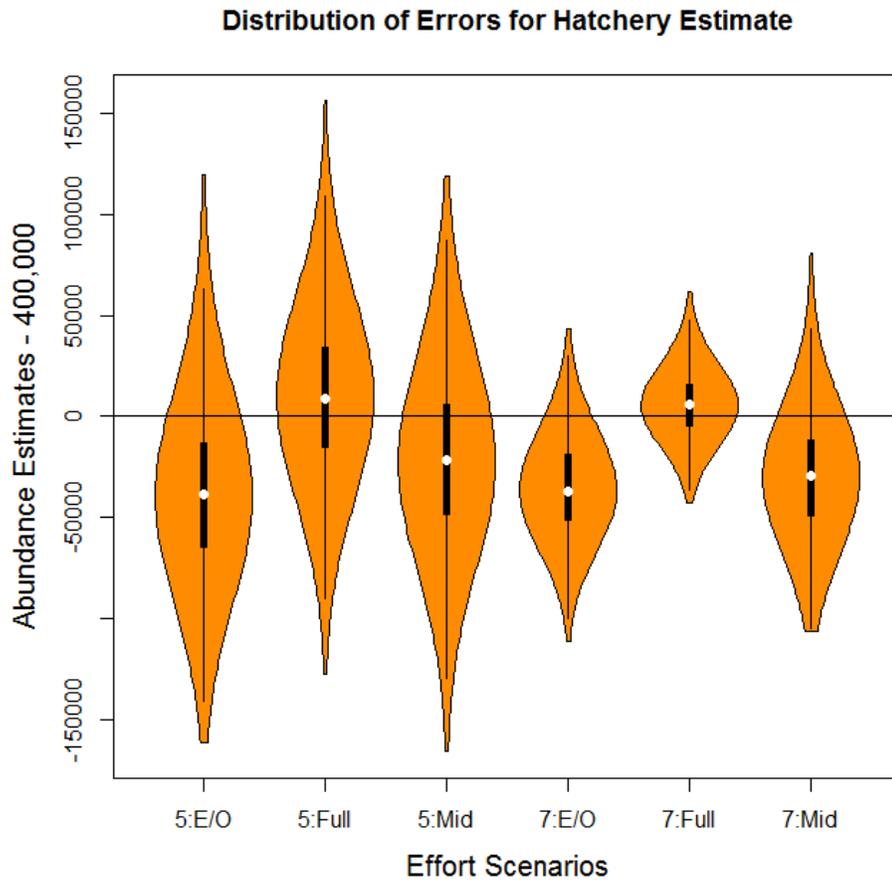


Figure 8. Distribution of errors (abundance estimates – 400,000) of hatchery juvenile Chinook Salmon passing the Willow Creek rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations.

Distribution of standard error estimates: Pear Tree RST

In addition to estimates of total abundance, the analysis software outputs estimates of the standard error of the abundance estimates. These are also statistics, and prone to sampling error.

For the total and natural abundance estimates at PT RST, bias and variance in the estimates are again more affected by mark-recapture reductions, with only modest changes induced by a reduction to 5 from 7 days per week sampling (Figures 9 –10), and all effort reduction leads to negative biases. For the standard error estimates of the hatchery abundance, variance is again substantially impacted by mark-recapture reductions, but even with the full mark-recapture effort, a reduction to 5 days leads to negative bias in the standard error estimates (Figure 11). With reduced mark-recapture effort, the estimates appear relatively unbiased, but the distribution of these estimates is too variable to counter any potential bias benefits. Also of note, is the negative bias in the standard error estimates given full sampling and mark-recapture effort, a phenomenon observed previously for these data (Schwarz et al. 2009).

Distribution of standard error estimates: Willow Creek RST

The distribution of standard error estimates from the WC RST were similar to those from PT. Reductions in mark-recapture effort lead to large increases in the variance of standard error estimates, and the reduction to 5 days of sampling per week for the entire season lead to negative biases for all mark-recapture scenarios (Figures 12 – 14), even when applying the current levels of mark-recapture effort.

Trend Detection: Pear Tree RST

Under the imposed scenario of a 6.5% continuous population increase at PT RST, it is projected that it would take less than 1 more year to detect a positive trend in abundance with sampling effort reduced to 5 days per week (Figure 15), and around 2 more years if the population continuously increases annually at 1.5% (Figure 16). For both rates of increase, any delays in trend detection under the scenario where sampling effort is reduced to 5 days per week in the latter 2 months of the season are generally imperceptible.

Trend Detection: Willow Creek RST

Under the imposed scenario of a 6.5% continuous population increase at WC RST, it is projected that it would take less than 1 year longer to detect a positive trend in abundance with 5 day-per-week sampling (Figure 17), and around 1 more year if the population continuously increases annually at 1.5% (Figure 18).

Distribution of rse values: Pear Tree RST

The balance of the rse values for all full mark-recapture effort scenarios at PT RST are well below the 0.12 threshold (Figures 19 – 21). The proportion of the rse values falling above the 0.12 threshold increases with decreased mark-recapture effort, and does so more substantially when effort is restricted to the middle of the RST season.

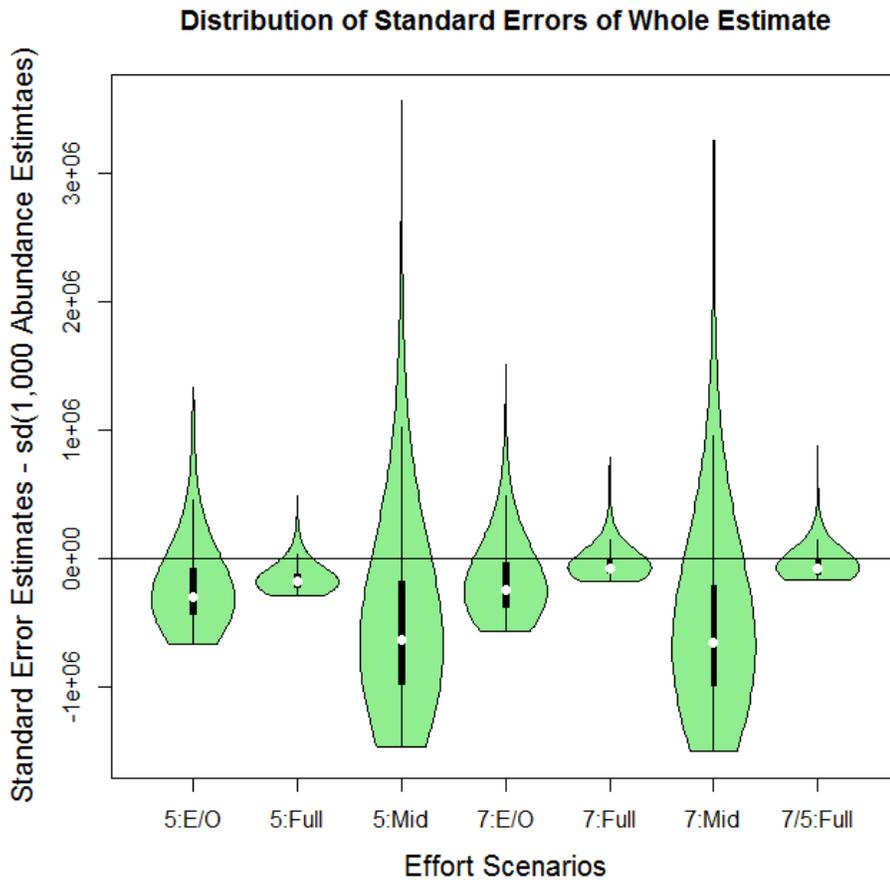


Figure 9. Distribution of standard error estimates (standard error estimates – standard deviation of 1,000 abundance estimates) for the whole population of juveniles passing the Pear Tree rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations.

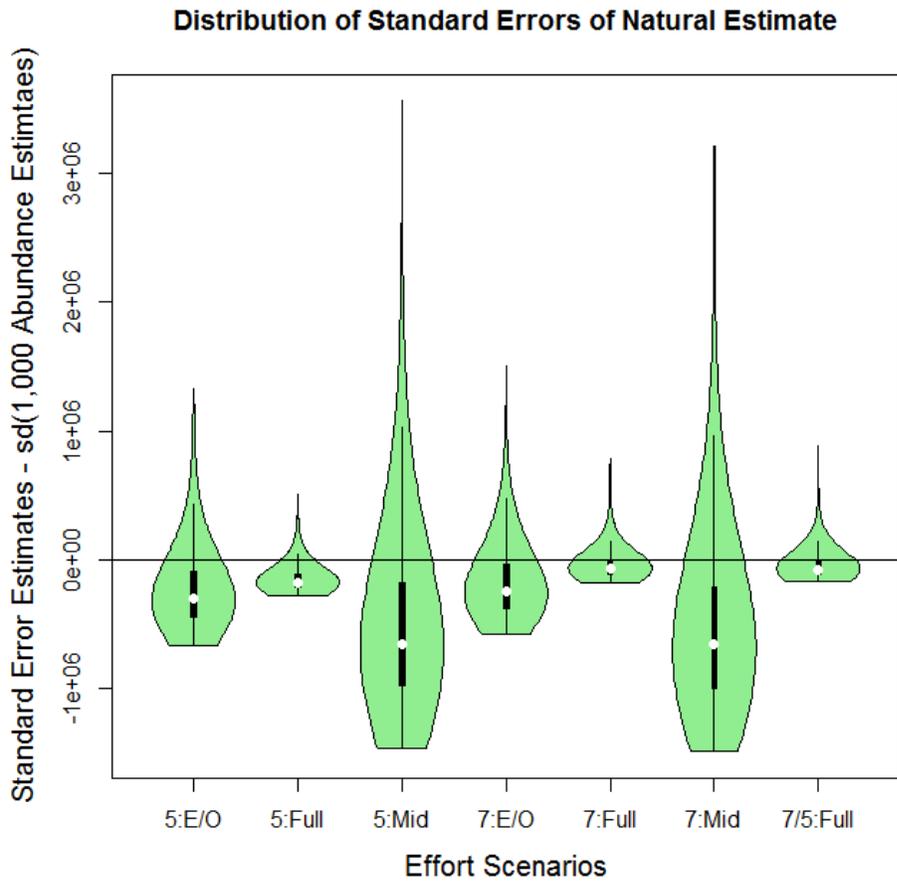


Figure 10. Distribution of standard error estimates (standard error estimates – standard deviation of 1,000 abundance estimates) for the natural population of juveniles passing the Pear Tree rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations.

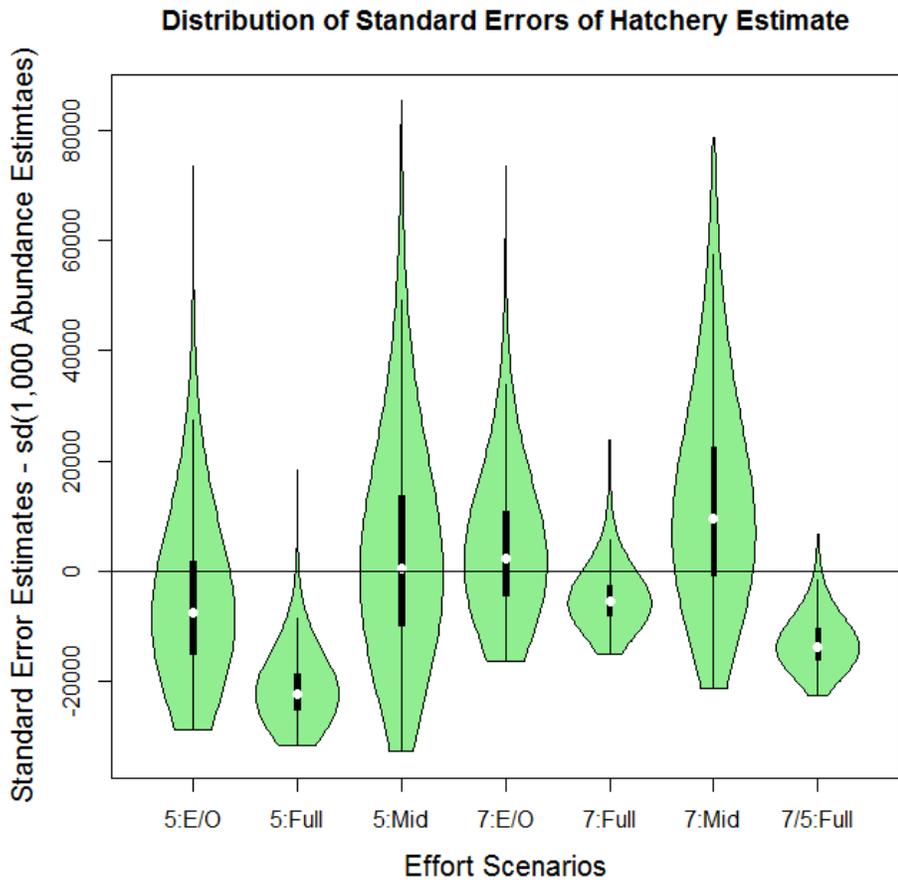


Figure 11. Distribution of standard error estimates (standard error estimates – standard deviation of 1,000 abundance estimates) for the hatchery population of juveniles passing the Pear Tree rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations.

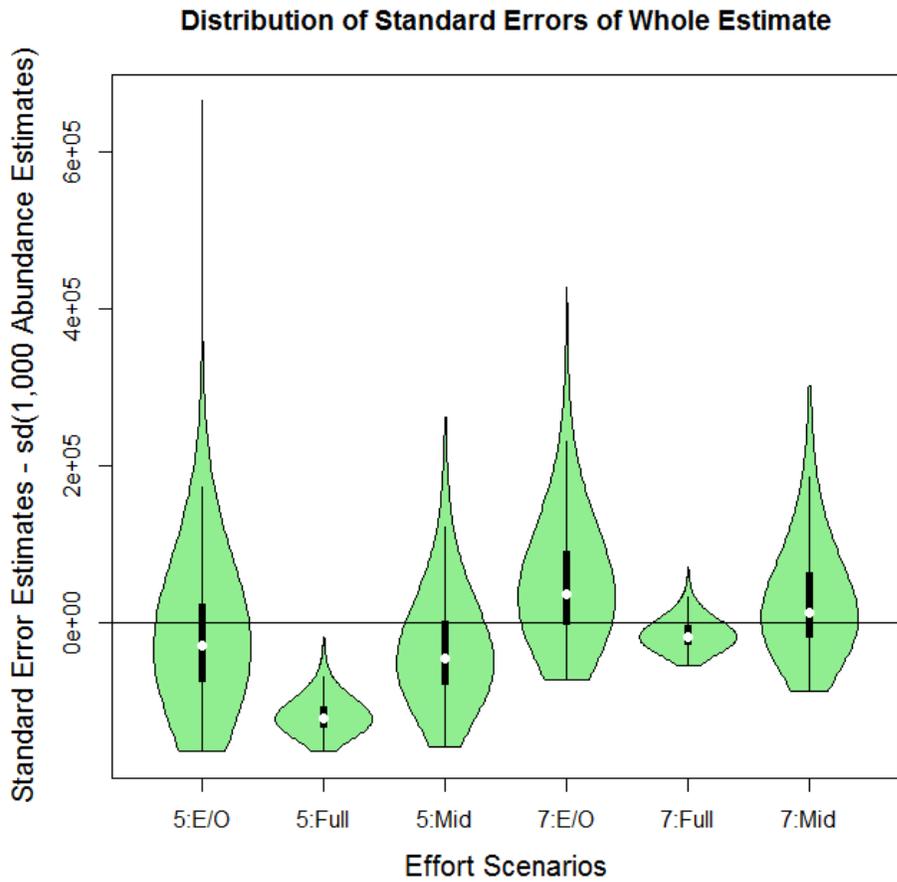


Figure 12. Distribution of standard error estimates (standard error estimates – standard deviation of 1,000 abundance estimates) for the whole population of juveniles passing the Willow Creek rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations.

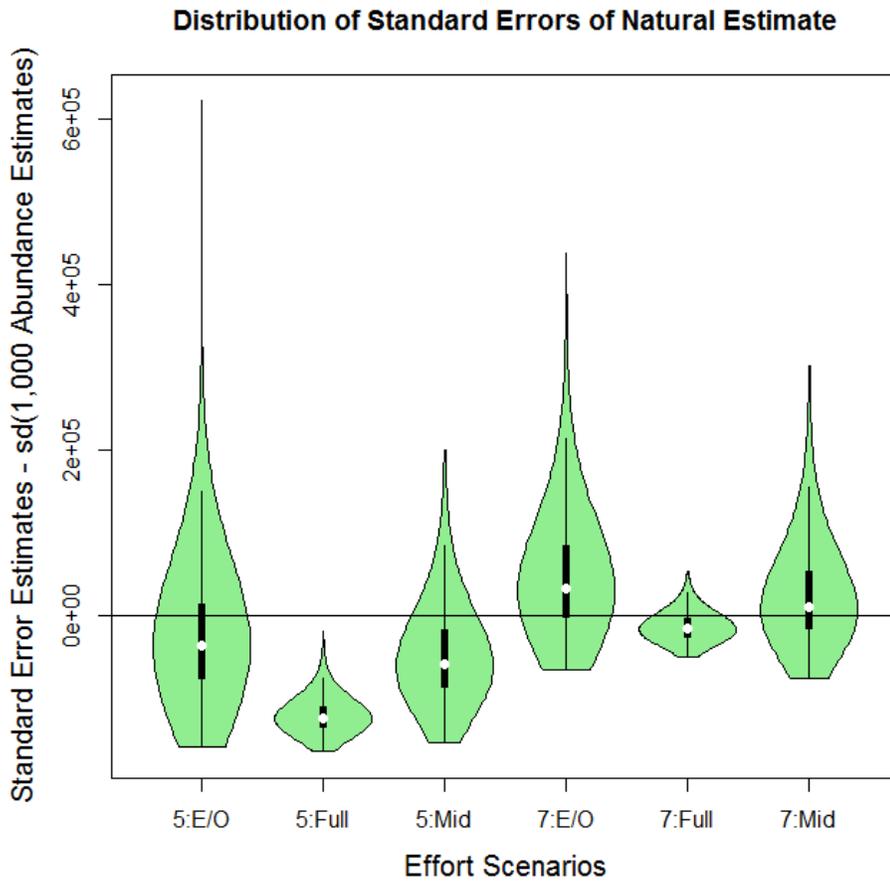


Figure 13. Distribution of standard error estimates (standard error estimates – standard deviation of 1,000 abundance estimates) for the natural population of juveniles passing the Willow Creek rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1000 simulations.

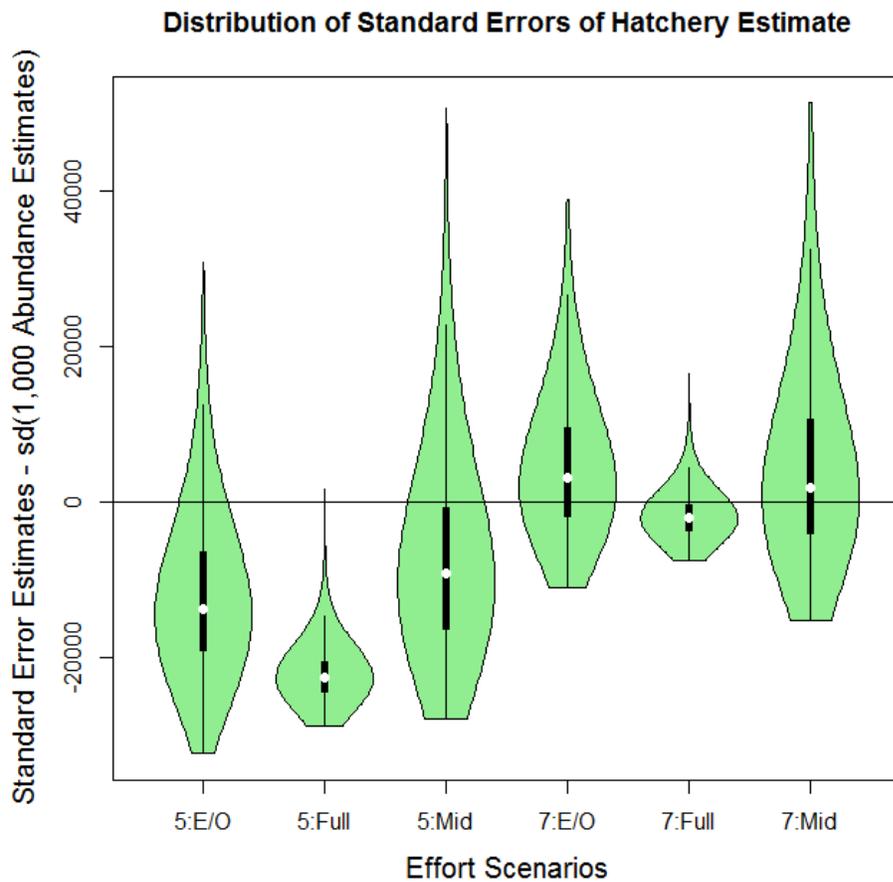


Figure 14. Distribution of standard error estimates (standard error estimates – standard deviation of 1,000 abundance estimates) for the hatchery population of juveniles passing the Willow Creek rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1000 simulations.

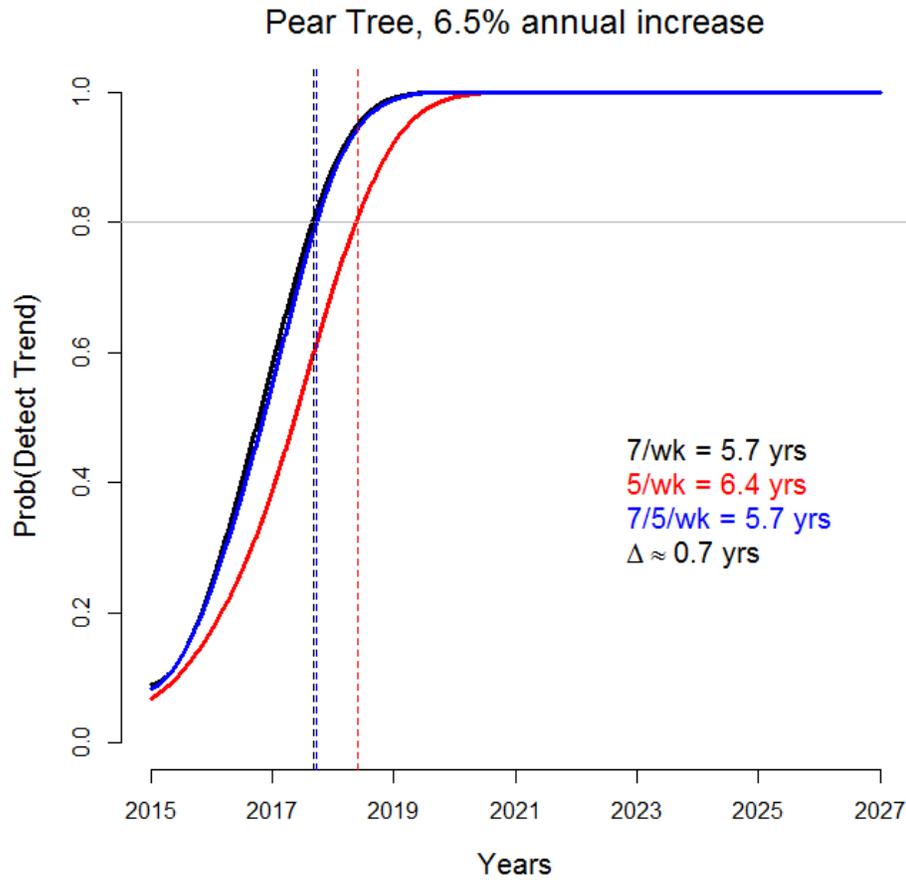


Figure 15. Probability of detecting a positive trend in abundance values with increasing number of years. Population abundances increased at 6.5% per year. The black line represents the Pear Tree site sampled 7 days-per-week, the red line represents a reduced sampling effort to 5 days-per-week, and the blue line represents reduced sampling effort in only the last two months of the season. All scenarios include full mark-recapture efforts. Dashed lines indicate the years at which each crosses the 80% threshold (Murphy et al. 2011).

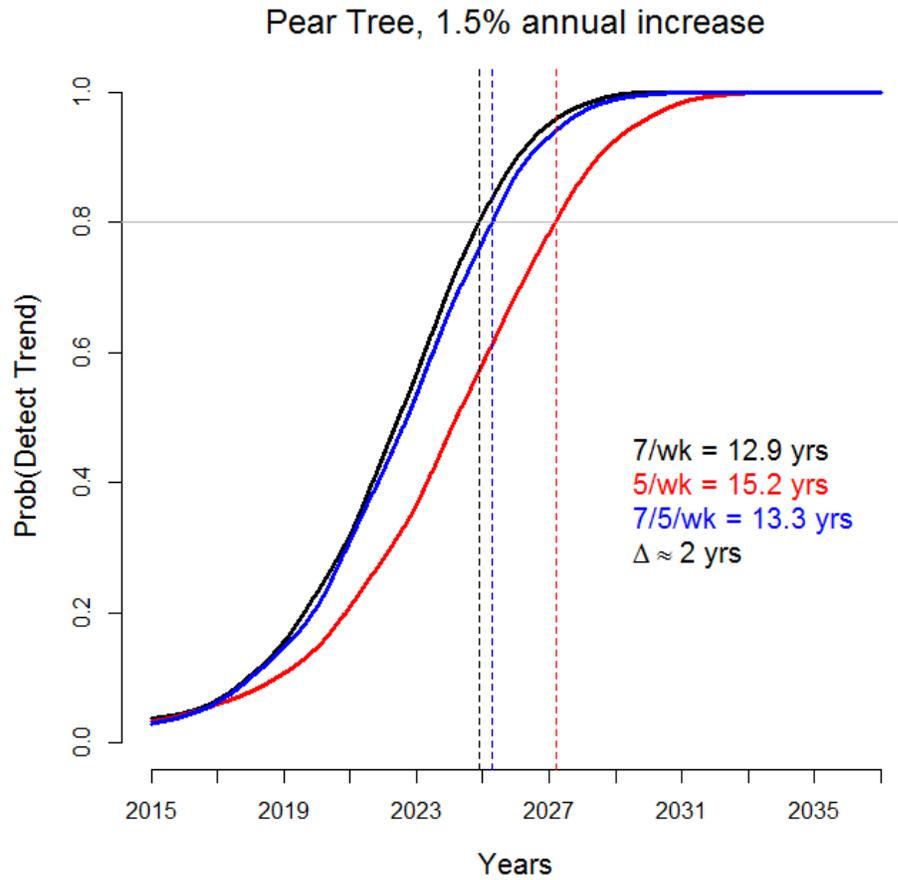


Figure 16. Probability of detecting a positive trend in abundance values with increasing number of years. Population abundances increased at 1.5% per year. The black line represents the Pear Tree site sampled 7 days-per-week, the red line represents a reduced sampling effort to 5 days-per-week, and the blue line represents reduced sampling effort in only the last two months of the season. All scenarios include full mark-recapture efforts. Dashed lines indicate the years at which each crosses the 80% threshold (Murphy et al. 2011).

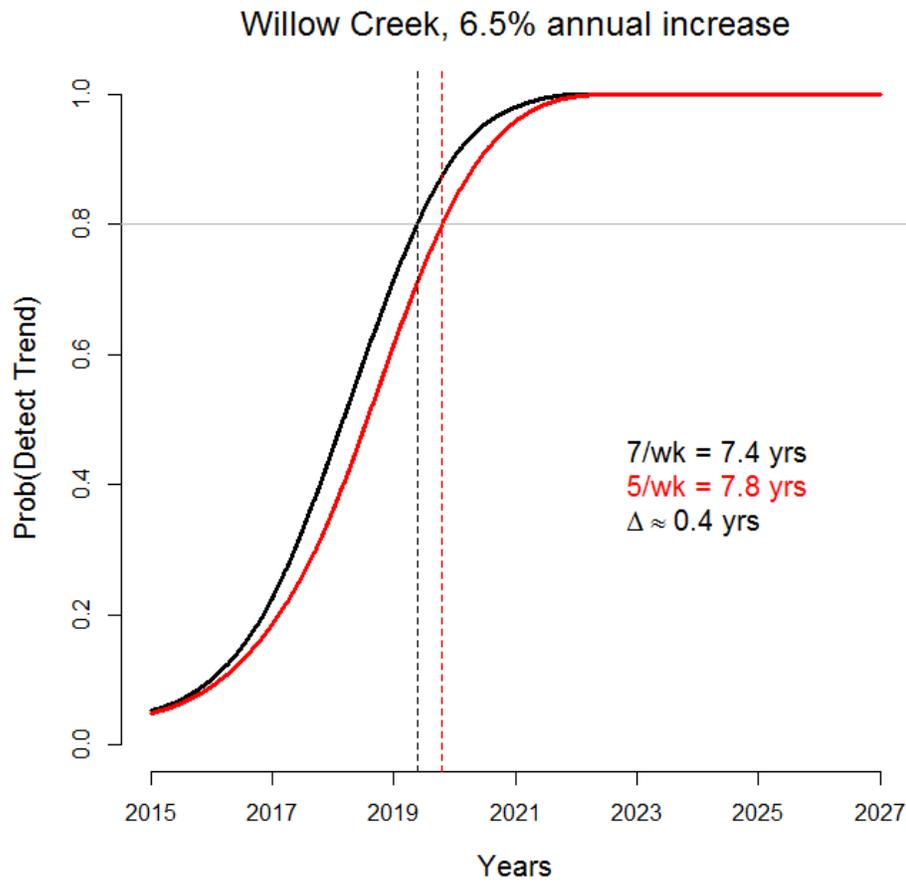


Figure 17. Probability of detecting a positive trend in abundance values with increasing number of years. Population abundances increased at 6.5% per year. The black line represents the Willow Creek site sampled 7 days-per-week, and the red line indicates a reduced sampling effort to 5 days-per-week. All scenarios include full mark-recapture efforts. Dashed lines indicate the years at which each crosses the 80% threshold (Murphy et al. 2011).

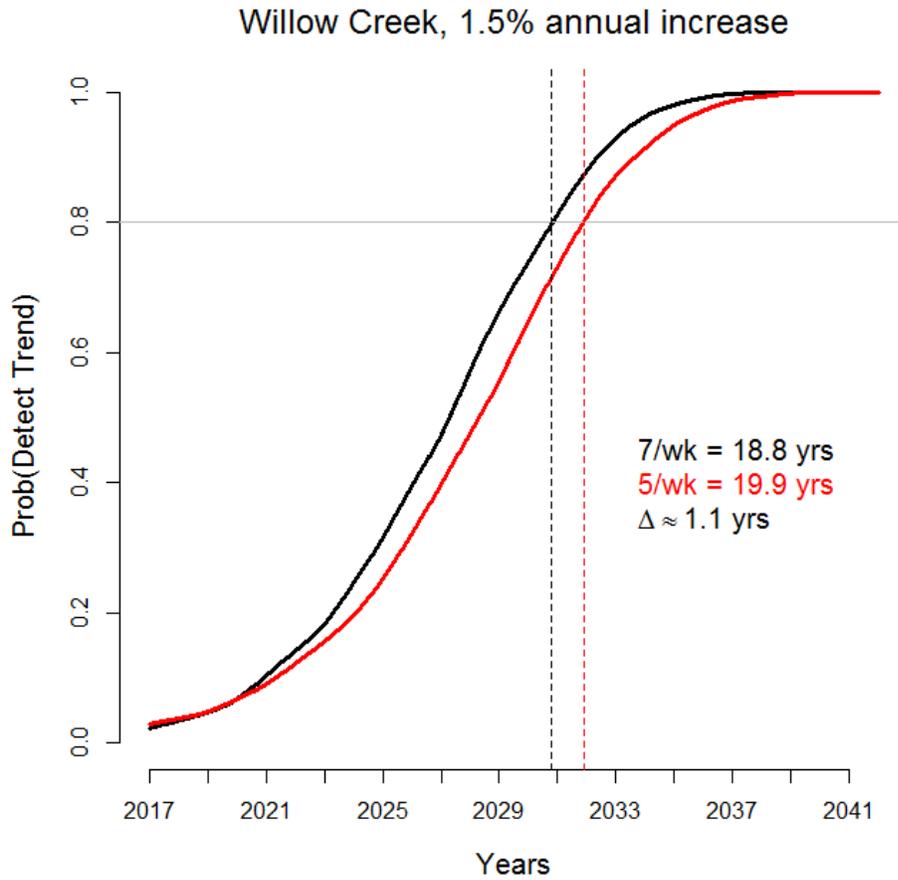


Figure 18. Probability of detecting a positive trend in abundance values with increasing number of years. Population abundances increased at 1.5% per year. The black line represents the Willow Creek site sampled 7 days-per-week, and the red line indicates a reduced sampling effort to 5 days-per-week. All scenarios include full mark-recapture efforts. Dashed lines indicate the years at which each crosses the 80% threshold (Murphy et al. 2011).

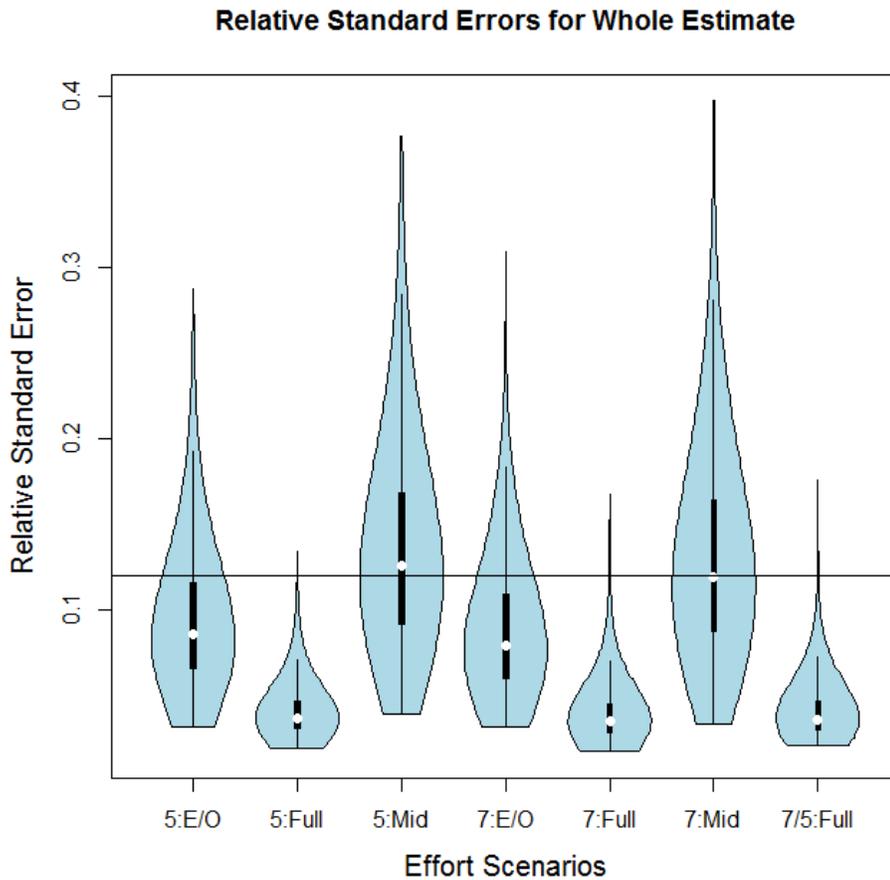


Figure 19. Distribution of relative standard errors ($rse = \text{estimated standard error} / \text{estimated abundance}$) for total juvenile Chinook Salmon passing the Pear Tree rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations. The horizontal line represents the 0.12 threshold of acceptable rse values (North State Resources et al. 2008).

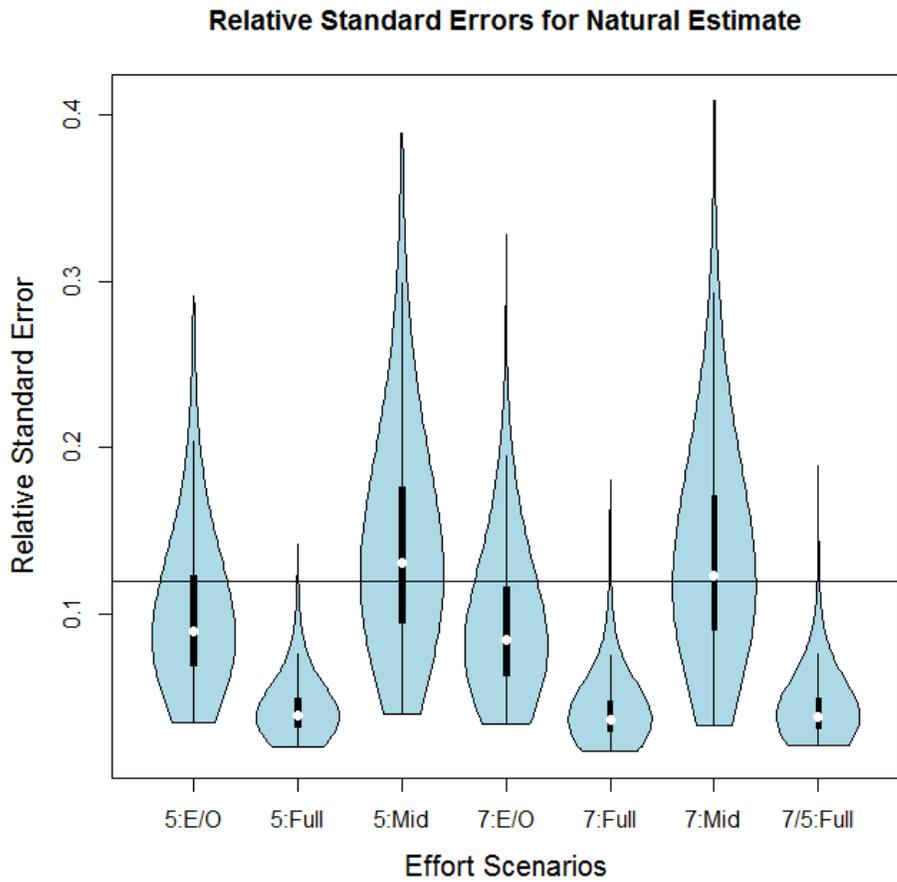


Figure 20. Distribution of relative standard errors ($rse = \text{estimated standard error} / \text{estimated abundance}$) for natural juvenile Chinook Salmon passing the Pear Tree rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations. The horizontal line represents the 0.12 threshold of acceptable rse values (North State Resources et al. 2008).

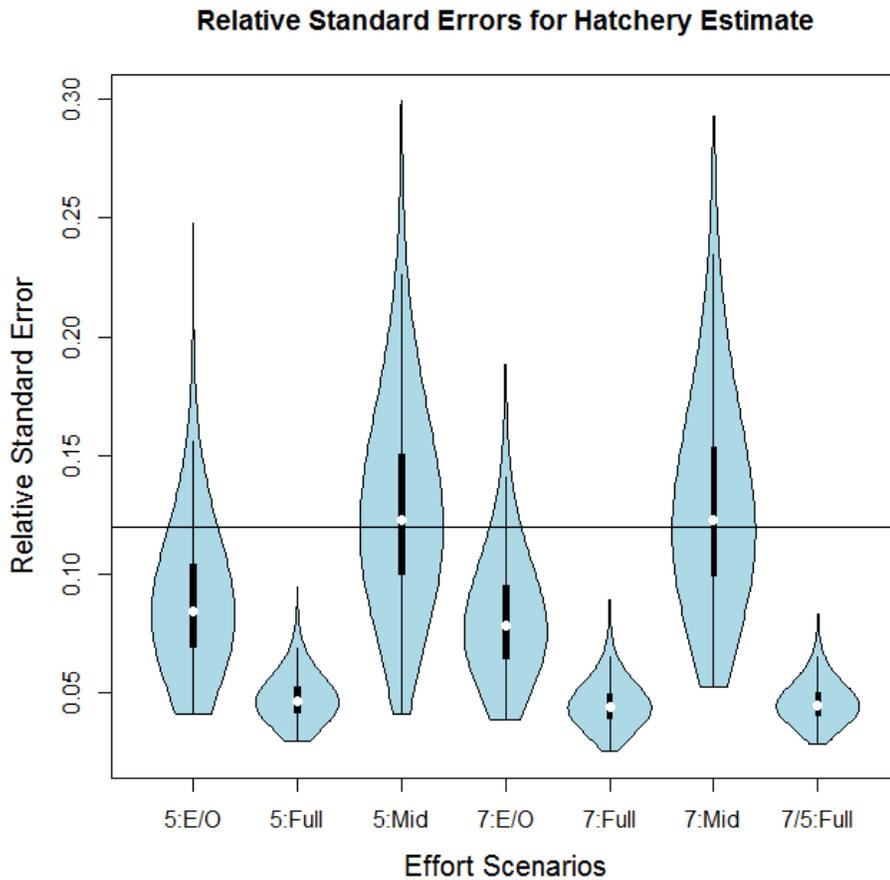


Figure 21. Distribution of relative standard errors ($rse = \text{estimated standard error} / \text{estimated abundance}$) for hatchery juvenile Chinook Salmon passing the Pear Tree rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations. The horizontal line represents the 0.12 threshold of acceptable rse values (North State Resources et al. 2008).

Distribution of rse values: Willow Creek RST

The majority of rse values for all effort scenarios at WC RST generally fall below the 0.12 threshold (Figures 22 – 24). The smallest, and most tightly distributed, rse values occur for the full mark-recapture scenarios. The size and variance of rse values increases with reductions to mark-recapture effort.

Discussion

Statistically speaking, any reduction in sampling effort will lead to increases in sampling induced variability. The direct consequences depend on the estimator(s) employed, and the sensitivity of the estimator to what effort is reduced, how much the effort is reduced, and when the effort is reduced. For a restoration program like the TRRP, decisions about allocation of future effort should balance the statistical and information costs of effort reduction with the monetary savings.

For the results of our exercise to be relevant to the TRRP, we first needed to simulate the population of migrating juvenile Chinook Salmon. The simulation methods employed were provided to the TRRP partners involved in the RST project before the analysis began. After their review, and approval following several suggested methodological changes, we commenced with the analyses. Though it is impossible to capture every nuance in a simulator, we believe that we captured, modeled, and effectively parameterized the aspects of the migrating population(s) that would reflect sensitivity to effort reductions in the RST programs.

More sophisticated methods for trend detection could certainly be employed, particularly those that incorporate the posterior distributions of the annual abundance estimates. Our aim for the power-type analysis was to look at the relative temporal costs in trend detection associated with reduced sampling effort applied over the course of many years. In this exercise we were less concerned with how precise our estimate of the actual amount of trend was, and instead focused on if a trend was detected, given the population was indeed increasing. Our method allowed us to incorporate the sampling distributions from our simulations, instead of computing estimates from larger simulated abundances, which drastically reduced the computational burden.

In all situations mark-recapture reductions caused bias and lead to increases in the standard errors of the abundance estimates. The standard error increases are not surprising, given that estimation variance will increase as the number of returned marks decreases. For reductions in number of days per week sampled, relative to the 7 days-per-week scenarios, a reduction to 5 days lead to standard errors that were 1.5-2 times higher, which can lead to increased amounts of time to detect trends in the abundances, if those populations are increasing.

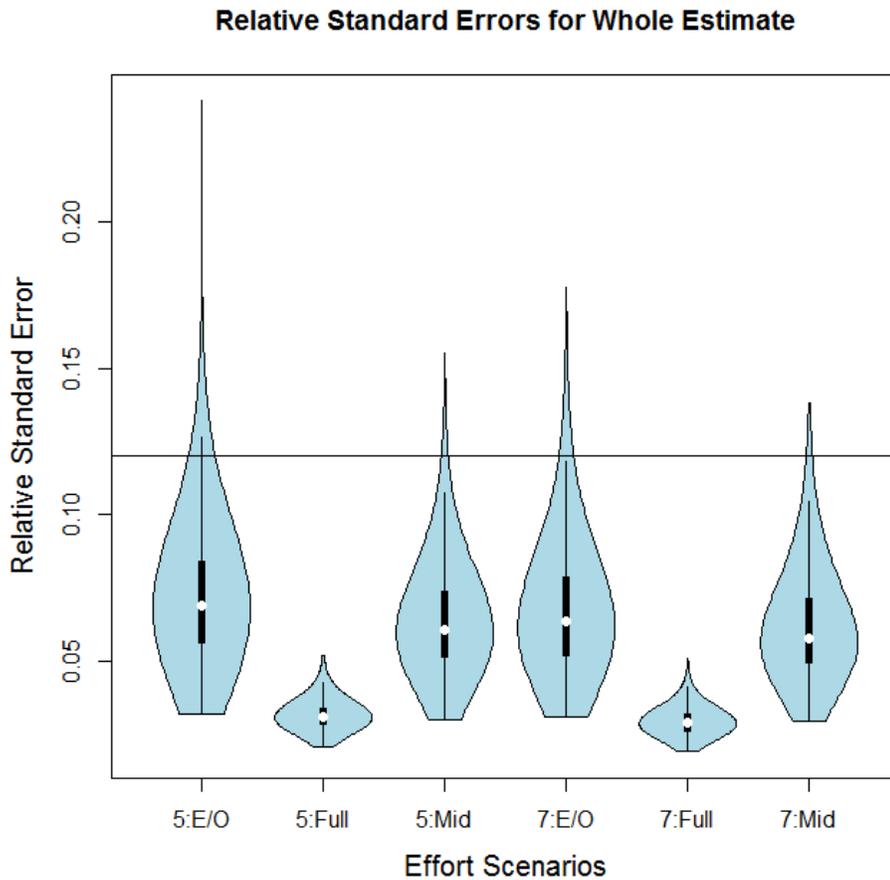


Figure 22. Distribution of relative standard errors ($rse = \text{estimated standard error} / \text{estimated abundance}$) for total juvenile Chinook Salmon passing the Willow Creek rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations. The horizontal line represents the 0.12 threshold of acceptable rse values (North State Resources et al. 2008).

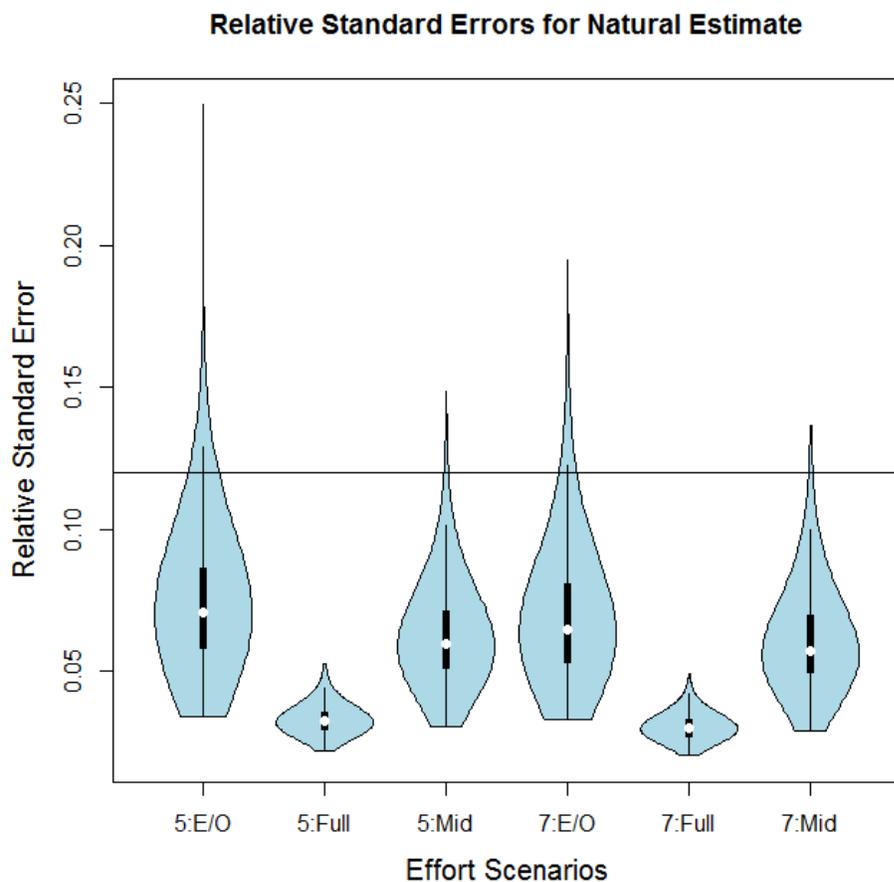


Figure 23. Distribution of relative standard errors ($rse = \text{estimated standard error} / \text{estimated abundance}$) for natural juvenile Chinook Salmon passing the Willow Creek rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations. The horizontal line represents the 0.12 threshold of acceptable rse values (North State Resources et al. 2008).

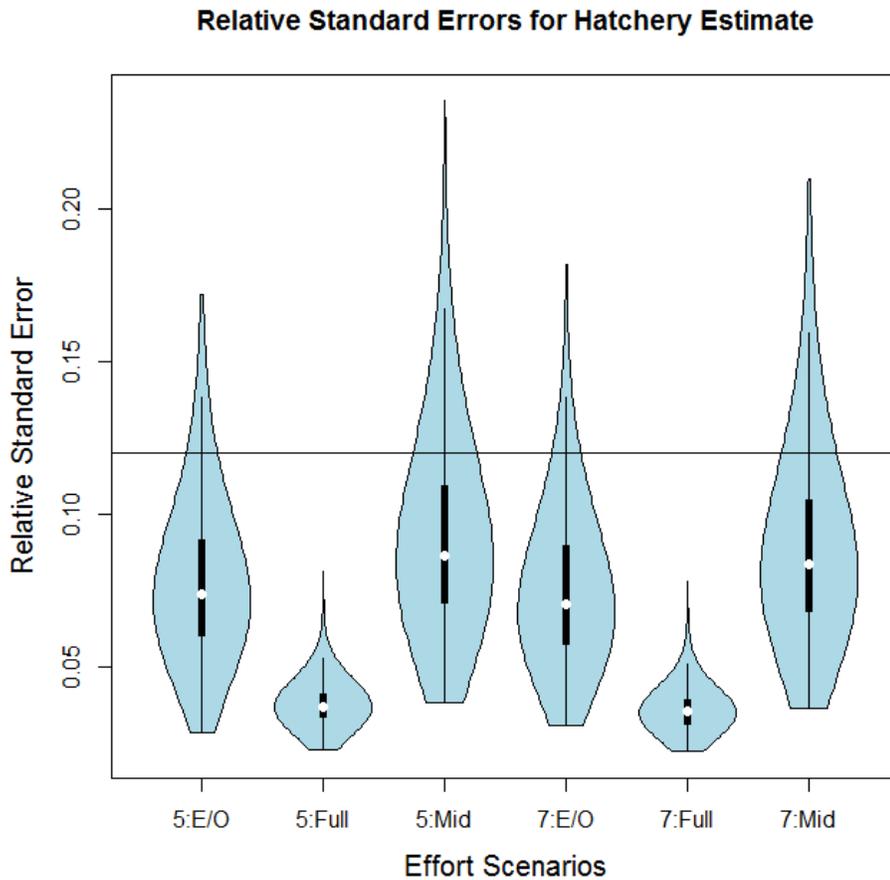


Figure 24. Distribution of relative standard errors ($rse = \text{estimated standard error} / \text{estimated abundance}$) for hatchery juvenile Chinook Salmon passing the Willow Creek rotary screw-trap site by within-week sampling effort and with-in season mark-recapture effort based on 1,000 simulations. The horizontal line represents the 0.12 threshold of acceptable rse values (North State Resources et al. 2008).

In addition to the planned effort reductions in our scenarios (5 days vs. 7 days), we also implemented unplanned missed sampling days. These unplanned days also contributed to the increased sampling variation of the abundance estimate, per our method of implementation. By random selecting missed days in each simulation, we allowed unplanned missed days to range from right after release days to days at the end of each sampling week. This changed the amount of returned marks among the simulations, and contributed to the increased sampling variability observed in the 5 days per week scenarios. This bolsters our decision to consider a hydrologic year with relatively high numbers of unplanned missed days, and suggests that years with fewer unplanned missed days could expect less sampling variation than we observed in our 5 days per week scenarios.

In general, for the WC simulations, and for hatchery estimates at the PT site, a reduction to 5 days-per-week sampling, even with full mark-recapture effort, led to negative biases in the estimates of the standard errors. If uncorrected for bias, this has the potential to complicate future recalibration of a fish production model by leading to abundance confidence intervals that are too narrow. The consequence here is a well calibrated model could appear to be performing less precise than it actually is in regards to assessing the survival of natural and hatchery fish. These potential negative consequences are buoyed by the fact that the abundance estimates remain relatively unbiased under the reduced effort to 5 days-per-week, the need to recalibrate a fish production model seems unlikely, and future research could rectify the negative bias of the estimator under reduced effort.

For the PT RST, reducing effort to 5 days-per-week in the latter 2 months of the season had very minor effects on the distribution of abundance estimates, and the only consequence of note is slightly more variant estimates of hatchery abundance. It appears this effort reduction bears no real consequence to detecting trends in the natural population of juveniles. This is most likely due to the fact that the effort reduction occurs when most of the natural population has emigrated downstream of the PT RST. For the whole-season reduction to 5 days, abundance estimates remained unbiased, but the variance of their sampling distribution did increase. Though this variance increase was not nearly as great as that imposed by reductions to the mark-recapture effort, it could result in delays in detecting a population trend, though our analysis above shows these delays may not be substantial.

For the both the PT and WC RST locations, with full mark-recapture effort, rse values appear to be well below the 0.12 threshold. We do note, that for the whole season 5 days-per-week sampling, we reported the potential for standard error estimates to be negatively biased, which would result in artificially small rse calculations. We also note, however, that even a doubling of rse values for the 5:Full effort scenario would result in values near or below the threshold. It appears that all full mark-recapture effort scenarios have rse values consistent with the recommendations of North State Resources et al. (2008).

Acknowledgements

The authors would like to thank our tribal partners for convening to discuss the effort reduction scenarios considered in this report. Further, we thank Paul Petros (Hoopa Tribal Fisheries) and Anthony Heacock (Yurok Tribal Fisheries) for gathering and organizing the data that was used to parameterize the simulating functions.

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Appendices

Appendix A. List of all acronyms referenced within the report. ·

Acronym	Definition
AD	Adipose Fin Clip
BTSPAS	Bayesian Time Stratified Peterson Analysis System
E/O	Every Other (referring to mark recapture schedule)
MCMC	Monte Carlo Markov Chain
M/R	Mark Recapture
NSR	North State Resources
PT	Pear Tree Bar
ROD	Record of Decision
RSE	Relative Standard Error
RST	Rotary Screw Trap
SAB	Science Advisory Board of the Trinity River Restoration Program
SE	Standard Error
TRRP	Trinity River Restoration Program
WC	Willow Creek

Appendix B. Notes on process error calculations. ·

There was one annual abundance estimate from the PT RST that appeared to not match other PT estimates or the general pattern among the estimates between the PT and WC sites. For the WC site the estimates for 2008 - 2013 are: 2,644,527; 2,987,837; 3,414,795; 3,047,673; 3,512,974; 4,828,842, respectively. At the PT sites the estimates for 2009 - 2013 are: 1,740,438; 1,525,536; 1,922,326; 4,987,106; 2,480,622, respectively. The estimate in question is that from 2012 at the PT site. The WC site is 84 river km downstream of the PT site, and integrates the production of the entire basin upstream of that RST. Across years where BTSPAS-generated estimates are available from both sites, the WC estimates are generally 1.6 - 2.2 times larger than those from PT. In 2012, the WC estimate is around 0.7 times the size of the PT estimate. Further, the PT estimate in 2012 is over two times larger than any other estimate from the PT site. Particularly given the small amount of data available, we considered this estimate large enough to warrant exclusion from the process error generation exercise. Instead, we imputed the 2012 PT value by fitting a linear regression between the abundance estimates from WC and PT (excluding 2012) and predicting the 2012 PT value according to that linear relationship. The imputed value is 1,894,964, and this leads to a process error value of 231,200.

We did conduct the same time to detect a trend exercise including the original value for the PT site in 2012. Including this value leads to a 6-fold increase in the process standard error, which becomes 1,366,000. In regards to this impact on times-to-trend detection, it increased the time until trends are detected, but given the total variance has a much larger component attributed to process error (compared to sampling error) the differences among the full mark-recapture effort scenarios are essentially zero. Under the 6.5% population increase, the times at which the 7:Full, 5:Full, and 7/5:Full scenarios have an 80% chance of detecting a trend are, respectively, 10.67 years, 10.81 years, and 10.77 years. Under the 1.5% population increase, the times at which the 7:Full, 5:Full, and 7/5:Full scenarios have an 80% chance of detecting a trend are, respectively, 28.87 years, 29.01 years, and 28.51 years.