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ARTICLE

Creel Survey Sampling Designs for Estimating Effort in Short-Duration Chinook Salmon Fisheries

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Abstract
Chinook Salmon *Oncorhynchus tshawytscha* sport fisheries in the Columbia River basin are commonly monitored using roving creel survey designs and require precise, unbiased catch estimates. The objective of this study was to examine the relative bias and precision of total catch estimates using various sampling designs to estimate angling effort under the assumption that mean catch rate was known. We obtained information on angling populations based on direct visual observations of portions of Chinook Salmon fisheries in three Idaho river systems over a 23-d period. Based on the angling population, Monte Carlo simulations were used to evaluate the properties of effort and catch estimates for each sampling design. All sampling designs evaluated were relatively unbiased. Systematic random sampling (SYS) resulted in the most precise estimates. The SYS and simple random sampling designs had mean square error (MSE) estimates that were generally half of those observed with cluster sampling designs. The SYS design was more efficient (i.e., higher accuracy per unit cost) than a two-cluster design. Increasing the number of clusters available for sampling within a day decreased the MSE of estimates of daily angling effort, but the MSE of total catch estimates was variable depending on the fishery. The results of our simulations provide guidelines on the relative influence of sample sizes and sampling designs on parameters of interest in short-duration Chinook Salmon fisheries.

Throughout much of their native distribution in the Columbia River basin, wild Chinook Salmon *Oncorhynchus tshawytscha* are listed as threatened under the Endangered Species Act (Myers et al. 1998). Hatchery production has been adopted to mitigate for declines in abundance of wild populations and currently provide the primary harvestable populations in sport fisheries throughout Idaho, Oregon, and Washington. Many sport fisheries in the Columbia River basin are managed with quotas or harvest shares that allow fish to escape to upriver fisheries or hatcheries and that distribute harvest to tribal and commercial fisheries (U.S. v. State of Oregon 1983; PSCJCTC 2012). Fisheries for mixed stocks (i.e., wild and hatchery) are also managed to reduce incidental mortality of wild salmon that are caught and released by anglers. Fisheries must be closed when a predetermined percentage of wild fish have been caught and released (typically between 0% and 2% depending on the run size and

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the fishery; Apperson and Wilson 1998). Because fisheries are based on quotas or harvest shares, in-season estimates of total catch and harvest are needed.

Although quotas or harvest shares are common in commercial fisheries, they are relatively uncommon in sport fisheries. Various forms of mandatory reporting are regularly used to estimate total catch in commercial fisheries. The highly dispersed angling effort and catch in Chinook Salmon sport fisheries in the Columbia River basin preclude the use of mandatory reporting. Additionally, these fisheries are often of relatively short duration, commonly lasting from days to a maximum of a few months (e.g., Janssen and Kiefer 1999; Apperson 2003; Keniry et al. 2004), which can further complicate creel survey design and total catch estimation.

In general, Chinook Salmon sport fisheries in the Columbia River basin occur on long sections of large rivers with dispersed shore access and multiple fixed access points (i.e., boat launches and public shore access). As such, estimates of effort and catch are typically derived from on-site creel surveys, such as access–access, aerial–access, roving–access, aerial–roving, or roving–roving surveys (Malvestuto 1983; Pollock et al. 1994, 1997). When designing creel surveys, there are multiple considerations, including survey type, number of days to survey, number of angler interviews, and number of angler counts. Survey type is typically determined by access to the fishery. For instance, access-based surveys are generally conducted in fisheries that have relatively few, well-defined access areas, whereas roving-based surveys are conducted in fisheries that have diffuse access (Pollock et al. 1994). Previous research has been conducted on the number of days to survey and the number of counts to conduct (Lester et al. 1991; Malvestuto and Knight 1991). However, because of the relatively short seasons in Chinook Salmon fisheries and the high variability in temporal and spatial trends in effort and catch due to the migratory nature of salmon, the number of days to survey and the number of counts can vary greatly depending on the length of the fishery (Martinson and Shelby 1992; Bernard and Clark 1996; Keefer et al. 2004).

Another consideration when designing a creel survey is the method used to select sampling units (Knight and Malvestuto 1991; Malvestuto and Knight 1991; Deroba et al. 2007). For instance, a three-stage cluster sample is common in creel surveys, where (1) days are randomly selected, (2) a portion of the day to be surveyed is randomly selected, and then (3) count times are randomly selected (Malvestuto 1983; Pollock et al. 1994). For creel surveys such as those used in Chinook Salmon sport fisheries, days are frequently identified as the primary sampling units (Malvestuto 1983; Pollock et al. 1994). In most probabilistic surveys, as the number of primary sampling units (i.e., days) sampled increases the distribution of the variable of interest (i.e., total effort, catch, or harvest in creel surveys) approaches a normal distribution (Thompson 2012). This serves as the statistical basis for expected parameter estimates of interest in probabilistic creel surveys. However, because the number of primary sampling units available for selection in many Chinook Salmon fisheries is limited and because in-season estimates are needed, the statistical properties of estimates are unknown.

In addition to selecting days to sample, scheduling the times to conduct counts also must be considered when instantaneous counts are used (Hoenig et al. 1993; Pollock et al. 1994). Counts can be scheduled by using various designs, including simple random, systematic, stratified, cluster, or nonuniform probability sampling (Malvestuto et al. 1978; Hoenig et al. 1993; Kozfkay and Dillon 2010). Bias and precision of effort and catch estimates in creel surveys can vary depending on the method used to select sampling units (Bernard et al. 1998). The relative efficiency of more complex survey designs in comparison with simple random sampling (SRS) is known as design effect and has not been extensively evaluated in short-duration fisheries (Cochran 1977).

Although research on creel survey sampling design is extensive, most research has focused on total catch over a month, season, or year (Malvestuto et al. 1978; Rasmussen et al. 1998). Daily or weekly catch and associated variability are rarely of interest to managers. As a result, very little previous research is applicable to sampling designs associated with estimating daily or weekly effort and catch. However, due to the quotas imposed and in-season management of Chinook Salmon fisheries in the Columbia River basin, estimates for short time periods are necessary. Therefore, the objectives of this research were to evaluate various sampling designs and sample sizes used to estimate effort and total catch in Chinook Salmon fisheries. The relative accuracy per unit cost was also evaluated.

METHODS

Thompson (2012) suggested that simulation of sampling distributions is one of the most effective tools to evaluate sampling strategies and estimators. As such, censuses of angling activity were conducted on reaches of three short-duration Chinook Salmon fisheries in Idaho, which served as theoretical angling populations. Monte Carlo simulations were then conducted based on these populations, and the resulting sampling distributions were evaluated to determine the performance of sampling designs and sample sizes.

Censuses of angling activity (i.e., fishing time and catch) were conducted on 200–700-m reaches of Chinook Salmon fisheries on the Clearwater, Little Salmon, and South Fork Salmon rivers, Idaho, by using direct visual observation. Observation reaches were selected nonrandomly to increase sample sizes (i.e., angling effort and total catch) and to facilitate discreet observations of anglers. It was assumed that the nonrandomly selected observation reaches were representative of the target population. Survey days were also selected nonrandomly and were conducted near the peak of angling activity in each fishery. Roving–roving or roving–access creel surveys throughout the entire fishery were conducted by Idaho Department of Fish and Game (IDFG) creel clerks while our observations of anglers were taking place concurrently in localized census reaches.

Based on the instantaneous counts of anglers in the census reach compared with IDFG creel clerks' counts of the entire fishery, census reaches accounted for approximately 28% of angling effort in the entire fishery on the Clearwater River, 19% of effort on the Little Salmon River, and 6% of effort on the South Fork Salmon River.

Distributions of angling effort and catch observed in the census reaches served as the theoretical angling population that was resampled by using Monte Carlo simulations. Observations were conducted for 7 d at each reach on the Clearwater, Little Salmon, and South Fork Salmon rivers, for a total of 21 observation days. An additional 2 d of observations were conducted on the Little Salmon River (i.e., days 8 and 9) to evaluate a nonuniform probability sampling (NUP) design. Observers arrived before the legal fishing time started and remained present until the end of legal fishing time; by regulation, fishing was limited to daylight hours only. Discreet observations were conducted so as not to influence angler decisions on fishing locations, fishing times, fish harvest, or reporting to IDFG creel clerks. For instance, in the Clearwater and Little Salmon rivers, angling activity was observed from afar by using spotting scopes. Two observers were used on the South Fork Salmon River: one observer fished and relayed information to the other observer, who discreetly recorded data. Data were recorded on the time each angler entered and exited the fishery, the total catch, the time of catch, the number of fish released, and the number of fish harvested.

Each angler was assigned a unique identification number at the start of their fishing episode, which was defined as the angler's first cast. The end of the fishing event was defined as the time the angler exited the fishing area and was no longer available for a roving interview or count. Anglers would frequently exit the fishery for short periods of time and were unavailable for counting in a roving creel survey. If an angler exited the fishery for 5 min or more, that angler was assumed to be unavailable for counting in a roving effort count and was recorded as not fishing. When such anglers re-entered the fishery, they were re-assigned their initial identification numbers. All data were recorded on a per-angler basis to avoid bias or variance that may arise from estimates associated with groups or parties (e.g., pooled effort and catch) of anglers (Lockwood 1997).

Sampling strategies.—In our simulations, primary sampling units (i.e., days) were selected by using SRS. Once a day was selected for sampling, six different within-day sampling strategies were simulated to create sampling distributions of angling effort and total catch in each fishery (i.e., SRS, systematic random sampling [SYS], two-cluster [morning and afternoon cluster] sampling [CL_2], four-cluster sampling [CL_4], eight-cluster sampling [CL_8], and NUP). With SRS, SYS, and NUP, the entire day was available for sampling, whereas with cluster designs half of the day was selected for sampling. Additional information on the designs is detailed below. Within-day allocation of sampling effort primarily affected the scheduling of instantaneous counts and allowed us to evaluate the effect of sampling design on estimates of effort. The IDFG typically conducts roving–roving surveys on the Clearwater, Little Salmon, and South Fork Salmon rivers. However, McCormick et al. (2012) showed that roving interviews in these fisheries can result in mean catch rate estimates that are highly biased due to nonstationary catch rates. Thus, the true catch rate during the survey period was multiplied by estimated effort from simulated counts to derive estimates of total catch. For instance, in simulating cluster sampling designs, when a cluster was selected, the true catch rate during the selected cluster(s) was used. Under an SRS, SYS, or NUP design, where the entire day was available for sampling, the true catch rate for the entire day was used. Simulations were conducted in this manner to avoid confounding sources of bias and variance that may arise either from interviewing anglers to estimate mean catch rate or from selecting sampling units for instantaneous counts.

Simple random sampling.—To estimate daily angling effort using SRS, sampling units (i.e., minutes to conduct counts) were selected with equal probability without replacement. Instantaneous counts were conducted at the selected count times. Total angling effort ($\hat{E}$) in hours for each day in all fisheries was estimated as

$$\hat{E}_{SRS} = T\bar{I}, \quad (1)$$

where T is the total number of hours in the fishing day and $\bar{I}$ is the mean of i angler counts. Sample variance (s^2_{SRS}) was estimated as

$$s^2_{SRS} = \frac{1}{n-1}\sum_{i=1}^{n}(\bar{I} - I_i)^2, \quad (2)$$

where n is the number of counts. Variance of the total angling hours ($\hat{V}[\hat{E}_{SRS}]$) was estimated using methods described by Pollock et al. (1994):

$$\hat{V}(\hat{E}_{SRS}) = T^2\left(\frac{s^2_{SRS}}{n}\right). \quad (3)$$

The finite population correction is ignored in equation (3) because the sampling fraction does not exceed 5% (Cochran 1977). We estimated 95% CIs for estimates of effort as

$$\hat{E}_{SRS} \pm \left[1.96 \times \sqrt{\hat{V}(\hat{E}_{SRS})}\right]. \quad (4)$$

Total daily catch ($\hat{C}_j$) for the jth day was estimated as

$$\hat{C}_j = \hat{E}_{SRS} \times R, \quad (5)$$

where R is the true mean daily catch rate for all anglers (i.e., ratio of means; Jones et al. 1995; McCormick et al. 2012).

Systematic sampling.—Systematic sampling was simulated in a manner similar to SRS, but angler counts were conducted systematically. The first instantaneous angler count time was randomly selected within the first k minutes of the day, where k equals the length of time in the day divided by the number of total counts (Cochran 1977). Additional counts were conducted at each kth time thereafter. The mean of angler counts ($\bar{I}_{SYS}$) and total daily effort were estimated using equation (1). It was assumed that the population was ordered randomly; sample variance, population variance, and 95% CIs were estimated using equations (2), (3), and (4), respectively (Scheaffer et al. 2006). Total daily catch was estimated using equation (5).

Cluster sampling.—Morning and afternoon cluster sampling is a design with two clusters available to be sampled, one of which is selected for sampling. This is one of the most common creel survey sampling designs (Malvestuto 1983; Pollock et al. 1997; Rasmussen et al. 1998). However, days may be divided into more than two clusters, and the number of clusters selected for sampling can vary. We evaluated the effect of using two, four, and eight clusters (CL_2, CL_4, and CL_8, respectively) on estimates of effort and catch. With each design, the number of clusters sampled was half the total number of clusters available for sampling. Such a design would require creel clerks to work the same number of hours regardless of the number of clusters available for sampling. Total effort was estimated using the methods described by Scheaffer et al. (2006):

$$\hat{E}_{CL} = \frac{N}{n}\sum_{i=1}^{n} M_i \bar{I}_i, \tag{6}$$

where N is the number of clusters in the population, n is the number of clusters selected in the sample, M_i is the number of elements (i.e., minutes) in the ith cluster, and $\bar{I}_i$ is the mean count of anglers in the ith cluster. Total daily catch was estimated using equation (5), with R in this case representing the catch rate within the clusters that were sampled. Nonparametric bootstrap 95% CIs were calculated for each estimate of total daily effort by using the percentile method (Efron and Tibshirani 1993).

Nonuniform probability sampling.—To simulate an NUP design, selection probabilities of sampling units (i.e., minutes to conduct counts) were calculated based on the mean number of anglers fishing during each minute of the fishing day from the initial 7-d observation period on the Little Salmon River. An additional 2 d of observation (i.e., days 8 and 9) were conducted on the Little Salmon River and served as the population that was resampled to evaluate the NUP design. A sample of count times was selected without replacement. Total daily effort was estimated using the Horvitz–Thompson estimator (Cochran 1977; Pollock et al. 1994):

$$\hat{E}_{H-T} = \sum_{i=1}^{n}(I_i/\pi_i), \tag{7}$$

where π_i is the inclusion probability of the ith unit (i.e., minute). The inclusion probability was estimated using methods described by Thompson (2012):

$$\pi_i = 1 - (1 - p_i)^n, \tag{8}$$

where p_i is the probability of unit i being selected. Total daily catch was estimated with equation (5). The additional 2 d were also sampled using the SRS and SYS designs to compare results with those from the NUP design.

Simulations and evaluation.—Sampling designs were evaluated using Monte Carlo simulations. For each design, 5,000 samples of effort and total daily catch were simulated. We conducted simulations in which the number of counts varied from two to eight to determine the effect of sample size on bias and precision. Because weekly estimates of harvest are needed in many Chinook Salmon fisheries, 5,000 estimates of total weekly catch were simulated for each daily sampling design. Total weekly catch was estimated using an SRS design in which days were selected with equal probability without replacement. Scenarios were examined where the number of days sampled varied from four to seven. Total weekly catch ($\hat{C}$)was estimated as

$$\hat{C} = \sum_{i=1}^{L} D_i \bar{C}_j, \tag{9}$$

where D_i is the number of days in the ith stratum (i.e., week) and $\bar{C}_j$ is the mean catch per day in the ith stratum.

Bias was estimated as the difference between the mean of the empirical sampling distribution and the true population parameter (i.e., effort, total daily catch, or total weekly catch). Relative bias was estimated as bias divided by the true population parameter. To assess the accuracy and precision of each estimator, the mean square error (MSE) was estimated as the mean squared difference between the estimate and the true value for each population parameter θ:

$$\text{MSE}(\hat{\theta}) = \frac{\sum_{i=1}^{5,000}(\hat{\theta}_i - \theta)^2}{5,000}. \tag{10}$$

Coverage of 95% CIs of daily effort estimates was also evaluated. In theory, 95% of all CIs should encompass the true population parameter; for iterations with CIs that did not encompass the true parameter values, 50% should be below the true value and 50% should be above the true value. The percentage of CIs that encompassed the true population parameter was calculated along with the direction of CIs that did not encompass the known population value. In an actual creel survey, catch rate would likely be estimated and would add variability to the sampling distribution of total daily and weekly catch estimates; therefore, CI coverage was only evaluated for estimates of daily effort. Simulations and statistical analysis were conducted using the R statistical computing language (R Development Core Team 2009).

Cost analysis.—Because not all survey designs are equal in cost, the accuracy per unit cost was evaluated. We did not evaluate all six designs because costs are likely to be highly variable among fisheries and may not be informative. Specifically, only the SYS and CL_2 designs were evaluated because an SYS design surveys the entire day and a CL_2 design will always survey half the day, thereby providing a more direct comparison of efficiency. Accuracy was defined as the reciprocal of MSE. The cost of a creel survey typically includes equipment, personnel, and travel costs. For the cost analysis, equipment and travel costs were assumed to be equal between survey designs. The relative cost of surveying one full day was set to 1 unit, and cost was increased by 1 unit for each additional day (e.g., 4 d cost 4 units, 5 d cost 5 units, and so forth). This was assumed to be the relative cost for an SYS design. Because a CL_2 design only requires a creel surveyor for half of a day, the relative cost for 1 d with this design was set to 0.5 units. The accuracy per relative unit cost was evaluated with the number of days surveyed varying from four to seven. The cost associated with conducting a count can vary by fishery depending on the length of time and amount of travel required to conduct a count; therefore, the accuracy per unit cost was evaluated for a design in which the number of counts was held constant at four. An increase in the accuracy per unit cost would indicate a more efficient design.

RESULTS

Over the 21-d observation period, anglers caught a total of 242 Chinook Salmon: 39 fish were caught on the Clearwater River, 130 were caught on the Little Salmon River, and 73 were caught on the South Fork Salmon River (Table 1). In total, 580 angler trips were observed, encompassing 2,620 h of angling effort. Overall, angler catch rates were relatively low and varied from 0.008 to 0.068 fish/h on the Clearwater River, from 0.092 to 0.229 fish/h on the Little Salmon River, and from 0.033 to 0.169 fish/h on the South Fork Salmon River.

Simulated estimates of daily angling effort for all sampling designs and all sample sizes were relatively unbiased (Figure 1).

TABLE 1. Summary of angling activity in Chinook Salmon fisheries observed for 7 d on the Clearwater River, 9 d on the Little Salmon River, and 7 d on the South Fork Salmon River, Idaho, during the 2011 season.

Day	Total anglers	Total hours fished	Mean hours fished per angler	Number of fish caught	Daily catch rate (fish/h)
			Clearwater River		
1	49	254.63	5.2	8	0.031
2	47	264.23	5.62	8	0.030
3	31	251.18	8.10	9	0.036
4	14	44.28	3.16	3	0.068
5	37	122.93	3.32	6	0.049
6	42	123.57	2.94	4	0.032
7	24	128.68	5.36	1	0.008
			Little Salmon River		
1	46	195.93	4.26	29	0.148
2	20	71.07	3.55	15	0.211
3	25	96.25	3.85	22	0.229
4	27	136.68	5.06	18	0.132
5	40	183.85	4.60	17	0.092
6	37	116.72	3.15	19	0.163
7	23	93.83	4.08	13	0.139
8	26	70.93	2.72	7	0.099
9	24	97.03	4.04	8	0.082
			South Fork Salmon River		
1	6	30.45	5.08	1	0.033
2	5	43.05	8.61	2	0.046
3	9	59.88	6.65	5	0.083
4	8	71.13	8.89	6	0.084
5	29	124.42	4.29	21	0.169
6	29	105.9	3.65	17	0.161
7	32	101.23	3.16	8	0.079

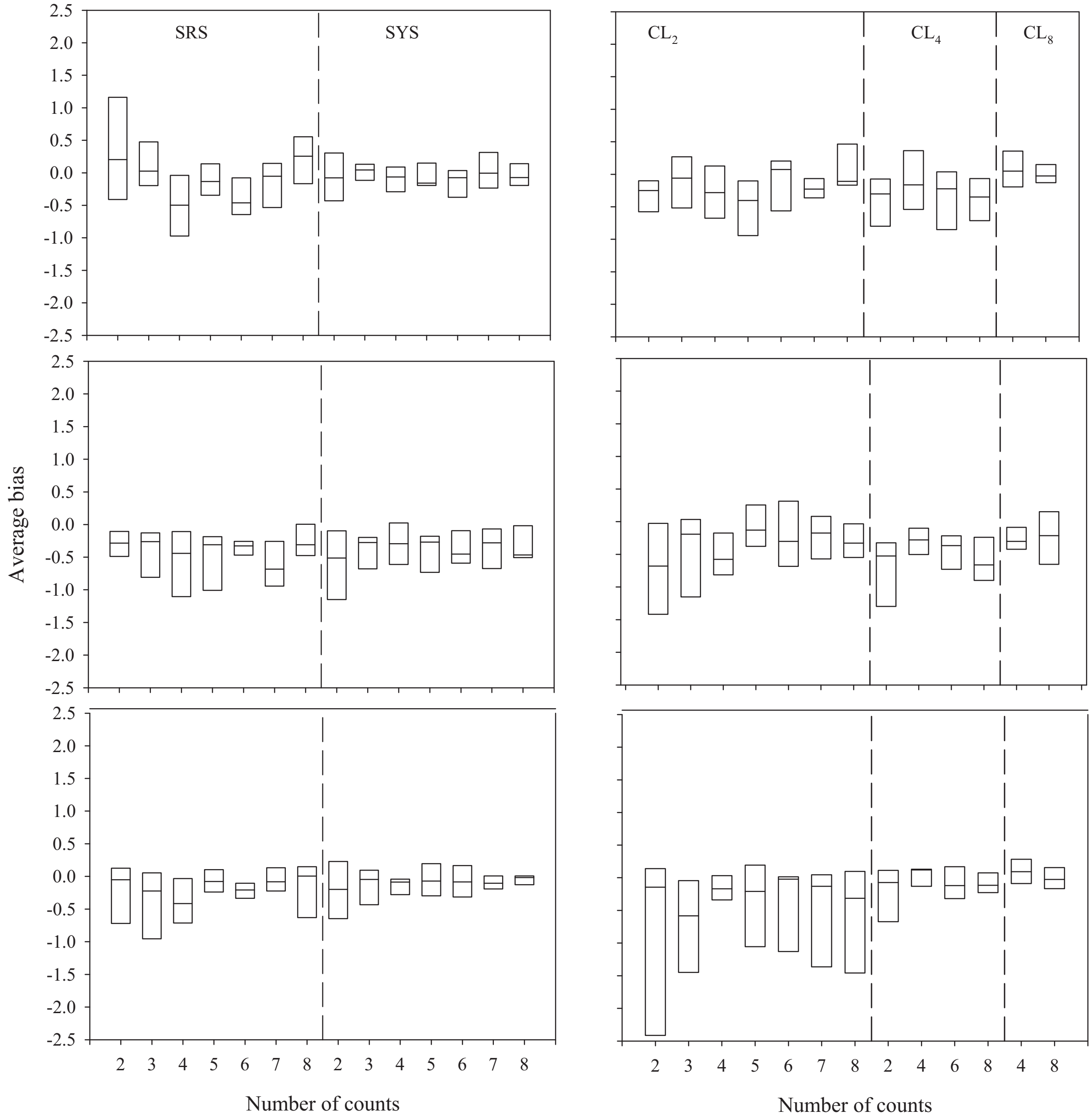

FIGURE 1. Average among-day bias in estimated angling effort from roving creel surveys in three simulated Chinook Salmon fisheries on the Clearwater River (top panels), Little Salmon River (middle panels), and South Fork Salmon River (bottom panels), Idaho, during the 2011 season. The number of instantaneous angler counts varied from two to eight, and five different sampling designs were evaluated: simple random sampling (SRS), systematic random sampling (SYS), a two-cluster design (CL_2), a four-cluster design (CL_4), and an eight-cluster design (CL_8). Left panels represent sampling designs in which the full day is available for sampling (SRS and SYS); right panels represent designs in which the day is subsampled. Box plots represent quartiles of among-day estimates of bias.

The largest estimated absolute bias for any survey day was calculated for the Clearwater River using a CL_4 sampling design with six counts, where effort was overestimated by 2.66 h and the relative bias was 2.1%. The largest relative bias was 5.62%, which was observed for the Clearwater River using a CL_2 sampling design and two counts. All other simulated estimates of relative bias were less than 1.6%. The SYS design resulted in the lowest variance in estimates of bias among days, whereas the CL_2 design resulted in the highest among-day variance (Figure 1). Increasing the number of angler counts generally failed to decrease bias in effort estimates for all designs. Among-day variance in bias tended to decrease with increasing counts for the SRS and SYS designs, whereas this trend was not generally observed with the cluster designs. Among-day variance in bias generally decreased with increasing numbers of clusters (Figure 1).

Because bias of all effort estimates was relatively small, variance of the sampling distribution accounted for most of the

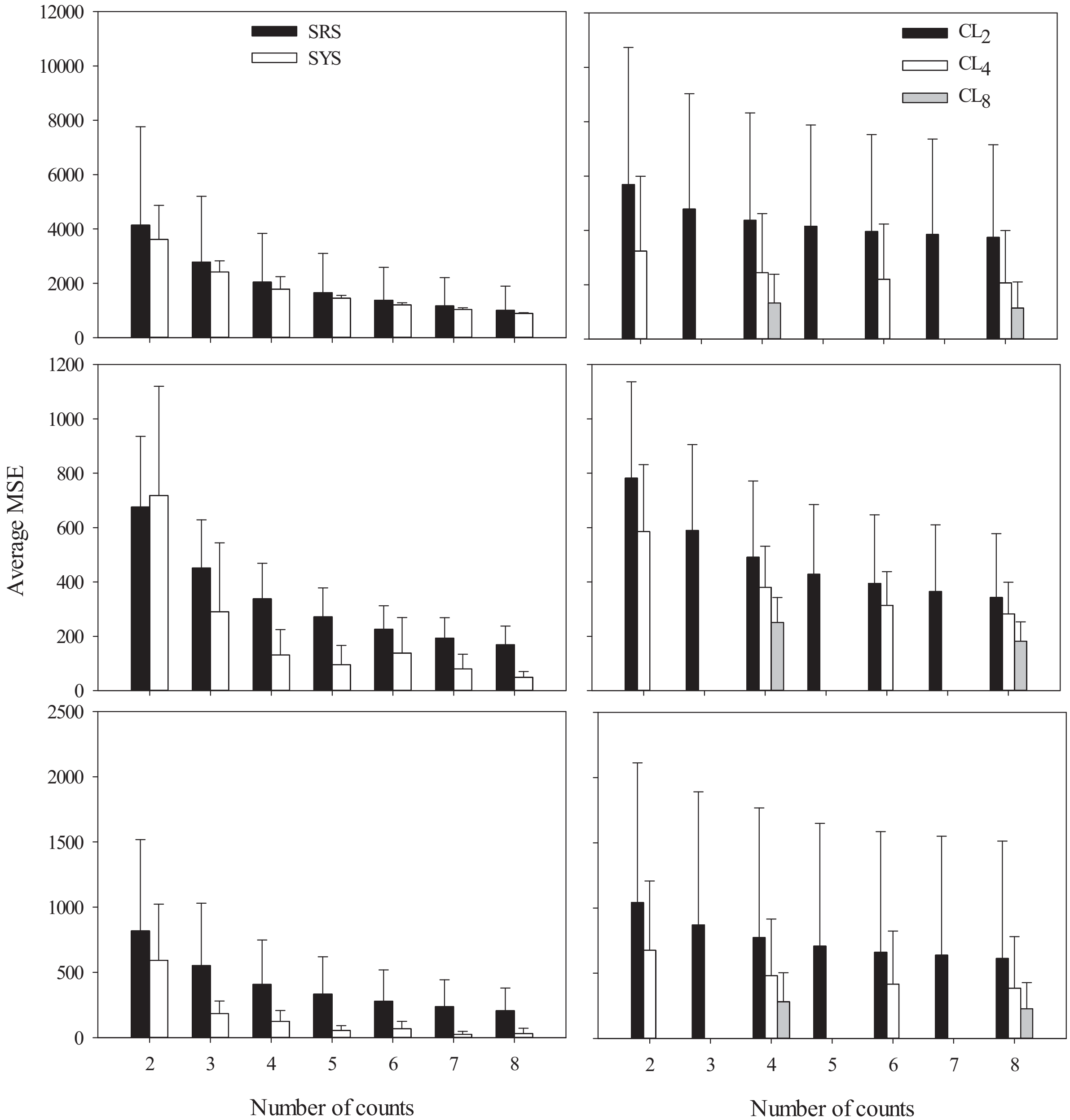

FIGURE 2. Average among-day mean square error (MSE) of estimated angling effort from roving creel surveys in three simulated Chinook Salmon fisheries on the Clearwater River (top panels), Little Salmon River (middle panels), and South Fork Salmon River (bottom panels), Idaho, during the 2011 season. The number of instantaneous angler counts varied from two to eight, and five sampling designs (defined in Figure 1) were evaluated. Left panels represent sampling designs in which the full day is available for sampling (SRS and SYS); right panels represent designs in which the day is subsampled. Error bars represent one SD of among-day MSE in each fishery.

observed MSE. As such, the MSE reduces to the approximate variance of the sampling distribution. Taking the square root of the variance equals the SD, which represents the expected SE of the estimate (Särndal et al. 1992). Therefore, trends in reported MSE between designs and sample sizes can be interpreted as the relative change in expected precision of the estimates. With the exception of a two-count SRS design on the Little Salmon River, the SYS design resulted in the lowest average MSE of all designs for each respective number of counts (Figure 2). The SYS design also resulted in the lowest among-day variance in MSE. Increasing the number of counts for all designs resulted in decreased MSE values. For both of the full-day sampling designs (i.e., SRS and SYS), large decreases in MSE were not observed beyond four counts. Relative decreases in MSE with increasing numbers of angler counts for the cluster designs were not as great as those observed for the full-day sampling designs.

Increasing the number of clusters consistently decreased the MSE of simulated estimates of effort. Average MSE from the CL_2 sampling design was consistently larger than that from the CL_4 design and more than twice as large as the MSE from the CL_8 design. Among-day variance of estimated MSE was, on average, more than double that observed for the full-day sampling designs and decreased at a much lower rate with increasing numbers of angler counts.

Use of an SRS design to estimate effort resulted in 95% CIs that were too small, regardless of the fishery and number of angler counts conducted (Figure 3). Overall, 95% CI coverage was most accurate when the SYS design was used. Confidence intervals were closest to 95% when four counts were conducted with the SYS design; beyond four counts, mean CIs were generally too large. For the cluster designs, four counts were necessary to produce CIs that were within 10% of true 95% CIs. Conducting more than five counts with all three cluster designs resulted in CIs that had greater coverage than 95%. For all designs, numbers of counts, and fisheries, the CI coverage was relatively unbiased (i.e., CIs that did not encompass true effort were not consistently overestimates or underestimates).

Similar to estimates of effort, bias in simulated estimates of total daily catch was relatively low. Total bias for all sampling designs and numbers of angler counts was less than 0.2 fish (Figure 4). The trends observed with estimates of effort were also observed with the MSE of total daily catch estimates in that the full-day sampling designs resulted in lower MSE and lower among-day variance than did the cluster designs (Figure 5). Unlike estimates of MSE for effort, increasing the number of clusters resulted in a larger MSE for total daily catch on the Little Salmon River. The CL_4 design also resulted in a larger average MSE than the CL_2 design for the Clearwater and South Fork Salmon rivers. The CL_8 design provided the lowest average MSE for the Clearwater and South Fork Salmon rivers.

Bias in estimated total weekly catch was also relatively small and did not exceed 1.2 fish for any sampling design, combination of days sampled, or number of counts (Figure 6). However, variability in bias among sampling designs and numbers of counts decreased as the number of days sampled increased. For the Little Salmon and South Fork Salmon rivers, bias tended to be negative (i.e., to underestimate actual total weekly catch) when SRS and SYS designs were used but was still relatively small. Bias for all other designs and sample sizes was evenly distributed about zero.

The SRS and SYS designs resulted in MSEs of total catch estimates that were consistently smaller than those from cluster designs (Figures 7, 8). For the Clearwater River, MSEs of total weekly catch estimates from the full-day sampling designs were less than half of the MSEs from the cluster designs. With all sampling designs, decreases in MSE were observed by increasing the number of sampling days from four to seven. This decrease was relatively consistent regardless of the sampling design or number of counts. On average, the CL_2 sampling design resulted in MSE estimates that were smaller than those of the CL_4 and CL_8 cluster designs, regardless of the number of days sampled (Figure 8). Similar to daily estimates of total catch, increasing the number of counts beyond four did little to decrease MSE estimates for the full-day sampling designs (Figure 7). Small decreases in MSEs of total weekly catch estimates were observed with the cluster designs by increasing the number of counts (Figure 8). Smaller decreases in MSE were observed by increasing the number of counts as the number of clusters increased (i.e., cluster size was reduced).

When sampling on the Little Salmon River was simulated for two additional days, estimates of total daily angling effort and total catch were unbiased when using the NUP, SRS, and SYS designs. All estimates of bias in total angling hours were less than 1.15 h, and all estimates of bias in total catch were less than 0.12 fish. On day 8 and day 9, the NUP design resulted in estimates of MSE for effort that were consistently smaller than those obtained from the SRS design (Figure 9). Except when one count or four counts were conducted on day 8, the SYS design consistently resulted in smaller MSEs of effort estimates. Conducting four counts on day 8 using the SYS design resulted in a larger MSE than when three counts were conducted. Conducting three counts with the SYS design on day 9 resulted in a larger MSE than when only two counts were conducted. Similar to the results for most other designs from previous days, large decreases in MSE were not observed beyond four counts with the NUP design. Because the same catch rate was used to compare effort and total catch, relative trends in MSE of total daily catch between sampling designs were identical to those observed in effort estimates. Trends in CI coverage of the SYS design for days 8 and 9 were similar to those observed with the SYS design during the primary simulation (i.e., days 1–7 in the Clearwater, Little Salmon, and South Fork Salmon River fisheries). However, CIs were biased when three counts were conducted on day 8 and when two or four counts were conducted on day 9. For day 8, 100% of the CIs that did not encompass the true effort were biased high; for day 9, 100% of the CIs that did not encompass the true effort were biased low when two or four counts were conducted.

Although the SYS design may cost up to twice as much as the CL_2 design, it generally resulted in greater efficiency (i.e., increasing accuracy per unit cost) than the CL_2 design when four counts were conducted (Figure 10). With both designs, efficiency increased as the number of days surveyed increased. For the Clearwater and South Fork Salmon rivers, accuracy per unit cost was always greater from the SYS design than from the CL_2 design; the disparity increased with an increasing number of days surveyed. For the Little Salmon River, the CL_2 design was more efficient when 4 or 5 d were surveyed, whereas the SYS design was more efficient when 6 or 7 d were surveyed.

DISCUSSION

All of the sampling designs evaluated in this study produced estimates of effort, total daily catch, and total weekly catch that

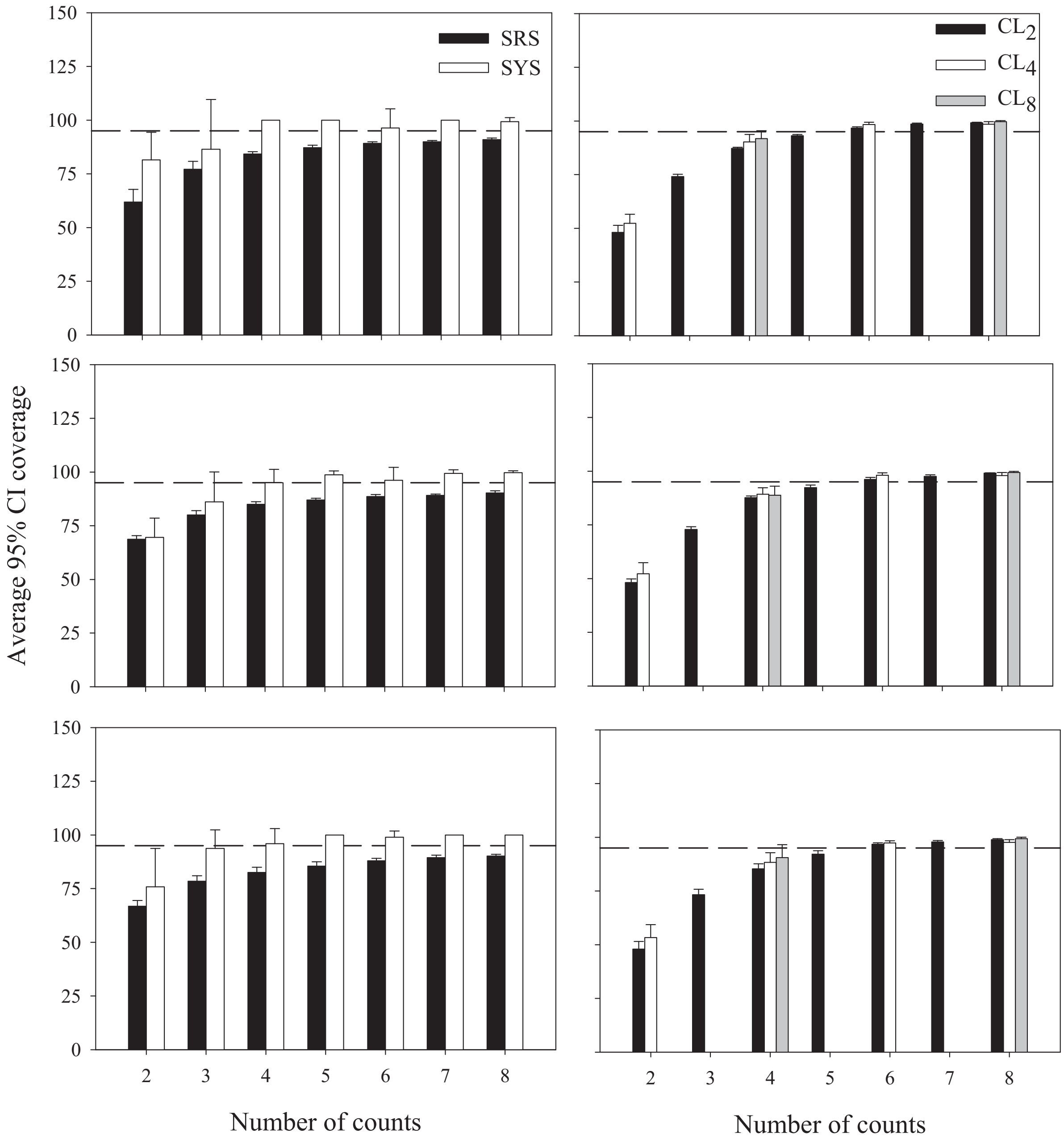

FIGURE 3. Average among-day 95% CI coverage of estimated angling effort from roving creel surveys in three simulated Chinook Salmon fisheries on the Clearwater River (top panels), Little Salmon River (middle panels), and South Fork Salmon River (bottom panels), Idaho, during the 2011 season. The number of instantaneous angler counts varied from two to eight, and five sampling designs (defined in Figure 1) were evaluated. Left panels represent sampling designs in which the full day is available for sampling (SRS and SYS); right panels represent designs in which the day is subsampled. Error bars represent one SD of among-day 95% CI coverage in each fishery. Dashed horizontal line denotes 95%.

were relatively unbiased. The characteristics of angler effort and catch for each day and river where census data were collected were highly variable, suggesting that over time, all of the sampling designs are likely unbiased (i.e., a wide range of fishing activity was observed, with similar trends in bias and precision among days and fisheries in the simulation). Actual catch rates were used to estimate total catch in this study, thereby allowing for evaluation of sampling designs used to estimate effort. However, estimation of mean catch rate may introduce bias into estimates of total catch (McCormick et al. 2012). The results of our simulation show that estimates of effort and total catch are likely unbiased when a well-designed probabilistic survey is used; therefore, emphasis can be placed on evaluating variance when planning surveys.

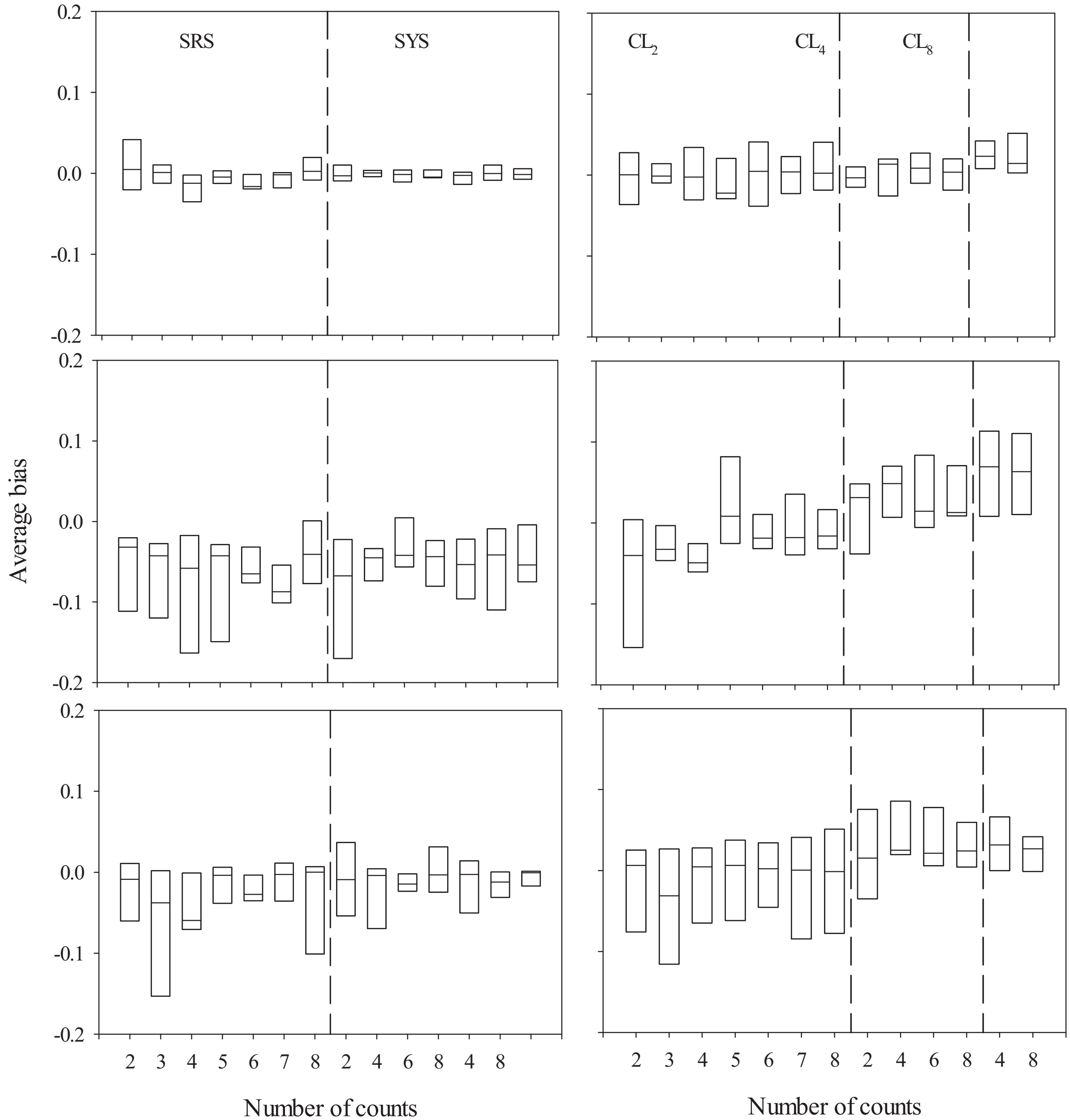

FIGURE 4. Average among-day bias of estimated daily catch from roving creel surveys in three simulated Chinook Salmon fisheries on the Clearwater River (top panels), Little Salmon River (middle panels), and South Fork Salmon River (bottom panels), Idaho, during the 2011 season. The number of instantaneous angler counts varied from two to eight, and five sampling designs (defined in Figure 1) were evaluated. Left panels represent sampling designs in which the full day is available for sampling (SRS and SYS); right panels represent designs in which the day is subsampled. Box plots represent quartiles of among-day estimates of bias.

Except when two counts were conducted, the SYS design consistently resulted in the lowest average MSE, followed by the SRS, CL_8, CL_4, and CL_2 designs. The SYS and SRS surveys also resulted in the lowest among-day variance in MSE. Cluster designs can result in multimodal estimates of effort and catch if angling activity has a multimodal distribution. For instance, if angling effort and catch rates are higher in the morning than in the afternoon and a CL_2 design is used, effort and catch will be overestimated when a morning shift is surveyed. Conversely, effort and catch will be underestimated when an afternoon shift is selected. Although this results in unbiased estimates over time, the bimodal distribution of effort and catch estimates will inflate the MSE.

In addition to having the lowest MSE, SYS samples are often easier to draw and execute (i.e., instantaneous counts; Cochran 1977; Pollock et al. 1994). Because instantaneous counts may

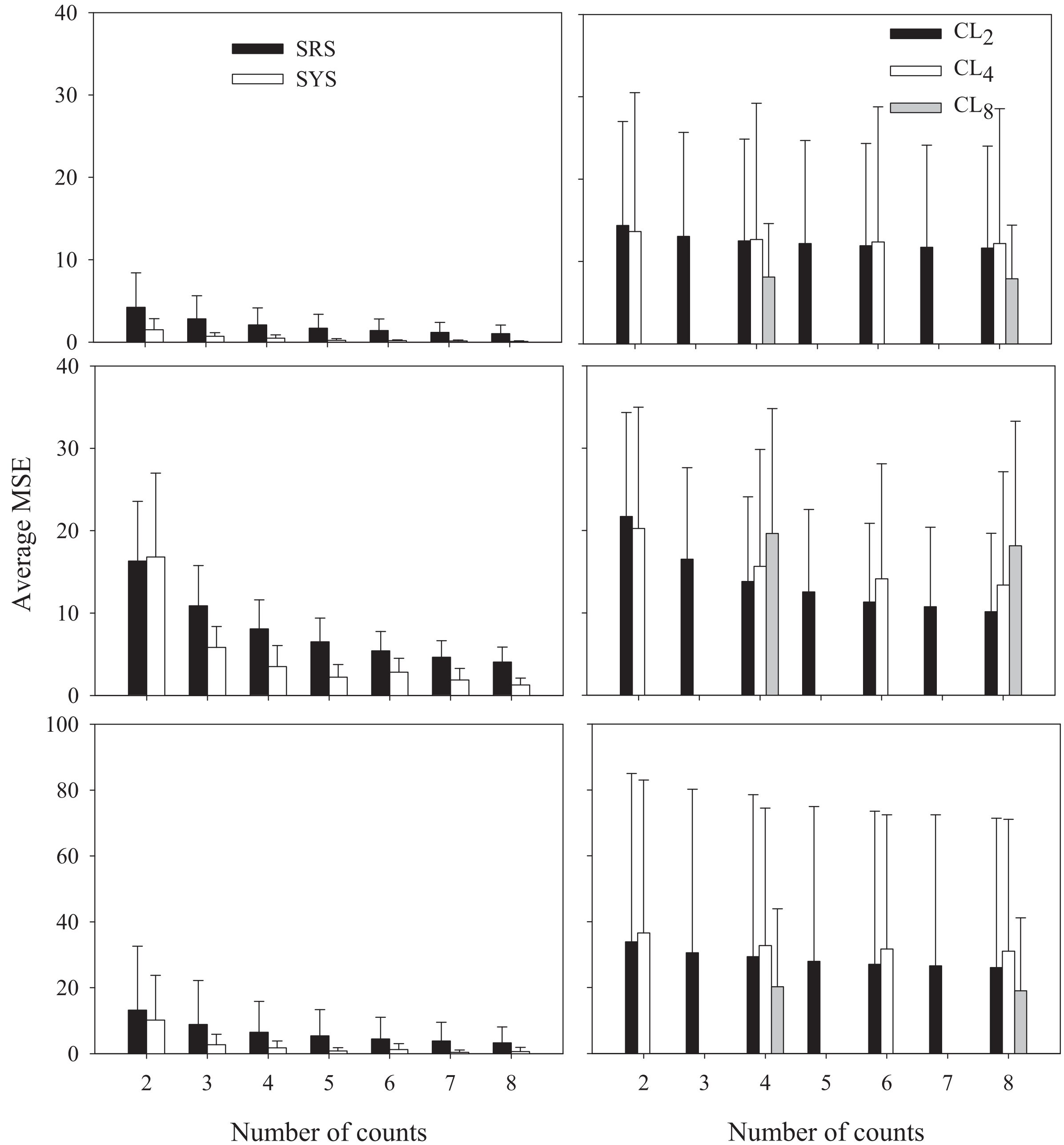

FIGURE 5. Average among-day mean square error (MSE) of estimated daily catch from roving creel surveys in three simulated Chinook Salmon fisheries on the Clearwater River (top panels), Little Salmon River (middle panels), and South Fork Salmon River (bottom panels), Idaho, during the 2011 season. The number of instantaneous angler counts varied from two to eight, and five sampling designs (defined in Figure 1) were evaluated. Left panels represent sampling designs in which the full day is available for sampling (SRS and SYS); right panels represent designs in which the day is subsampled. Error bars represent one SD of among-day MSE for total daily catch in each fishery.

take up to an hour to conduct, an SYS design allows for time between counts that may not be present with an SRS design (Pollock et al. 1994); this time may allow creel clerks to conduct angler interviews and ensures that sampling effort is spread evenly throughout the sampling period (Cochran 1977). Although the SYS design provided the lowest MSE for estimates of effort and catch, if the population is not randomly ordered then the MSE can be highly variable, as was observed for sampling days 8 and 9 on the Little Salmon River. On those days, angling effort on the Little Salmon River was apparently periodic and caused variable MSE depending on the *k*-value (i.e., number of counts) that was used (Cochran 1977). When *k* was

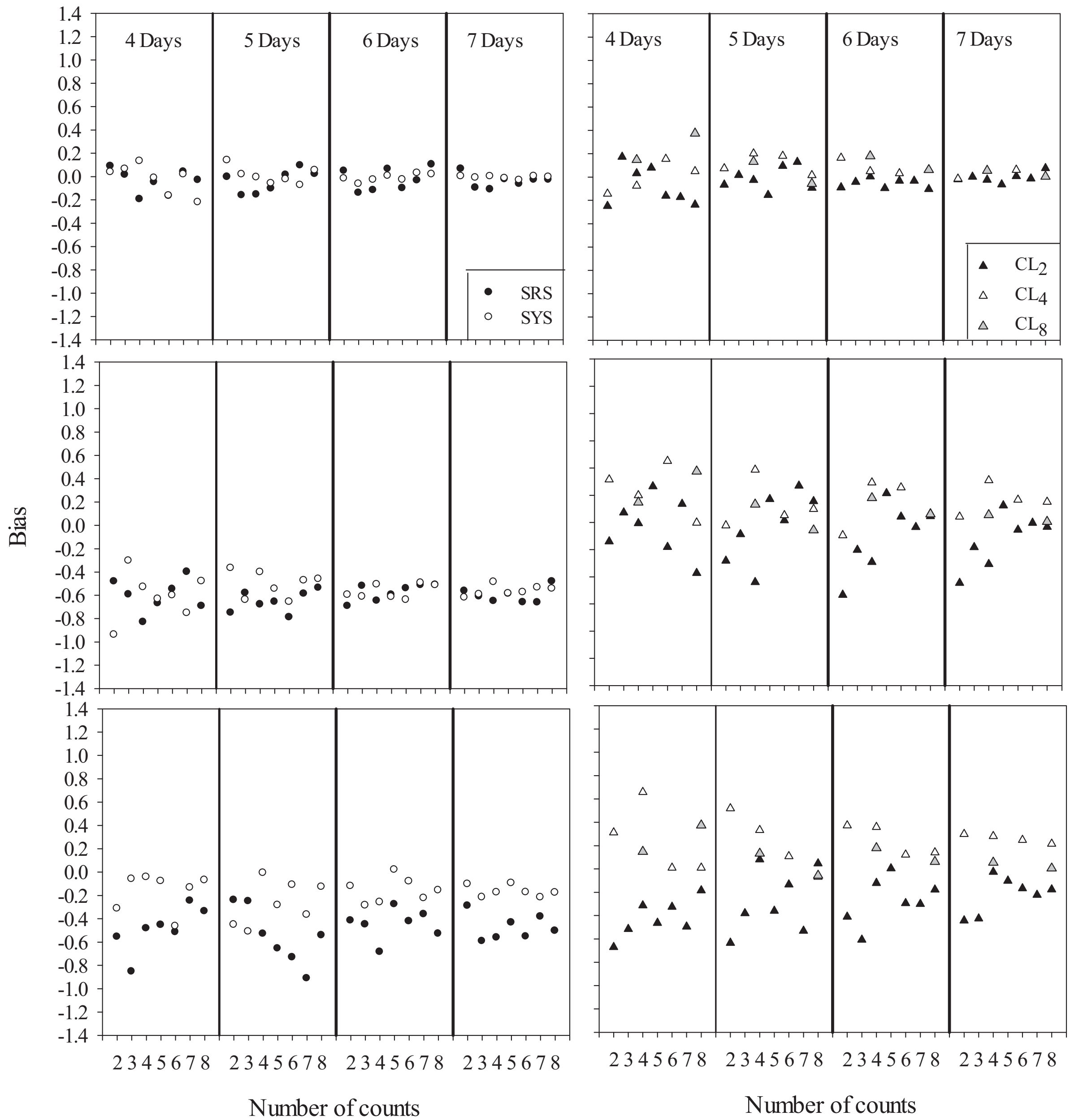

FIGURE 6. Bias of estimated weekly catch from roving creel surveys in three simulated Chinook Salmon fisheries on the Clearwater River (top panels), Little Salmon River (middle panels), and South Fork Salmon River (bottom panels), Idaho, during the 2011 season. The number of instantaneous angler counts varied from two to eight, and five sampling designs (defined in Figure 1) were evaluated. The number of days sampled also varied from four to seven. Left panels represent sampling designs in which the full day is available for sampling (SRS and SYS); right panels represent designs in which the day is subsampled.

equal to the period, all observations were similar and resulted in low MSE estimates. Although the SYS design resulted in the lowest MSE, the use of an SYS design to select sampling units within clusters could have reduced the MSEs obtained with the cluster designs.

With few exceptions, trends that were observed for daily effort estimates between sampling designs were also observed for daily catch estimates. The SYS and SRS designs consistently resulted in lower average MSE values than the cluster designs, with SYS surveys providing the lowest average MSE. Although increasing the number of clusters available for sampling decreased the MSE of effort estimates, the MSE of total daily catch estimates was variable between fisheries. Because actual catch rates were used to estimate total catch, the relationship between catch rate and effort within the clusters that were sampled was responsible for the variation. While the

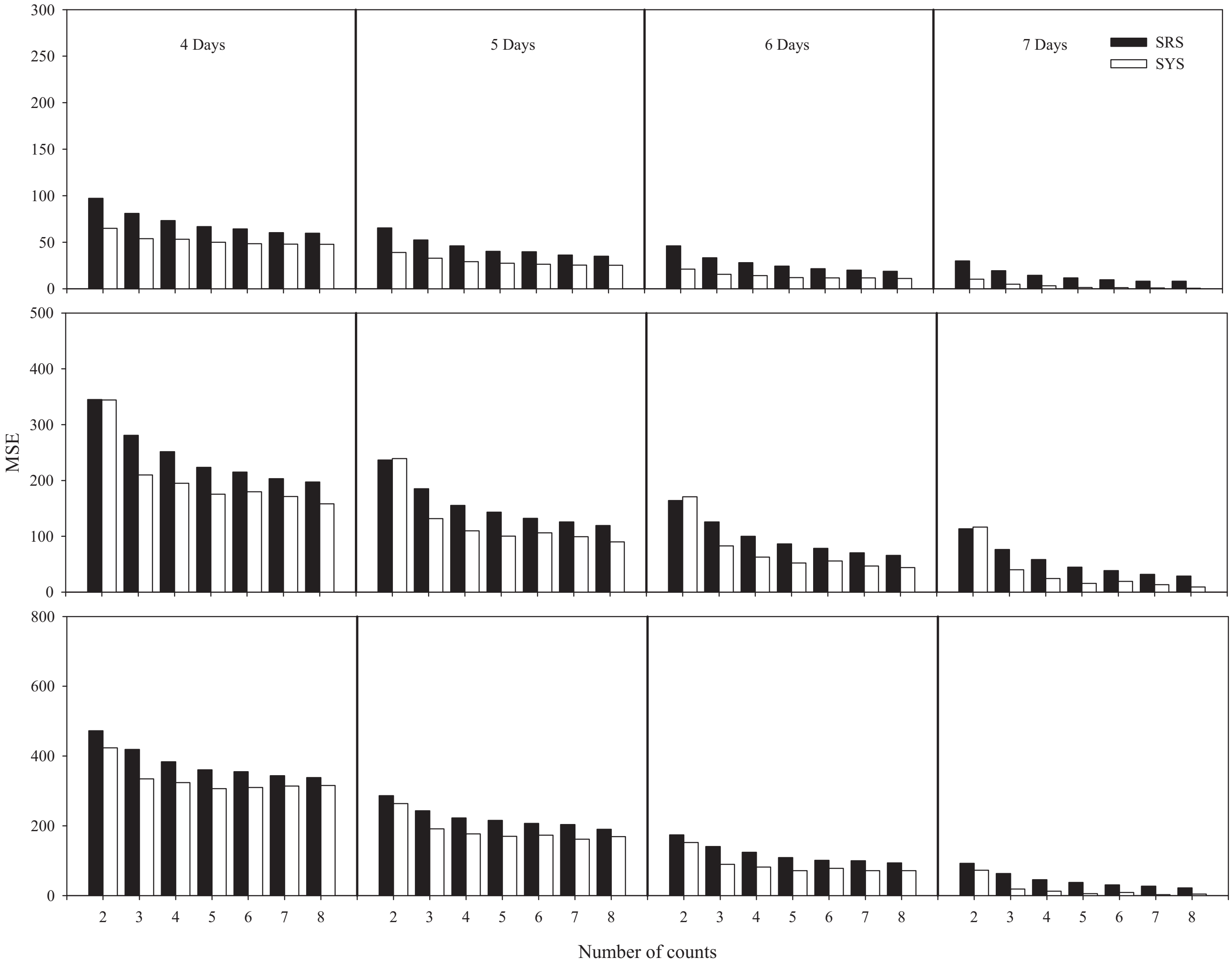

FIGURE 7. Mean square error (MSE) of estimated weekly catch from roving creel surveys in three simulated Chinook Salmon fisheries on the Clearwater River (top panel), Little Salmon River (middle panel), and South Fork Salmon River (bottom panel), Idaho, during the 2011 season. The number of instantaneous angler counts varied from two to eight, and two different sampling designs were evaluated: simple random sampling (SRS) and systematic random sampling (SYS). The number of days sampled varied from four to seven.

cluster designs were unbiased in our simulations, care should be taken when conducting interviews to estimate mean catch rate by using cluster designs. Rasmussen et al. (1998) and Su and Clapp (2013) found that bias was introduced into daily estimates of harvest when using a CL_2 sampling design. This resulted from conducting afternoon interviews of anglers who had fished in the morning, whereas effort was only estimated for the evening shift. In a roving–roving or roving–access survey, effort and catch rate should be estimated on the same sample of anglers. The authors (Rasmussen et al. 1998; Su and Clapp 2013) suggested using an estimate of harvest rate over the entire stratum (i.e., week in our simulations) instead of calculating daily estimates or asking anglers to split their harvest between shifts to alleviate this potential bias. Bernard et al. (1998) recognized that if the day is subsampled (i.e., cluster sample) via a roving–access design, bias can be introduced into estimates of catch rate, particularly for anadromous fisheries that have short-term trends in abundance and catch. Bernard et al. (1998) also suggested that fisheries with low bag limits (e.g., most of the short-duration Chinook Salmon fisheries in the Columbia River basin) increase the potential for bias. Bias can be reduced and the precision of estimates can be increased if the sampling periods are the same length as the fishing day (Bernard et al. 1998).

Even though our results constitute a direct comparison of bias and precision among various sampling designs with the same amount of sampling effort (i.e., angler counts), the results did not necessarily provide a direct comparison of cost. Despite the benefits of SYS and SRS designs relative to cluster designs,

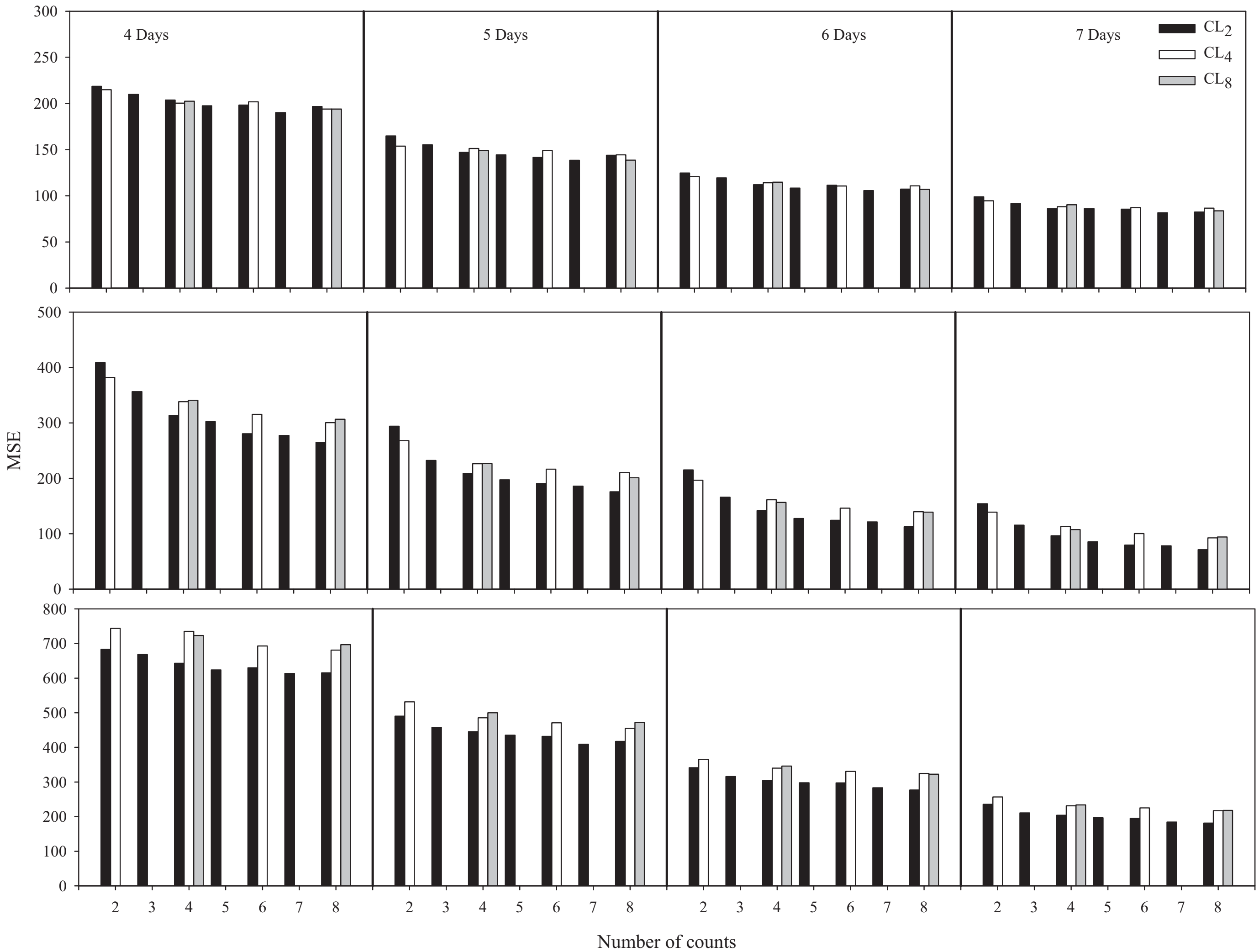

FIGURE 8. Mean square error (MSE) of estimated weekly catch from roving creel surveys in three simulated Chinook Salmon fisheries on the Clearwater River (top panel), Little Salmon River (middle panel), and South Fork Salmon River (bottom panel), Idaho, during the 2011 season. The number of instantaneous angler counts varied from two to eight, and three different sampling designs were evaluated: two-cluster (CL_2), four-cluster (CL_4), and eight-cluster (CL_8) designs. The number of days sampled varied from four to seven.

the cost of executing full-day samples will likely be higher than the cost of obtaining cluster samples (Cochran 1977). The SYS and SRS designs require that counts have the potential to occur throughout the entire fishing day. As a result, creel clerks either must be available for the entire day or must work periodically throughout the day. A CL_2 design would require creel personnel to only work half of the survey day, a likely reason for the design's popularity in creel surveys. However, the SYS design was generally more efficient (i.e., accuracy per cost) than the CL_2 design. Increasing the number of clusters available for sampling beyond two creates a potential need for creel clerks to work periodically throughout the day, and costs will likely be highly variable among fisheries. The cost for each fishery will also vary with differing numbers of counts. In this study, cost comparisons were only made for the SYS and CL_2 designs, where the number of counts was held constant because of the potential variability in costs among fisheries. However, the MSEs reported in this study can be used to assess relative efficiencies of designs for situations in which costs are known. Additionally, accuracy was similar or greater when the number of clusters was increased, suggesting that efficiency would also decrease. Increasing the number of clusters will always increase the cost relative to that of the CL_2 design. When planning a survey, cost and personnel availability should be weighed against the relative bias and precision of estimates (McCormick et al. 2012).

Previous research has been conducted on sample sizes that are necessary to achieve desired levels of precision in roving creel surveys. In a study of fisheries in Ontario lakes, Lester et al. (1991) evaluated the relationship between within- and

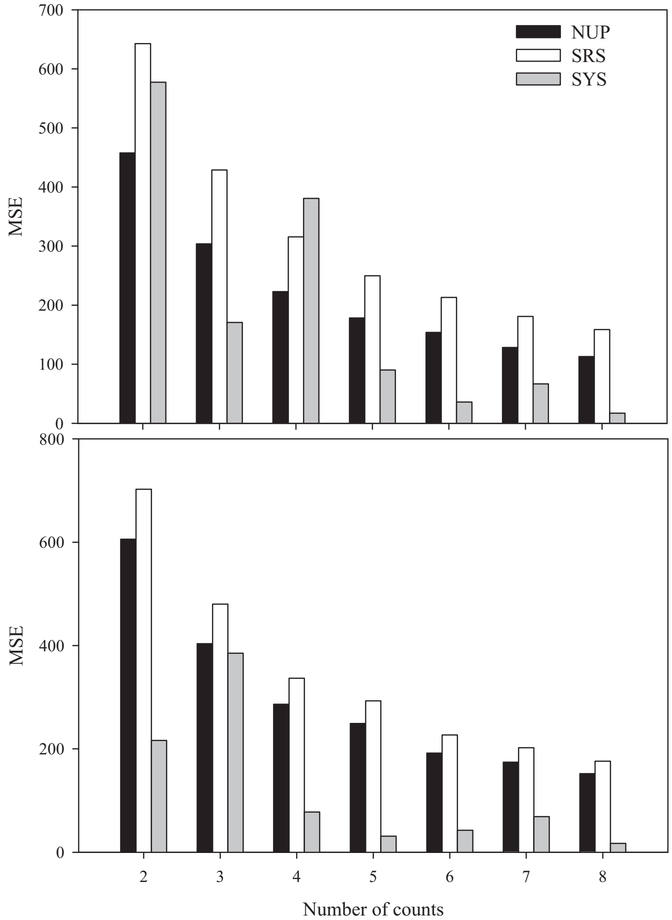

FIGURE 9. Mean square error (MSE) of estimated angling effort from roving creel surveys in a simulated Chinook Salmon fishery on day 8 (top panel) and day 9 (bottom panel) for the Little Salmon River, Idaho, during the 2011 season. The number of instantaneous angler counts varied from two to eight, and three different sampling designs were evaluated: nonuniform probability sampling (NUP), simple random sampling (SRS), and systematic random sampling (SYS).

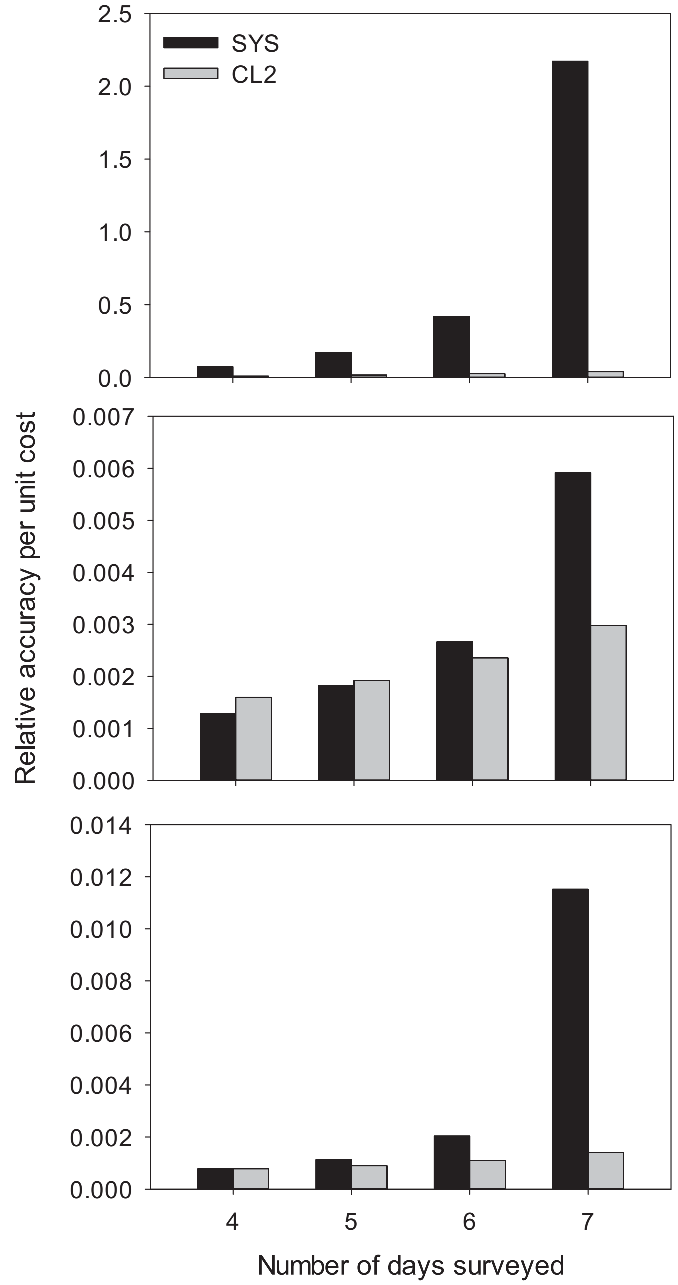

FIGURE 10. Relative accuracy of total weekly catch estimates per unit cost from roving creel surveys in three simulated Chinook Salmon fisheries on the Clearwater River (top panel), Little Salmon River (middle panel), and South Fork Salmon River (bottom panel), Idaho, during the 2011 season. The number of instantaneous angler counts was four, and two different sampling designs were evaluated: systematic random sampling (SYS) and a two-cluster design (CL_2). The number of days sampled varied from four to seven.

among-day variability to provide guidelines on the number of sample days and number of counts that would achieve a coefficient of variation of 0.2. However, Lester et al. (1991) did not evaluate the effect of various sampling designs on sample size requirements. Results of our simulations suggest that the choice of survey design can have a large effect on the precision of estimates. Exact estimates of precision were not presented in our simulations because census data were only collected on a portion of a larger fishery. Since simulated estimates of effort and daily and weekly catch were unbiased, the reported MSEs can provide guidelines on expected relative precision based on the sampling design, number of counts, and number of days sampled. For instance, increases in precision of daily effort estimates from increasing the number of counts are expected to be greater with SRS and SYS designs than with cluster designs. The trend was exacerbated as the number of clusters increased, and this was a result of increasing the between-cluster variance and decreasing the within-cluster variance by reducing the size of the cluster. In most simulated sampling designs, increases in precision were not observed beyond four counts; however, conducting four counts with n number of sampling days frequently resulted in MSEs that were similar to those obtained from conducting eight counts in $n - 1$ sampling days. In this scenario, the cost of both options can be assessed and surveys can be planned to maximize precision per unit cost (Cochran 1977; Lester et al. 1991; Scheaffer et al. 2006). Additionally, allocating time to counts can potentially reduce the number of interviews that can be conducted, thus reducing the precision of mean catch rate estimates (Pollock et al. 1994).

The SYS design consistently produced the most accurate 95% CIs on estimates of daily effort in our primary simulation (i.e., days 1–7 in the Clearwater, Little Salmon, and South Fork Salmon River fisheries). However, CIs were biased for estimates from days 8 and 9. The difference in accuracy of CIs likely occurred because the population was ordered randomly on days 1–7, whereas it was periodic on days 8 and 9. The bias in CIs was only present when the length of time between counts was equal to the period of the population. Variance was calculated under the assumption that the population was ordered randomly (Scheaffer et al. 2006). Repeated systematic sampling can be conducted to determine the structure of the population being sampled (i.e., random, ordered, or periodic) and to provide more accurate estimates of variance and CIs (Cochran 1977; Pollock et al. 1994; Scheaffer et al. 2006). Pollock et al. (1994) recommended taking several independent samples and estimating variance directly from the replicate samples. Results of our simulations, particularly for the Little Salmon River on days 8 and 9, confirm that angling effort can be periodic and that repeated sampling increases the accuracy of variance estimates.

Most probabilistic creel survey designs have the potential to be unbiased over time if they are planned and executed properly, but not all designs will result in similar precision (Pollock et al. 1994). Additionally, methods used to conduct angler interviews can influence bias in total catch estimates from creel surveys (Bernard et al. 1998; Rasmussen et al. 1998; McCormick et al. 2012). Because our simulations did not incorporate estimates of bias and precision from estimation of mean catch rate, which can be highly variable depending on the survey design (McCormick et al. 2012), our estimated MSEs of daily and weekly catch were conservative. However, the results of the simulations provide guidelines on the relative influence of sample size and designs on fishery parameters. Such information is useful in preventing inefficient use of resources (i.e., oversampling) or ineffective management based on unreliable data (i.e., from too little sampling).

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