North American Journal of Fisheries Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ujfm20

Effect of Survey Design and Catch Rate Estimation on Total Catch Estimates in Chinook Salmon Fisheries

Joshua L. McCormick [a] , Michael C. Quist [b] & Daniel J. Schill [c]

[a] Idaho Cooperative Fish and Wildlife Research Unit, Department of Fish and Wildlife Sciences, University of Idaho, Post Office Box 441141, Moscow, Idaho, 83844, USA

[b] U.S. Geological Survey, Idaho Cooperative Fish and Wildlife Research Unit, Department of Fish and Wildlife Sciences, University of Idaho, Post Office Box 441141, Moscow, Idaho, 83844, USA

[c] Idaho Department of Fish and Game, 1414 East Locust Lane, Nampa, Idaho, 83686, USA
Version of record first published: 31 Oct 2012.

To cite this article: Joshua L. McCormick , Michael C. Quist & Daniel J. Schill (2012): Effect of Survey Design and Catch Rate Estimation on Total Catch Estimates in Chinook Salmon Fisheries, North American Journal of Fisheries Management, 32:6, 1090-1101

To link to this article: http://dx.doi.org/10.1080/02755947.2012.716017

North American Journal of Fisheries Management 32:1090–1101, 2012

ISSN: 0275-5947 print / 1548-8675 online
DOI: 10.1080/02755947.2012.716017

ARTICLE

Effect of Survey Design and Catch Rate Estimation on Total Catch Estimates in Chinook Salmon Fisheries

Joshua L. McCormick*
Idaho Cooperative Fish and Wildlife Research Unit, Department of Fish and Wildlife Sciences, University of Idaho, Post Office Box 441141, Moscow, Idaho 83844, USA

Michael C. Quist
U.S. Geological Survey, Idaho Cooperative Fish and Wildlife Research Unit, Department of Fish and Wildlife Sciences, University of Idaho, Post Office Box 441141, Moscow, Idaho 83844, USA

Daniel J. Schill
Idaho Department of Fish and Game, 1414 East Locust Lane, Nampa, Idaho 83686, USA

Abstract
Roving–roving and roving–access creel surveys are the primary techniques used to obtain information on harvest of Chinook salmon *Oncorhynchus tshawytscha* in Idaho sport fisheries. Once interviews are conducted using roving–roving or roving–access survey designs, mean catch rate can be estimated with the ratio-of-means (ROM) estimator, the mean-of-ratios (MOR) estimator, or the MOR estimator with exclusion of short-duration (≤0.5 h) trips. Our objective was to examine the relative bias and precision of total catch estimates obtained from use of the two survey designs and three catch rate estimators for Idaho Chinook salmon fisheries. Information on angling populations was obtained by direct visual observation of portions of Chinook salmon fisheries in three Idaho river systems over an 18-d period. Based on data from the angling populations, Monte Carlo simulations were performed to evaluate the properties of the catch rate estimators and survey designs. Among the three estimators, the ROM estimator provided the most accurate and precise estimates of mean catch rate and total catch for both roving–roving and roving–access surveys. On average, the root mean square error of simulated total catch estimates was 1.42 times greater and relative bias was 160.13 times greater for roving–roving surveys than for roving–access surveys. Length-of-stay bias and nonstationary catch rates in roving–roving surveys both appeared to affect catch rate and total catch estimates. Our results suggest that use of the ROM estimator in combination with an estimate of angler effort provided the least biased and most precise estimates of total catch for both survey designs. However, roving–access surveys were more accurate than roving–roving surveys for Chinook salmon fisheries in Idaho.

The abundance of wild adult spring- and summer-run Chinook salmon *Oncorhynchus tshawytscha* in the Columbia River basin has declined over the last several decades. In 1995, Snake River spring- and summer-run Chinook salmon were listed as threatened under the Endangered Species Act (ESA; Myers et al. 1998). As a result of these declines, hatchery production was adopted to mitigate for loss of wild stocks and to provide sport, commercial, and ceremonial tribal fisheries in the Snake River basin. Section 9 of the ESA prohibits direct take of listed species (i.e., wild salmon); therefore, the only harvestable salmon sport fisheries in Idaho are supported by hatchery salmon. Since the 1950s, sport fishery seasons, locations, and bag limits for spring- and summer-run Chinook salmon in Idaho have varied depending on adult returns (Sam Sharr, Idaho Department of Fish and Game [IDFG], personal communication).

*Corresponding author: mcco7627@vandals.uidaho.edu
Received May 14, 2012; accepted July 23, 2012

Due to the status of Chinook salmon in Idaho, there are multiple constraints on sport fisheries. For instance, harvest of hatchery fish is managed based on a quota system that allows sufficient returns to hatcheries for maintaining broodstock. Preliminary estimates of adult returns are forecasted and updated as Chinook salmon enter the Columbia River and travel through fish passage facilities at Bonneville Dam on the Columbia River and at Lower Granite Dam on the Snake River. Sportfishing seasons are then established by IDFG based on estimated returns of hatchery salmon to their parent hatcheries throughout Idaho, and the number of harvestable fish is shared equally between sport and tribal fisheries (Janssen and Kiefer 1999). Mixed-stock fisheries (wild and hatchery fish and mixtures of hatchery stocks) are managed to allow the return of fish to upriver fisheries and hatcheries and to minimize potential effects on wild stocks. In sport fisheries that target hatchery fish (Snake River, Salmon River, and South Fork Salmon River [SFSR]), the ESA limits the allowable incidental mortality (e.g., hooking mortality) of listed wild salmon that are caught and released to 0–2% depending on the run size. Fisheries must be closed when this condition is met (Apperson and Wilson 1998). A constant mortality rate of 10% is assumed for all listed stocks of wild Chinook salmon that are caught and released.

In addition to the above incidental mortality quota, fisheries may be closed once the harvest share of hatchery fish has been met. Throughout most of the Snake River basin in Idaho, IDFG typically closes fisheries based on the harvest share before the incidental mortality quota is met (Dale Allen, IDFG, personal communication). Maximization of angling opportunity and harvest is the primary goal of the IDFG hatchery program. Thus, precise estimates of harvest and release of both wild and hatchery fish are required to maximize angling opportunity while minimizing the incidental mortality of wild fish.

Creel surveys are the primary technique used to obtain information on angler use and harvest in sport fisheries. The design and scale of creel surveys vary greatly depending on the sampling frame, desired precision, and available resources (Pollock et al. 1994). Roving creel surveys are typically conducted in fisheries that have diffuse access, whereas access surveys are conducted in fisheries that have few access points. Both survey designs may use an estimate of angling effort (i.e., based on angler counts) that is expanded over the hours in the fishing day to estimate total angler-hours (Robson 1960, 1961). Surveys may also include an angler interview component that is used to estimate mean catch rate, often based on incomplete trips for roving creel surveys and complete trips for access surveys. Estimates of angling effort are then multiplied by mean catch rate to estimate total catch (Robson 1961).

Pollock et al. (1997) provided a naming protocol to describe creel surveys that employ complemented designs; the name specifies the effort survey type followed by the interview survey type (e.g., "roving–access" design). The IDFG currently uses both roving–roving and roving–access survey designs in salmon fisheries depending on the characteristics of the fishery. To estimate catch rate in roving–roving surveys, angler interviews are conducted primarily while anglers are fishing (i.e., incomplete trips; Malvestuto 1983; Robson 1991; Pollock et al. 1994). In Idaho, creel clerks travel through the fishery in a vehicle or on foot and intercept shore anglers. Because anglers are intercepted during their fishing trips, the probability of being surveyed is not equal among all anglers. Instead, the probability of being surveyed is proportional to the angler's trip length (Robson 1961; Hoenig et al. 1997; Pollock et al. 1997). An unequal interview probability among anglers can introduce bias into estimates of mean catch rate if anglers who fish for different durations have different catch rates (e.g., anglers who fish longer have a higher catch rate than anglers who fish for a shorter duration; Malvestuto 1983; Pollock et al. 1994, 1997); this has been referred to as "length-of-stay bias." In a roving–roving survey, because the anglers are interviewed before their trips are completed, it is also assumed that each angler's catch rate is stationary and does not change after the angler is interviewed (MacKenzie 1991; Pollock et al. 1994, 1997). Thus, accuracy and precision of total catch estimates from roving–roving designs could be sensitive to both length-of-stay bias and nonstationary catch rates.

In roving–access surveys, anglers are intercepted as they exit the fishery at the completion of their fishing trips (Robson 1960; Hayne 1991; Pollock et al. 1994). Because interviews are based on completed trips, anglers have an equal probability of being interviewed and the catch rate estimates are not subject to length-of-stay bias. Contrary to roving–roving surveys, the assumption of stationary catch rates is not required for roving–access surveys because the actual final catch rate is observed. Although roving–access surveys are desirable because they require fewer assumptions than roving–roving creel surveys, they may be subject to bias if access points are numerous, not well defined, or overlooked by creel clerks (Pollock et al. 1994). As with most creel surveys, the choice of survey design (roving–access or roving–roving) for Chinook salmon fisheries in Idaho is typically determined by the number of access points. Access is diffuse throughout most salmon fisheries in Idaho, but a large proportion of angling effort takes place in a few localized areas. Such areas may be surveyed by using roving–access surveys, while the remaining areas of the fishery can be surveyed with a roving–roving design.

Regardless of the angler contact approach used, once the interviews are conducted the mean catch rate is estimated by using either the ratio-of-means (ROM) estimator or the mean-of-ratios (MOR) estimator depending on the survey design (Jones et al. 1995; Hoenig et al. 1997; Pollock et al. 1997). The ROM estimator calculates mean catch rate as the total catch divided by the total time fished for all anglers in the sample, thus producing an estimate of mean catch rate per day. The MOR estimator calculates mean catch rate as the mean of catch rates for all anglers who were interviewed and results in an estimate of mean catch rate per angler. The two estimators typically result in two different estimates of catch rate (Crone and Malvestuto 1991; Keefe et al. 2009). Several authors have suggested that the ROM estimator should be used to estimate mean catch rate and total catch when anglers are surveyed with equal probability (roving–access surveys), whereas the MOR estimator should be used when anglers are surveyed with unequal probability (roving–roving surveys; Jones et al. 1995; Hoenig et al. 1997; Lockwood 1997; Pollock et al. 1997). Moreover, use of the MOR estimator in roving–roving surveys can result in estimates of mean catch rate with unstable variance if the interviewed anglers have large catches and short trip lengths (Jones et al. 1995; Hoenig et al. 1997; Pollock et al. 1997). However, if short trips (i.e., ≤0.5 h) are ignored, the variance of estimates of mean catch rate may stabilize with no appreciable bias (Hoenig et al. 1997; Pollock et al. 1997).

Previous research on survey designs and catch rate estimation has been based on simulation models of fisheries by using either completed trip data or simulated data (Jones et al. 1995; Hoenig et al. 1997). These simulation models do not account for actual temporal changes in catch rate, and they fail to capture the unique characteristics that define Chinook salmon fisheries in Idaho. Furthermore, such modeling is based on an assumed or simulated distribution instead of observed data (Hoenig et al. 1997; Dauk and Schwarz 2001; Lockwood 2004). Various authors (e.g., Hoenig et al. 1997; Pollock et al. 1997) have identified the need for additional research to determine the properties of catch rate estimates for fisheries with different specific characteristics (e.g., temporal changes in catch rate).

Due to the nature of Chinook salmon fisheries in Idaho and other fisheries across the Columbia River basin, poorly designed creel surveys or improper statistical analyses could result in premature closing of a fishery or insufficient adult returns to hatcheries. The results from angler surveys could affect future fisheries or could jeopardize the sustainability of a threatened species. Constraints on these fisheries (i.e., harvest share and catch-and-release quota) create the necessity for accurate and precise short-term (e.g., daily or weekly), in-season estimates of total catch. Therefore, the objective of this research was to compare angler interview strategies (roving–access and roving–roving) and catch rate estimators (ROM and MOR) for estimating total catch in Idaho Chinook salmon fisheries.

METHODS

Study area.—The Snake River originates in Jackson Lake (Grand Teton National Park), Wyoming. After draining much of the southern portion of Idaho, the Snake River flows north, forming the Oregon–Idaho border, and then enters the Columbia River at Burbank, Washington. Anadromous fishes currently have access to portions of the Snake River below Hells Canyon Dam. Major Idaho tributaries below Hells Canyon Dam include the Salmon River and the Clearwater River (CR). Angler observations were conducted on the CR, the SFSR, and the Little Salmon River (LSR) near its confluence with the Salmon River.

Field methods.—Censuses of angling activity were completed on 200–700-m reaches of three Chinook salmon fisheries in Idaho based on direct visual observations that served as a theoretical angling population. Resampling simulations were then conducted, and the resulting sampling distributions were evaluated to determine the effect of survey type and catch rate estimator on the bias and precision of total catch estimates. Based on instantaneous counts of anglers in the census reach compared with simultaneous counts of anglers in the entire fishery (i.e., conducted by IDFG creel clerks), the observed census reach accounted for approximately 28% of angling effort in the entire fishery of interest on the CR, 19% of angling effort on the LSR, and 6% of angling effort on the SFSR. We assumed that these nonrandomly selected observation reaches were representative of the target population. These distributions served as the theoretical angling population that was resampled using Monte Carlo simulations. Observations were conducted for 6 d at each fishery (CR, SFSR, and LSR), for a total of 18 observation days. On the SFSR, two different reaches were observed during the 6-d period due to spatial shifts in angling activity. On the CR and LSR, observations were conducted at the same site throughout the 6-d period. Observation reaches were selected nonrandomly based on known fishing locations that allowed for discreet observations of anglers and adequate sample sizes (i.e., angling effort and total catch). Observation days were also selected nonrandomly and were conducted near the peak of the fishing season in each fishery to maximize observation of angling activity. Fishing hours for all fisheries were during daylight; on a given observation day, observers were present before the start of the legal fishing period, and they remained until after the end of the legal fishing period.

Observers remained “hidden” so as not to influence angler decisions on fishing locations, fishing times, fish harvest, or reporting to IDFG creel clerks. On the CR and LSR, angling activity was observed from afar using spotting scopes. However, this was not possible on the SFSR. Consequently, two observers were used to monitor fishing activity on the SFSR: one observer fished and relayed information to the other observer, who discreetly recorded data. The recorded data included the time each angler entered and left 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 arbitrary identification number, and a physical description was recorded.

The start of a fishing event was defined as the angler’s first cast, and 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. If an angler took a “break” and exited the fishery (i.e., was out of the field of visibility for the IDFG creel clerks who were conducting the roving counts) for a period of 5 min or greater, that angler was assumed to be unavailable for counting in a roving effort count. If an angler re-entered the fishery, that angler was re-assigned his initial identification number. All data were recorded on a per-angler basis to avoid bias or variance that may arise from estimates associated with angler groups or parties (e.g., pooled effort and catch; Lockwood 1997).

Sampling strategies.—Once the census data were collected, angling populations were created for simulation analysis. Angling populations were sampled using Monte Carlo simulations that employed various sampling and estimation strategies to evaluate bias and precision. Simple random sampling without replacement was used to estimate total effort, mean catch rate, and their product (i.e., total catch) in each fishery from the census data set. Effort was estimated with a simple random sampling design, where minutes were defined as the sampling units (i.e., count times) and were selected with equal probability. The sampling frame for count times included all minutes during legal fishing hours. Four count times were selected for each fishery and day, and counts of anglers were conducted instantaneously. To evaluate mean catch rate estimation using the roving–roving method, simulated interviews of 60% of all anglers were conducted each day at random times during their fishing trips. Anglers were selected for interview with selection probabilities proportional to the time fished. To evaluate mean catch rate estimation using the roving–access survey method, simulated interviews of 60% of all anglers were conducted at the conclusion of their fishing trips. In the roving–access survey, anglers were selected for interview with equal selection probabilities. Total catch was estimated in both roving–roving and roving–access simulations and included fish that were harvested and fish that were released.

Effort, catch rate, and total catch estimation.—Total angling effort ($\hat{E}$) in angler-hours in all simulated fisheries was estimated as

$$\hat{E} = T\bar{I}, \tag{1}$$

where T is the total number of hours in the fishing day and $\bar{I}$ is the mean of the four angler counts. Mean daily catch rate in all simulated fisheries was estimated using the ROM estimator ($\hat{R}_1$),

$$\hat{R}_1 = \frac{\sum_{i=1}^{n} c_i/n}{\sum_{i=1}^{n} L_i/n}, \tag{2}$$

and the mean catch rate per angler was calculated using the MOR estimator ($\hat{R}_2$),

$$\hat{R}_2 = \frac{\sum_{i=1}^{n} c_i/L_i}{n}, \tag{3}$$

where c_i is the number of fish caught by the ith angler, L_i is the number of hours fished by the ith angler, and n is the total number of anglers interviewed. Hoenig et al. (1997) and Pollock et al. (1997) suggested that the variance of mean catch rate estimates obtained by use of MOR could be stabilized by excluding the interviews of anglers whose trips were 0.5 h or less. Therefore, the MOR catch rate for each simulated fishery was estimated (1) with truncation of the data set to exclude short fishing trips of 0.5 h or less (MOR_{tr}) and (2) without truncation. Total catch in each simulated fishery was estimated by using the ROM catch rate (total catch $\hat{C}_1$),

$$\hat{C}_1 = \hat{E} \times \hat{R}_1, \tag{4}$$

and the MOR catch rate (total catch $\hat{C}_2$; with and without exclusion of trips ≤ 0.5 h),

$$\hat{C}_2 = \hat{E} \times \hat{R}_2. \tag{5}$$

For roving–roving surveys, mean catch rate was estimated using the three estimators (ROM, MOR, and MOR_{tr}), whereas for roving–access surveys the mean catch rate was estimated using the MOR and ROM estimators only. Mean catch rate was estimated on the same sample of anglers selected for each survey design and estimator at each iteration of the simulation. Nonparametric bootstrap 95% CIs were calculated for each estimate using the percentile method (Efron and Tibshirani 1993).

Simulations and evaluation.—For each survey design (roving–roving or roving–access) and catch rate estimator, Monte Carlo simulations were conducted that included 1,000 iterations of effort, mean catch rate, and their product (i.e., total catch estimate). This provided an empirical sampling distribution. Bias was estimated as the difference between the mean of the sampling distribution and the true population parameter. Relative bias was estimated as bias divided by the true population parameter. To assess the accuracy and precision of each estimator, the root mean square error (RMSE) was estimated as the square root of the mean squared difference between the estimate ($\hat{\theta}$) and the true value (θ):

$$\text{RMSE}(\hat{\theta}) = \sqrt{\frac{\sum_{i=1}^{1,000} (\hat{\theta}_i - \theta)^2}{1,000}}. \tag{6}$$

Coverage of the 95% CIs of total catch estimates was also evaluated. In theory, 95% of all bootstrap CIs should encompass the true population parameter, 2.5% should be below the true value, and 2.5% should be above the true value. The percentage of CIs that encompassed the true population parameter was determined along with the direction of CIs that did not encompass the known population value. Simulations and statistical analyses were conducted with R (R Development Core Team 2009).

When an angler is interviewed before their trip is complete (i.e., roving–roving surveys), the expectation is that the angler will be interviewed at the midpoint of the trip and that the angler's catch rate is stationary during the trip (Pollock et al. 1994; Jones et al. 1995; Hoenig et al. 1997). Linear regression was used to examine the effect of this assumption on the relative bias of catch rate estimates. Relative bias in total catch estimates from simulations was regressed against the true mean change in catch rate from the midpoint of the trip to the completion of the trip for all anglers for each day in the fishery. The slope and coefficient of determination (r^2) from the linear regression models were used to evaluate the effect of nonstationary catch rates on relative bias for all three catch rate estimators in roving–roving surveys. Greater slopes and r^2 values indicated greater effects of nonstationary catch rates on the relative bias of mean catch rate.

TABLE 1. Summary of angling activity observed for 6 d on each of three Chinook salmon fisheries in Idaho (Clearwater, Little Salmon, and South Fork Salmon rivers) during the 2011 fishing season.

Day	Total number of anglers	Total hours fished	Mean hours fished per angler	Number of fish caught	Daily catch rate (fish/h)
			Clearwater River		
1	49	254.6	5.2	8	0.031
2	47	264.2	5.6	8	0.030
3	31	251.1	8.1	9	0.036
4	14	44.2	3.1	3	0.068
5	37	122.9	3.3	6	0.049
6	42	123.5	2.9	4	0.032
			Little Salmon River		
1	46	195.9	4.2	26	0.133
2	20	71.0	3.5	15	0.211
3	25	96.2	3.8	22	0.229
4	27	136.6	5.0	18	0.132
5	40	183.8	4.6	17	0.092
6	37	116.7	3.1	19	0.163
			South Fork Salmon River		
1	6	30.4	5.0	1	0.033
2	5	43.0	8.6	2	0.046
3	9	59.8	6.6	5	0.083
4	8	71.1	8.8	6	0.084
5	29	124.4	4.2	21	0.169
6	29	105.9	3.6	17	0.161

RESULTS

Over the 18-d observation period, 2,296 h of angling effort and 501 angler trips were observed (Table 1). Observed anglers caught 207 Chinook salmon, with 10% of anglers catching 58% of the fish. Seventy-three percent of anglers were unsuccessful in catching a fish. Fishing time (mean $\pm$ SE) for all anglers was 4.6 ± 0.16 h (Figure 1). Fishing time for observed anglers who were successful in catching a fish averaged 6.9 ± 0.31 h, whereas anglers who were unsuccessful fished for an average of 3.7 ± 0.16 h. Total catch per day for all anglers varied from 1 to 26 fish (mean $\pm$ SE $= 11.5 \pm 1.84$ fish). The true mean daily catch rate (ROM) for observed anglers varied from 0.030 to 0.229 fish/h and averaged 0.099 ± 0.0029 fish/h. Mean per-angler catch rate (MOR) varied from 0.000 to 0.677 fish/h and averaged 0.085 ± 0.0096 fish/h. For anglers who caught fish, the time of the first catch varied from 0.02 to 14.90 h (mean $\pm$ SE $=$ 3.8 ± 0.27 h) after the beginning of the trip.

Simulations for all 18 observation days using simple random sampling to estimate angling effort resulted in relatively unbiased and precise estimates (Table 1; Figure 2). Relative bias in effort estimates varied from 0.25% to 1.22% (mean $\pm$ SE $=$ 0.62 ± 0.064%). The RMSE of simulated estimates of angling effort varied from 7.72 to 64.65 h (mean $\pm$ SE $= 25.00 \pm 3.95$ h). Bias and RMSE were highest for the CR fishery, where effort was greatest; bias and RMSE were lowest for the SFSR fishery, where effort was the lowest. The direction of bias in total effort estimates was not consistent among days but tended toward negative bias. Effort was overestimated on 4 of the 18 survey days and was underestimated on 14 survey days. The largest bias in any one sampling distribution was less than 3 h (i.e., on day 2 for the CR fishery). Although estimates of effort added further variability to estimates of total catch when combined with mean catch rate, they added little to overall bias.

Overall, among the three estimators, the ROM estimator provided the most accurate and precise estimates of mean catch rate (Figure 3) and total catch (Figure 4) for both survey designs (Table 2). Although the MOR_{tr} estimator generally performed better than the nontruncated MOR estimator, it did not perform as well as the ROM estimator. For roving–roving surveys, bias and RMSE of mean catch rate (Figure 3) and total catch (Figure 4) using the MOR estimator were highest on day 4 for the LSR fishery and day 6 for the SFSR fishery; bias was positive (i.e., mean catch rate and total catch were overestimated) on both days. The truncation of the data set to remove short-duration trips (MOR_{tr} estimator) reduced bias and RMSE on these days. Direction of bias for roving–roving surveys was not consistent over the 18-d period for any of the estimators. Mean catch rate and total catch were overestimated on 7 d when the MOR and MOR_{tr} estimators were used. The ROM overestimated mean

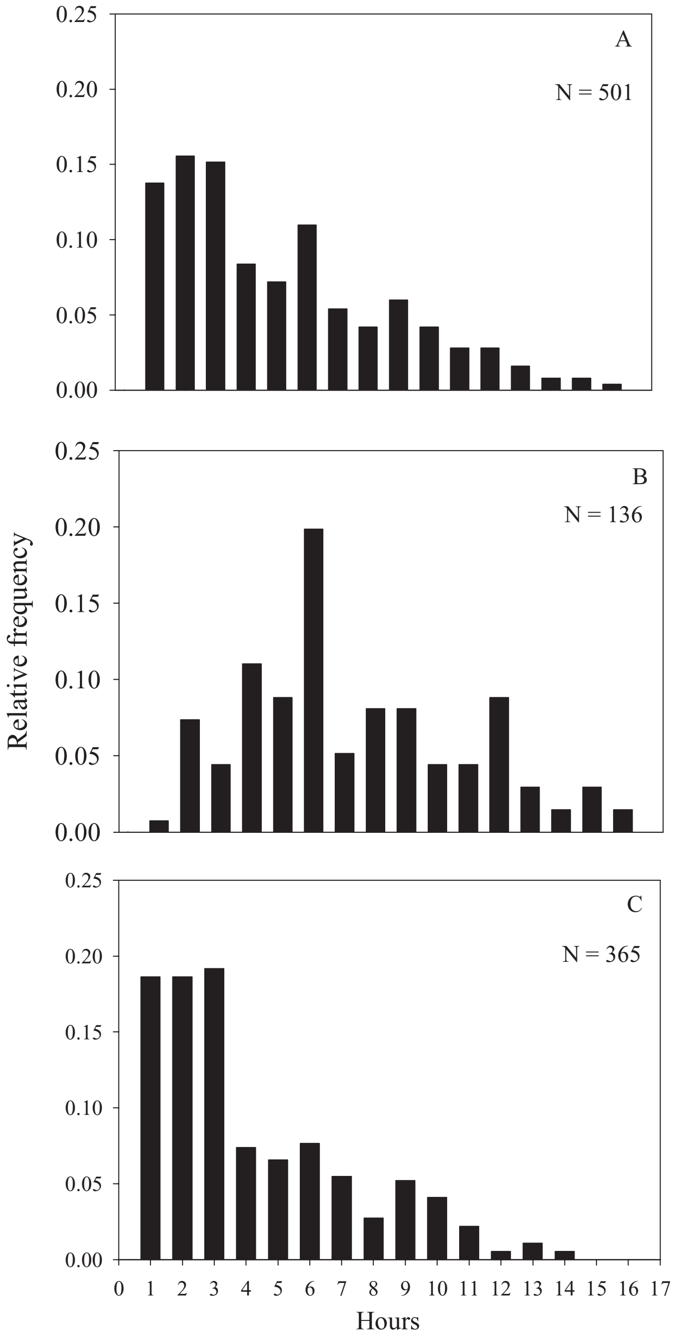

FIGURE 1. Distribution of hours fished for the 501 anglers observed in Chinook salmon fisheries on the Clearwater, Little Salmon, and South Fork Salmon rivers, Idaho, during the 2011 season: **(A)** all anglers, **(B)** anglers who caught one or more fish, and **(C)** anglers who did not catch any fish.

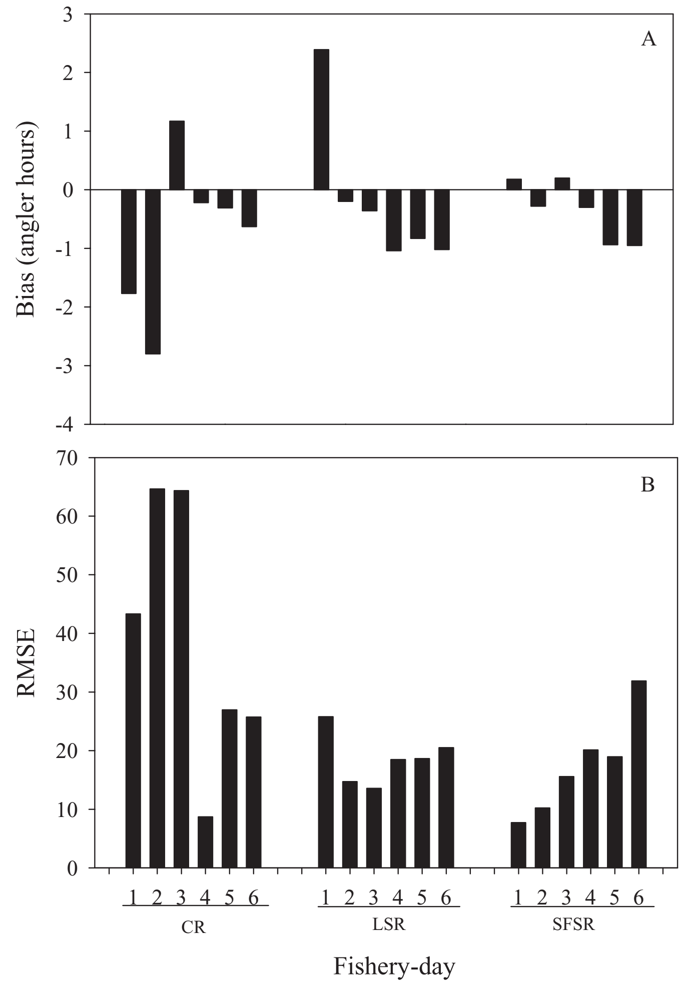

FIGURE 2. **(A)** Bias and **(B)** root mean square error (RMSE) of estimated angling effort (angler-hours) from roving creel surveys in three simulated Chinook salmon fisheries on the Clearwater River (CR), Little Salmon River (LSR), and South Fork Salmon River (SFSR), Idaho, during the 2011 season. Angling activity was observed for 6 d on 200–700-m reaches in each fishery to obtain profiles of angling effort.

catch rate and total catch on 6 d for the roving–roving survey design.

For the roving–roving design, the mean CI coverage of total catch estimates for all days was closest to 95% when the ROM estimator was used (mean $\pm$ SE $= 87.8 \pm 3.75\%$; Table 2). With use of the MOR_{tr} estimator, the CIs resulted in a mean coverage of $78.6 \pm 4.00\%$, indicating slightly better performance than that of the nontruncated MOR estimator (mean $\pm$ SE $=$ $75.0 \pm 4.10\%$). For all estimators used with the roving–roving design, the CIs that did not contain the true total catch were typically biased low. For all estimators over the 18-d period, an underestimate of CI coverage was observed approximately 96% of the time (i.e., mean between days) when the CI did not encompass the true parameter.

Use of the ROM estimator in a roving–access survey consistently resulted in a smaller relative bias and higher precision than use of the MOR estimator (Figures 3, 4). The only exception was on day 6 for the CR fishery, when performance was similar between estimators. Bias from use of the ROM estimator was less than 0.6 fish for every day in the fishery. The direction of bias was not consistent between days for either estimator. Mean catch rate and total catch were overestimated on 11 d and

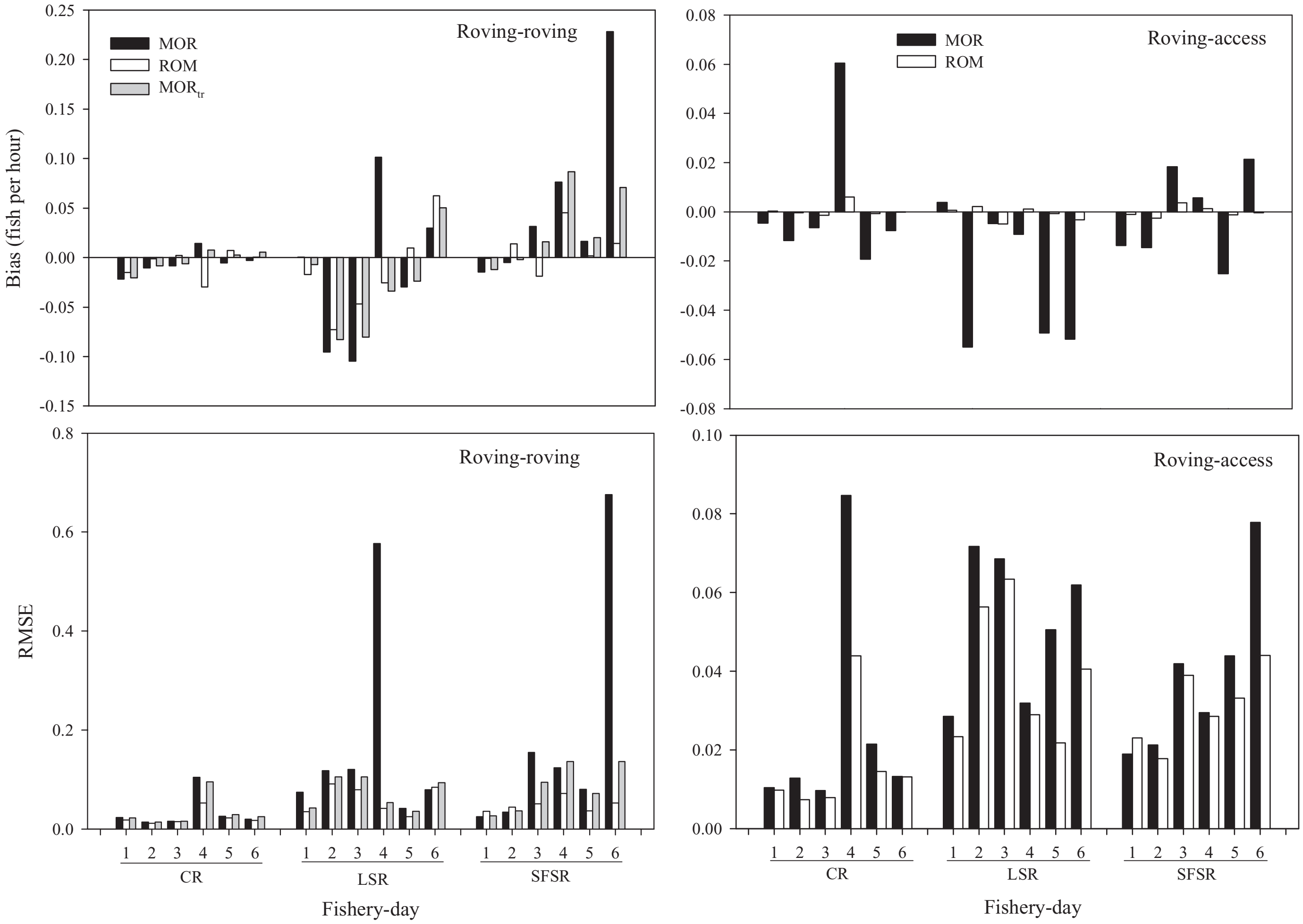

FIGURE 3. Bias and root mean square error (RMSE) of estimated mean catch rate (fish/h) from roving–roving (left panels) and roving–access (right panels) creel surveys conducted in three Chinook salmon fisheries (Clearwater River [CR], Little Salmon River [LSR], and South Fork Salmon River [SFSR], Idaho) during 2011. The mean-of-ratios (MOR) and ratio-of-means (ROM) estimators were calculated for simulated roving–roving and roving–access surveys. The MOR estimator with truncation of the data set to exclude 0.5-h or shorter fishing trips (MOR$_{tr}$) was also evaluated for the roving–roving surveys. Simulations for each fishery encompassed 6 d.

underestimated on 7 d when the ROM was used; with the MOR estimator, mean catch rate and total catch were overestimated on 13 d and underestimated on 5 d. For the roving–access design, mean CI coverage for all days was $95.3 \pm 1.67\%$ (mean $\pm$ SE) when using the ROM estimator and $83.7 \pm 4.03\%$ when using the MOR estimator (Table 2). Similar to the roving–roving survey design, CI coverage was biased low. Over the 18-d period, when the CIs did not encompass the true parameter, they were underestimated approximately 97% of the time for both estimators.

The RMSE of total catch estimates for roving–roving surveys was 1.42 times greater (range = 1.04–2.24 times greater) than that observed for roving–access surveys on average. This suggests that accuracy would be 1.42 times less in a roving–roving survey than in a roving–access survey. Roving–roving surveys resulted in total catch estimates that were 160.13 times more biased on average (range = 0.02–2,500.06 times more biased) than those from roving–access surveys.

Length-of-stay bias and nonstationary catch rates in roving–roving surveys appeared to affect estimates of mean catch rate and total catch. Figure 5 illustrates the potential effect of nonstationary catch rates on bias in roving–roving surveys; the three observation days depicted in the figure were selected because of the observed relative bias from the simulations. For instance, on day 6 for the SFSR fishery, anglers had a higher catch rate (on average) at the midpoint of their trips than at the completion of their trips (Figure 5), resulting in an overestimate of total catch by use of all three estimators (Figure 4). The opposite scenario was observed on day 2 for the LSR fishery, when anglers had a lower catch rate at the midpoint of their trips and the total catch was underestimated. On day 1 for the LSR fishery, anglers had a relatively small change in catch rate on average, and total catch

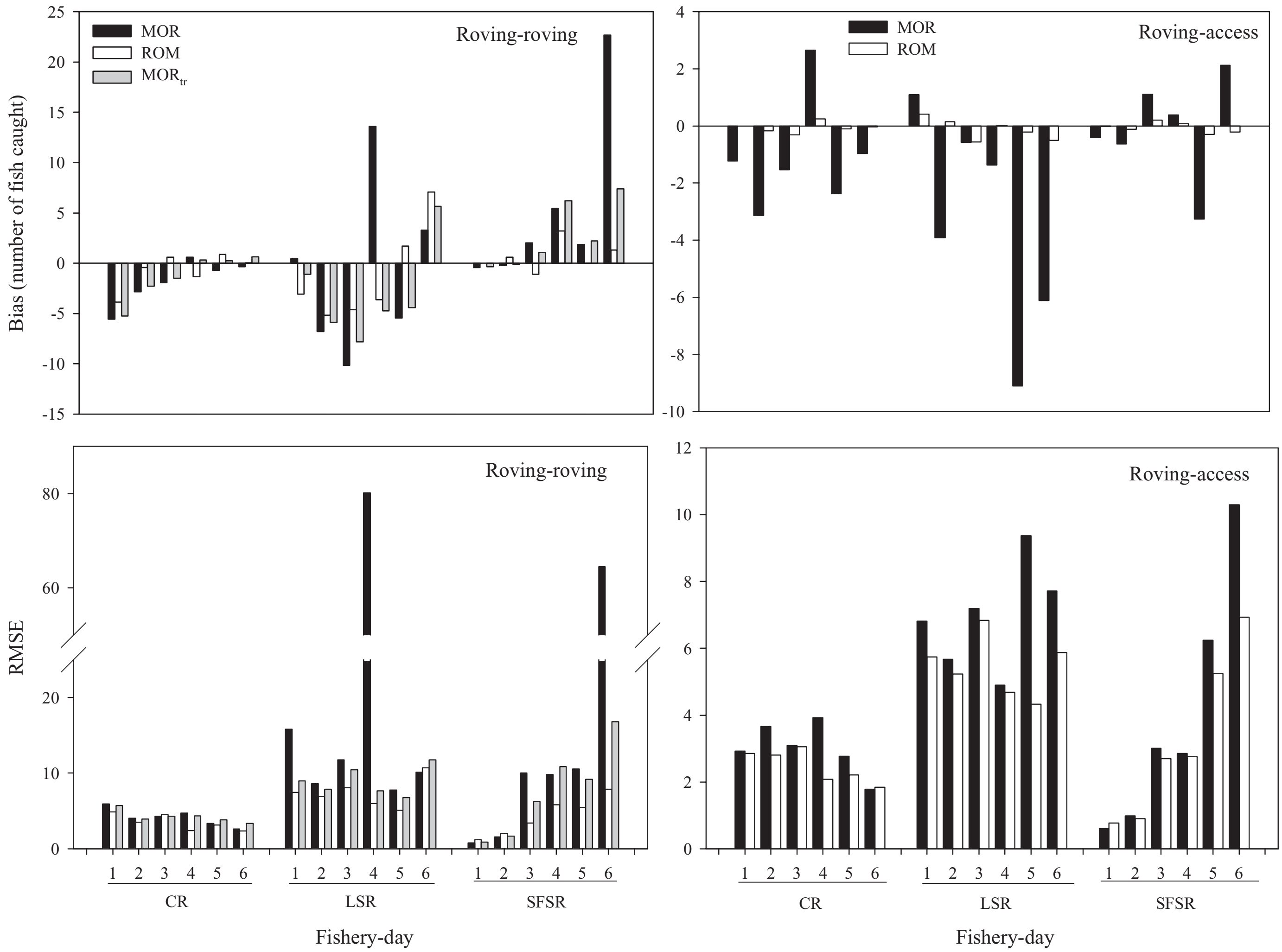

FIGURE 4. Bias and root mean square error (RMSE) of estimated total catch from roving–roving (left panels) and roving–access (right panels) creel surveys conducted in three Chinook salmon fisheries (Clearwater River [CR], Little Salmon River [LSR], and South Fork Salmon River [SFSR], Idaho) during 2011. The mean-of-ratios (MOR) and ratio-of-means (ROM) estimators were calculated for simulated roving–roving and roving–access surveys. The MOR estimator with truncation of the data set to exclude 0.5-h or shorter fishing trips (MOR_{tr}) was also evaluated for the roving–roving surveys. Simulations for each fishery encompassed 6 d.

estimates were relatively unbiased. The three estimators were not equally sensitive to nonstationary catch rates. Nonstationary catch rates explained 64% of the variability in relative bias of total catch estimates from the MOR, 21% of the variability in relative bias from the MOR_{tr}, and 14% of the variability in relative bias from the ROM (Figure 6). The slope of the regression line describing the change in catch rate versus relative bias of simulated total catch estimates from the MOR estimator was 2.4 times higher than the slope for the MOR_{tr} estimator and 4.3 times higher than the slope for the ROM estimator.

DISCUSSION

Results from this study are consistent with recommendations from previous research with regard to roving–access surveys but differ from previous work on roving–roving surveys (Jones et al. 1995; Hoenig et al. 1997; Lockwood 1997; Pollock et al. 1997). Jones et al. (1995) suggested that the ROM and MOR estimators do not estimate the same theoretical catch rate. Instead, the ROM estimates the per-day catch rate and the MOR estimates the per-angler catch rate. When interviews are combined with an estimate of total effort, the ROM estimates total catch when interviews are from completed trips (i.e., roving–access surveys), whereas the MOR estimates total catch when interviews are from incomplete trips (i.e., roving–roving surveys). Hoenig et al. (1997) and Pollock et al. (1997) provided a theory to explain why the estimators are appropriate in different situations (i.e., complete versus incomplete trips), and showed that the MOR estimator could be improved by excluding interviews representing fishing trips that were 0.5 h or shorter in

TABLE 2. Percent CI coverage for simulated estimates of total catch (percentage of CIs that encompassed the true value of total catch) on 6 d for each of three Chinook salmon fisheries in Idaho (Clearwater, Little Salmon, and South Fork Salmon rivers) during the 2011 season. Two survey designs (roving–roving and roving–access surveys) were simulated. Three estimators of mean catch rate were used for roving–roving surveys (mean of ratios [MOR], ratio of means [ROM], and MOR with truncation of the data set to exclude fishing trips ≤ 0.5 h [MOR_{tr}]), and two estimators of catch rate were used for roving–access surveys (MOR and ROM).

		Roving–roving survey			Roving–access survey	
Day	Number of fish caught	MOR	ROM	MOR_{tr}	MOR	ROM
Clearwater River						
1	8	36.8	76.1	44.1	89.3	97.7
2	8	76.7	96.0	81.2	75.2	97.8
3	9	84.3	97.5	87.0	91.4	95.4
4	3	52.1	52.0	46.5	93.2	94.1
5	6	86.8	98.1	91.7	77.5	98.2
6	4	84.1	90.7	88.5	85.8	97.5
Little Salmon River						
1	26	89.6	97.6	93.4	97.8	99.3
2	15	59.9	88.0	68.7	87.4	98.9
3	22	58.6	92.4	75.8	94.6	96.4
4	18	79.8	95.8	81.4	94.8	99.4
5	17	69.7	99.6	82.1	25.4	97.9
6	19	92.8	99.8	95.7	70.0	96.8
South Fork Salmon River						
1	1	47.7	47.8	47.7	67.5	68.1
2	2	72.9	73.6	72.9	87.9	90.6
3	5	77.8	80.6	77.4	95.8	97.6
4	6	94.8	96.7	94.5	94.5	93.9
5	21	93.8	99.2	96.4	90.5	98.4
6	17	91.3	97.5	90.1	88.2	96.6

duration. Hoenig et al. (1997), Jones et al. (1995), Lockwood (1997), and Pollock et al. (1997) all presented simulation studies that were consistent with this theory. Our study results suggest that using the ROM estimator in combination with an estimate of angler effort provided the least biased and most precise estimates of total catch for both survey designs used in Idaho Chinook salmon fisheries.

The properties of the ROM estimator when used with roving–access surveys are well understood because anglers are interviewed with equal probability at the completion of their trips (Pollock et al. 1994, 1997; Jones et al. 1995). With few exceptions, mean catch rate estimates for roving–access surveys are not affected by bag limits, length-of-stay bias, or nonstationary catch rates (Pollock et al. 1994; Bernard et al. 1998; Rasmussen at al. 1998). Empirical studies have likely been consistent with regard to the correct estimator in roving–access surveys because of the properties of the ROM estimator and the lack of assumptions (e.g., stationary catch rates) in surveys based on access interviews. When multiplied by an estimate of effort, the ROM estimator provides an unbiased estimate of total catch. In contrast, when the MOR estimator is multiplied by an estimate of effort in a roving–access survey, it does not provide a true estimate of total catch (Jones et al. 1995; Pollock et al. 1997). Our results are consistent with previous research indicating that the ROM is the appropriate estimator in roving–access surveys when total catch is the parameter of interest (Jones et al. 1995; Lockwood 1997; Pollock et al. 1997).

Simulations based on effort and catch data from Chinook salmon fisheries in Idaho suggest that the ROM estimator was the least biased and most precise estimator for roving–roving creel surveys. This finding is inconsistent with simulation results presented by Jones et al. (1995) and Hoenig et al. (1997); however, their simulations were conducted for fisheries with characteristics that were vastly different from those of Chinook salmon fisheries in Idaho. Specifically, the disparity between successful and unsuccessful anglers in terms of catch rates (>70% of observed anglers did not catch any fish) and time fished was greater in the present study than in the previous studies. In addition, previous simulations did not account for actual changes in angler catch rates over time. Jones et al. (1995) suggested that the ROM estimator in roving–roving surveys typically overestimates catch, but this was generally not observed in our study. When simulated catch rates were overestimated in comparison with known values, we found that it was likely a result of

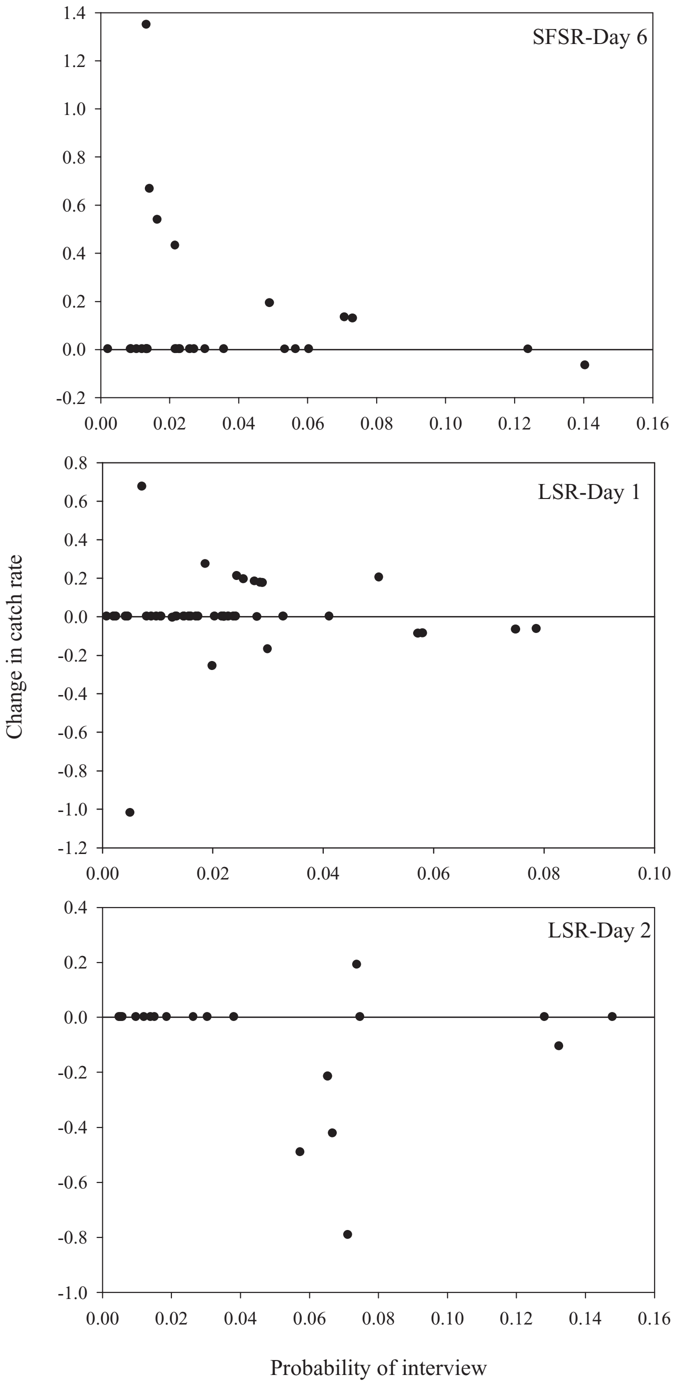

FIGURE 5. Probability that an angler would be interviewed versus the change in catch rate from the midpoint to the completion of the fishing trip for individual anglers in Chinook salmon fisheries, as illustrated by 2 d on the Little Salmon River (LSR) and 1 d on the South Fork Salmon River (SFSR), Idaho, in 2011. Theoretically, it is assumed that (1) anglers are interviewed at the midpoint of their fishing trips in a roving survey design and (2) the catch rate at the midpoint of an angler's trip should represent the final catch rate for that trip (i.e., assumption of stationary catch rate).

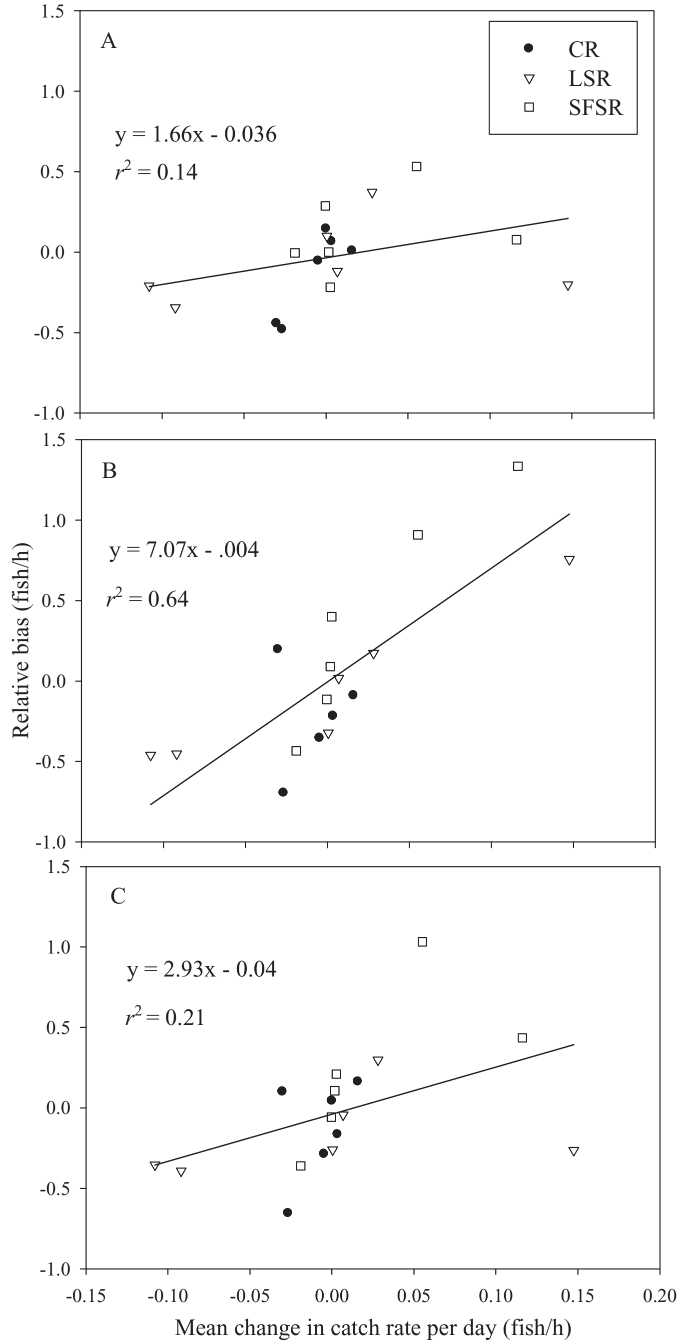

FIGURE 6. Relationship between the mean change in catch rate (fish/h) from the midpoint of an angler's fishing trip to the completion of the trip for all anglers on each day and the relative bias of total catch estimates from simulations using three catch rate estimators: **(A)** ratio of means, **(B)** mean of ratios, and **(C)** mean of ratios with truncation of the data set to exclude 0.5-h or shorter fishing trips. Chinook salmon fisheries on the Clearwater River (CR), Little Salmon River (LSR), and South Fork Salmon River (SFSR), Idaho, were each evaluated for 6 d (i.e., 18 total observation days).

interviewing a few anglers who fished for a relatively short time and caught a fish. Not surprisingly, these anglers had an extremely high catch rate, which biased estimates of mean catch rate. The ROM estimator was not affected by these anglers to the same extent as the MOR estimator. When the MOR estimator is used, each angler is equally weighted, whereas the ROM estimator involves weighting each angler by the length of time fished. The effect of high catch rates and low effort on mean catch rate has been recognized in the literature. For instance, Hoenig et al. (1997) and Pollock et al. (1997) suggested that to alleviate the effect of anglers with inflated catch rates, short trips ($\leq$0.5 h) should be excluded when using the MOR estimator with roving–roving surveys. The MOR_{tr} estimator has been recommended for use in roving–roving surveys (Hoenig et al. 1997). Hoenig et al. (1997) reported that the MOR_{tr} and ROM estimators typically resulted in similar estimates on average, but the MOR_{tr} estimator resulted in a smaller mean square error. Our results are consistent in that the MOR_{tr} and ROM estimators resulted in similar estimates; however, the ROM estimator resulted in a lower RMSE, lower bias, and more accurate CI coverage than either of the MOR estimators. The removal of trips of different durations may have been more consistent with previous research (e.g., excluding trips $\leq$ 1 h instead of trips $\leq$ 0.5 h). Although bias was decreased by truncating short trips in this study, caution should be taken when subjectivity is used (i.e., deciding to ignore trips of a given length) in an attempt to improve estimates. Such actions may result in additional and unpredictable bias.

In addition to producing a smaller average bias and lower RMSE, the ROM estimator was associated with 95% CI coverage that was closest to targeted values for both the roving–roving and roving–access survey designs. However, the skewed distributions of catch rates (i.e., most anglers were unsuccessful in catching a fish) resulted in CIs that were biased low. Jones et al. (1997) found similar results (80–99% of the rejection area was concentrated in the left tail) when using closed-form variance estimators. Jones et al. (1997) suggested that a sample size of 100 interviews would result in CI coverage equal to targeted levels but that the coverage would still be asymmetrical due to the skewed distribution of catch rates. Chinook salmon fisheries in Idaho and elsewhere are characterized by high localized densities of angler effort relative to that observed for many other fisheries (Martinson and Shelby 1992). Interviewing 100 or more anglers on most survey days is a realistic and reasonable target when planning surveys and hiring creel survey personnel. However, catch rates in Idaho Chinook salmon fisheries are typically skewed to a greater extent than those in the fisheries described by Jones et al. (1997), and thus a higher sampling intensity may be necessary to reach targeted CIs.

In the roving–roving surveys, biased estimates of total catch may have resulted from both length-of-stay bias and nonstationary angler catch rates. Anglers who caught fish tended to have longer fishing durations and therefore a higher probability of being interviewed than anglers who were unsuccessful in catching fish (Pollock et al. 1994). Given the disparate distributions of trip duration between groups of anglers with differing catch rates, we would expect catch rate and total catch to be consistently overestimated because anglers with higher catch rates were more likely to be interviewed. However, with the exception of the SFSR fishery, use of all three estimators with the roving–roving surveys resulted in a negative bias on most days. This suggests that variable catch rates are more responsible for the bias observed in our study.

It is assumed that anglers are interviewed at the midpoint of their fishing trips in a roving survey, and their catch rate at that point is assumed to be constant (stationary catch rate; Pollock et al. 1994; Hoenig et al. 1997). In the Chinook salmon fisheries we studied, anglers failed to meet the stationary catch rate assumption on the days of observation. For instance, on day 6 for the SFSR fishery, successful anglers tended to have a higher catch rate at the midpoint of their trips relative to the end of their trips; this resulted in overestimation of catch rate and total catch for that day. The opposite scenario was observed on day 2 for the LSR fishery, where anglers had a lower catch rate at the midpoint than at the end of their trips and estimates were negatively biased. Individual anglers' catch rates were not constant on LSR day 1, but the change in catch rate was inconsistent among anglers, thereby resulting in unbiased estimates of mean catch rate and ultimately total catch.

Multiple methods have been proposed to account for differences in catch rates between incomplete trips and completed trips. Pollock et al. (1997) suggested that complete and incomplete catch rates should be estimated on the same sample of anglers to validate the use of the MOR estimator with roving surveys. Keefe et al. (2009) provided methodology to use linear regression models that correct for apparent bias in catch rates based on incomplete trips. Dauk and Schwarz (2001) proposed a model that improved catch rate estimates for a gill-net fishery by assuming declining catch rates instead of stationary catch rates. However, in the three Chinook salmon fisheries we evaluated, the trajectory of catch rates through time was not consistent among the fisheries or among days, thus precluding use of the models similar to those proposed by Dauk and Schwarz (2001) and Keefe et al. (2009). Validation of catch rates from the same sample of anglers, as was suggested by Pollock et al. (1997), would be impractical because it would have to be performed daily due to inconsistency in catch rates. When properly designed, roving–access surveys are free from length-of-stay bias and the assumption of stationary catch rates. Consequently, access surveys are preferable whenever logistically possible.

Although use of the ROM estimator with roving–roving surveys provided the most precise and unbiased estimates in our study, use of the ROM with a roving–roving survey should be done with caution. Hoenig et al. (1997) showed that using the ROM catch rate estimator with a roving–roving survey did not provide the most unbiased and precise estimates of total catch. Instead, those authors recommended using the MOR_{tr} estimator.

Our simulations showed that the ROM is the preferred estimator for both roving–roving and roving–access surveys, probably due to the characteristics of Chinook salmon fisheries in Idaho. However, all of the mean catch rate and total catch estimates were biased when a roving–roving survey design was used. Given the inconsistent properties of estimators used with roving–roving creel surveys, roving–access surveys are preferable when circumstances allow.

ACKNOWLEDGMENTS

We thank Nick Porter for assistance with data collection; IDFG management biologists for sharing their expertise on sampling locations and current survey designs; and B. Stevens, K. Pollock, and two anonymous reviewers for providing comments on earlier versions of this manuscript. Funding for this project was provided by IDFG through the Federal Aid in Sport Fish Restoration Act. The Idaho Cooperative Fish and Wildlife Research Unit is jointly sponsored by the University of Idaho, U.S. Geological Survey, IDFG, and Wildlife Management Institute. The use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES

Apperson, K. A., and G. R. Wilson. 1998. 1997 Chinook salmon fishery on the South Fork Salmon River, Idaho. Idaho Department of Fish and Game, IDFG 98-32, Boise.

Bernard, D. R., A. E. Bingham, and M. Alexandersdottir. 1998. Robust harvest estimates from on-site roving-access creel surveys. Transactions of the American Fisheries Society 127:481–495.

Crone, P. R., and S. P. Malvestuto. 1991. Comparison of five estimators of fishing success from creel survey data on three Alabama reservoirs. Pages 61–66 *in* D. Guthrie, J. M. Hoenig, M. Holliday, C. M. Jones, M. J. Mills, S. A. Moberly, K. H. Pollock, and D. R. Talhelm, editors. Creel and angler surveys in fisheries management. American Fisheries Society, Symposium 12, Bethesda, Maryland.

Dauk, P. C., and C. J. Schwarz. 2001. Catch estimation in the presence of declining catch rate due to gear saturation. Biometrics 57:287–293.

Efron, B., and R. J. Tibshirani. 1993. An introduction to the bootstrap. Chapman and Hall, New York.

Hayne, D. W. 1991. The access point creel survey: procedures and comparison with the roving-clerk creel survey. Pages 123–138 *in* D. Guthrie, J. M. Hoenig, M. Holliday, C. M. Jones, M. J. Mills, S. A. Moberly, K. H. Pollock, and D. R. Talhelm, editors. Creel and angler surveys in fisheries management. American Fisheries Society, Symposium 12, Bethesda, Maryland.

Hoenig, J. M., C. M. Jones, K. H. Pollock, D. S. Robson, and D. L. Wade. 1997. Calculation of catch rate and total catch in roving surveys of anglers. Biometrics 53:306–317.

Janssen, P., and S. W. Kiefer. 1999. Little Salmon River, Idaho spring Chinook salmon (*Oncorhynchus tshawytscha*) 1998 sport harvest report. Idaho Department of Fish and Game, IDFG 99-01, Boise.

Jones, C. M., D. S. Robson, H. D. Lakkis, and J. Kressel. 1995. Properties of catch rates used in analysis of angler surveys. Transactions of the American Fisheries Society 124:911–928.

Keefe, D. G., R. C. Perry, and J. G. Luther. 2009. A comparison of two methodologies for estimating brook trout catch and harvest rates using incomplete and complete fishing trips. North American Journal of Fisheries Management 29:1058–1064.

Lockwood, R. N. 1997. Evaluation of catch rate estimators from Michigan access point angler surveys. North American Journal of Fisheries Management 17:611–620.

Lockwood, R. N. 2004. Comparison of access and roving catch rate estimates under varying within-trip catch-rates and different roving minimum trip lengths. Michigan Department of Natural Resources, Fisheries Research Report 2069, Ann Arbor.

MacKenzie, C. 1991. Comparison of northern pike catch and harvest rates estimated from uncompleted and completed fishing trips. Pages 47–50 *in* D. Guthrie, J. M. Hoenig, M. Holliday, C. M. Jones, M. J. Mills, S. A. Moberly, K. H. Pollock, and D. R. Talhelm, editors. Creel and angler surveys in fisheries management. American Fisheries Society, Symposium 12, Bethesda, Maryland.

Malvestuto, S. P. 1983. Sampling the recreational fishery. Pages 397–419 *in* L. A. Nielsen and D. L. Johnson, editors. Fisheries techniques. American Fisheries Society, Bethesda, Maryland.

Martinson, K. S., and B. Shelby. 1992. Encounter and proximity norms for salmon anglers in California and New Zealand. North American Journal of Fisheries Management 12:559–567.

Myers, J. M., R. G. Kope, G. J. Bryant, D. Teel, L. J. Lierheimer, T. C. Wainwright, W. S. Grant, F. W. Waknitz, K. Neely, S. T. Lindley, and R. S. Waples. 1998. Status review of Chinook salmon from Washington, Idaho, Oregon, and California. NOAA Technical Memorandum NMFS-NWFSC-35.

Pollock, K. H., J. M. Hoenig, C. M. Jones, D. S. Robson, and C. J. Greene. 1997. Catch rate estimation for roving and access point surveys. North American Journal of Fisheries Management 17:11–19.

Pollock, K. H., C. M. Jones, and T. L. Brown. 1994. Angler survey methods and their applications in fisheries management. American Fisheries Society, Special Publication 25, Bethesda, Maryland.

R Development Core Team. 2009. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna.

Rasmussen, P. W., M. D. Staggs, T. D. Beard Jr., and S. P. Newman. 1998. Bias and confidence interval coverage of creel survey estimators evaluated by simulation. Transactions of the American Fisheries Society 127: 469–480.

Robson, D. S. 1960. An unbiased sampling and estimation procedure for creel censuses of fishermen. Biometrics 16:261–277.

Robson, D. S. 1961. On the statistical theory of a roving creel census of fishermen. Biometrics 17:415–437.

Robson, D. S. 1991. The roving creel survey. Pages 19–24 *in* D. Guthrie, J. M. Hoenig, M. Holliday, C. M. Jones, M. J. Mills, S. A. Moberly, K. H. Pollock, and D. R. Talhelm, editors. Creel and angler surveys in fisheries management. American Fisheries Society, Symposium 12, Bethesda, Maryland.