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MANAGEMENT BRIEF

A Mark–Recapture-Based Approach for Estimating Angler Harvest

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Abstract
Fishing effort in "traditional" creel surveys is derived from instantaneous angler counts, which in some fisheries can carry a high cost in personnel time, resources, and safety. To estimate angler effort more efficiently and at lower cost, we used mark–recapture methods to estimate weekly angler populations in Pacific salmon *Oncorhynchus* spp. and steelhead *O. mykiss* fisheries on the Salmon River, Idaho. Weekly harvest estimates were the product of weekly angler population, mean number of days fished per angler per week, and mean harvest per angler per day. We compared traditional and mark–recapture estimates of weekly harvest using paired analysis on a sample of 48 weeks. We found no significant difference in harvest estimates between traditional and mark–recapture methods, and the mark–recapture estimates in our fisheries could be made at a savings of up to 50% in vehicle mileage associated with conducting angler counts. However, the width of 95% CIs around harvest estimates was significantly higher for the mark–recapture method, due to higher upper confidence limits resulting from right-skewness of the sampling distribution of the mark–recapture-based estimator. Precision could be improved by replacing time spent on counts in the traditional method with more time spent "capturing" anglers at access sites, still providing savings in vehicle mileage.

To manage exploited fish stocks, it is essential to develop estimates of the number of fish harvested by anglers (Slaney et al. 1996; Dauble and Mueller 2000; Griffiths et al. 2010). To accomplish this, researchers and managers have developed and applied a number of traditional and innovative methods. Examples of traditional surveys include roving or access surveys (Hayne 1991) and phone surveys (Weithman and Haverland 1991). Estimation of fish mortality based on recoveries of reward (Hearn et al. 1999), radiotelemetry (Hightower et al. 2001), and PIT (Pine et al. 2003) tags is now commonplace. More recently, technological advances are allowing researchers to develop innovative methods for estimating fish harvest, such as direct observation via the use of cameras on fishing vessels (Wallace et al. 2015). A combination of web cameras and on-site creel surveys to collect effort and catch data at boat ramps has been successfully tested for estimating fish harvest along the northeastern coast of New Zealand's North Island (Hartill et al. 2016). Recently, the Oregon Department of Fish and Wildlife has explored the possibility of using smartphone applications to estimate the number of salmon caught in fisheries (McCormick 2017).

Recent innovations in the monitoring of exploited fisheries have been motivated by the need to conduct high-precision estimates of effort, harvest, and other parameters at higher efficiency and lower cost. Such a need motivated us to develop an alternative method for estimating angler effort in a fishery in which traditional angler counts carry high personnel, resource, and safety costs. In Idaho, approximately 1,232 km of river are seasonally open for Chinook Salmon *Oncorhynchus tshawytscha* and steelhead *O. mykiss* recreational fisheries. To collect data for estimating harvest in these fisheries, the Idaho Department of Fish and Game (IDFG) uses off-site phone surveys and on-site access-point and roving-roving creel surveys. However, Idaho's salmon fisheries are managed on a weekly or daily basis because of limited harvest quotas. Therefore, only on-site surveys can be used to assess estimated angler harvest of salmon by sport fishers for the purposes of determining in real time when quotas have been met.

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In "traditional" roving-roving or roving-access creel surveys, fishing effort is derived from instantaneous counts of anglers and is expressed in angler-hours (Malvestuto et al. 1978; Hoenig et al. 1997; Bernard et al. 1998). Catch rates are derived from angler interviews conducted by roving or access-site methods and are usually expressed in fish per angler-hour (Hoenig et al. 1997; Pollock et al. 1997; McCormick et al. 2012). Total catch is then equal to the product of total effort and catch rate (Hoenig et al. 1997). Instantaneous counts can be conducted by air, boat, or vehicle or on foot, depending on the nature of the fishery. In some cases, the number of counts required to obtain truly unbiased estimates of fishing effort can be great (Pierce and Bindman 1994). In the salmon and steelhead fisheries of the upper Salmon River, Idaho, the only effective method of obtaining instantaneous angler counts is from a vehicle. During 2015, IDFG personnel drove approximately 42,961 km along the upper Salmon River while exclusively conducting instantaneous counts of salmon anglers at an estimated cost of US$12,029 annually. This mileage cost is in addition to that required to conduct interviews. Between 2013 and 2016, six vehicle collisions involving animals and vehicles cost more than $20,000. In these types of situations, fisheries managers would benefit from a safer, less expensive method of estimating angler effort, as long as the alternative method produces unbiased results of equal precision.

At the same time, land management agencies, local governments, and emergency services providers could benefit, for the purposes of budgeting and planning, from knowledge of the number of anglers using particular roads and access sites. For this need, fishing effort measured in angler-hours may not be the most appropriate measure of use. Rather, the population of anglers using a given area during a particular time period may be more relevant (Pope et al. 2017). To reduce operating costs and potential for vehicle accidents, as well as to provide estimates of angler populations, we tested a roving, interview-based survey method that does not require counts of anglers to estimate fishery harvest but instead uses mark–recapture population estimators.

The use of mark–recapture methods to estimate populations of people for purposes of sociological, medical, or recreational fishing surveys is well documented (Fraidenburg and Bargmann 1982; Mastro et al. 1994; Tillings 2001; Böhning 2008; Ellender et al. 2010; Zischke and Griffiths 2014). For fishery surveys, anglers can be "marked" in the field during creel interviews and later identified as "recaptured" when encountered in subsequent interviews. Mark–recapture methods such as those of Peterson (Ricker 1975), Schnabel (Schnabel 1938), or Jolly–Seber (Krebs 1989) can then be used to estimate populations of participants. In our case, we used mark–recapture methods to estimate the population of anglers in the fishery each week and then multiplied the number of anglers by the mean number of days fished per week per angler to obtain an estimate of weekly effort in angler-days. Multiplying angler effort by mean number of fish harvested per day per angler yielded an estimate of total weekly harvest. All data needed for this estimate are obtained solely from angler interviews.

Beginning in 2013, we began testing a mark–recapture-based method for estimating angler harvest in the salmon and steelhead fisheries of the upper Salmon River and conducted paired comparisons of estimated weekly harvest between traditional (roving-roving and roving-access) and mark–recapture methods. The objectives of the study were to (1) estimate weekly population of anglers using mark–recapture methods, (2) from appropriate mark–recapture methods, identify the method that created the most precise estimates, (3) combine the variables of angler population, days fished per week, and catch per day to estimate harvest, (4) develop confidence intervals for mark–recapture-based estimates of harvest, (5) compare estimated harvest and precision generated from traditional roving creel methods against those generated from mark–recapture-based roving creel methods, and (6) estimate cost savings from eliminating vehicle-based instantaneous counts.

METHODS

Study Site

The upper Salmon River is a 415-km, eighth-order reach of the Salmon River located in Lemhi and Custer counties in east-central Idaho (Figure 1). The terrain is mountainous with narrow valleys. When vehicle access is present, roads and highways often parallel the river in close proximity. Salmon and steelhead migrate as juveniles to the Pacific Ocean via the Snake River and Columbia River and return as adults, traveling a distance of approximately 1,400 km each direction. Differentially marked, hatchery-reared Chinook Salmon and steelhead return to hatcheries located near the headwaters of the Salmon River.

For management purposes, IDFG has stratified the upper Salmon River into distinct river reaches, ranging in length from 34 to 75 km, and identified them by numerical location codes. We tested the mark–recapture method against the traditional survey method on the four river reaches with location codes 16, 17, 18, and 19 (Figure 1). Fishery characteristics varied among the river reaches. In reaches 16–18, angling effort was nearly uniformly split between boat and bank anglers, whereas in reach 19, bank anglers dominated the fishing effort. Catch was split between salmon and steelhead in all reaches except reach 16, where steelhead dominated the catch. Spatial

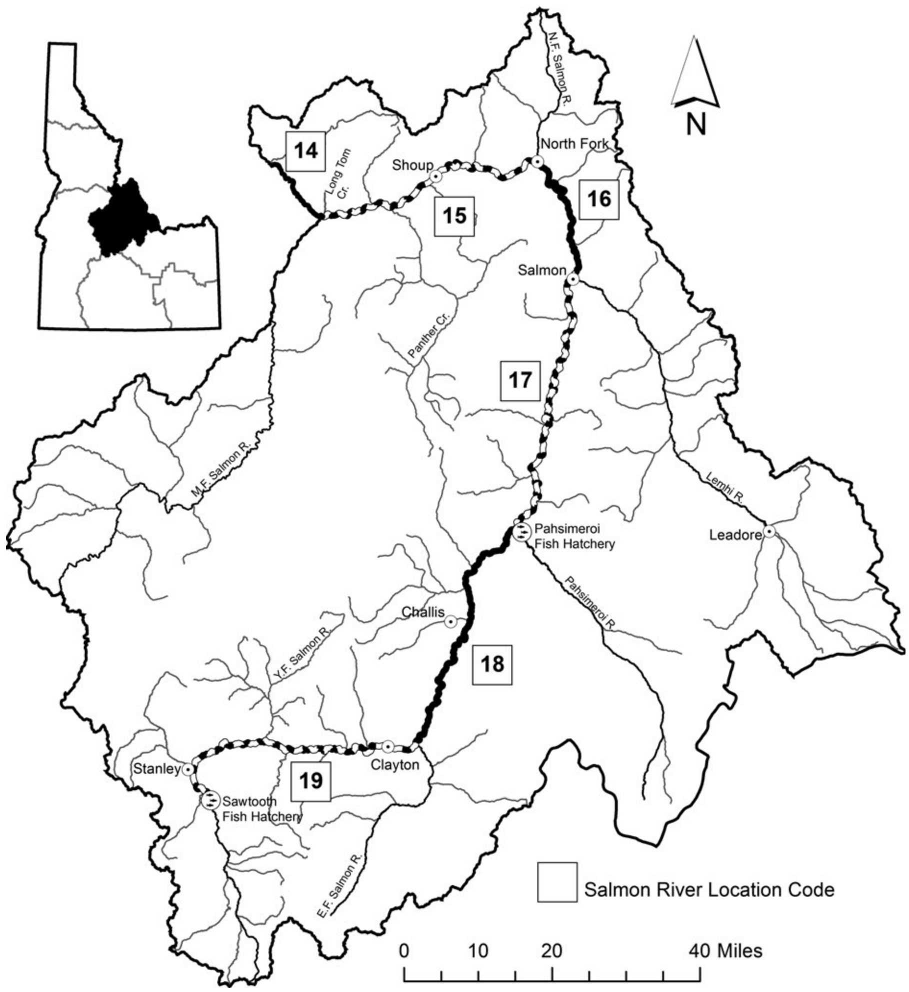

FIGURE 1. Study area in Idaho showing distinct river reaches and their numerical location codes.

distribution of angling effort was not uniform in some reaches. In reach 17, angling effort was concentrated in the upstream third of the reach, and in reach 18, the salmon fishery was heavily weighted toward large numbers of bank anglers in a single, confined area. Anglers were both local and out-of-area residents. Often, nonlocal anglers camped near fishing sites for several days or more each week.

Survey Techniques

During steelhead fisheries (fall, winter, and spring), work schedules for creel clerks consisted of one 9-h work shift on each day selected for survey. During salmon fisheries, work schedules for creel clerks consisted of two 8-h shifts per day (designated A.M. and P.M.). The increased creel effort for salmon fishers was necessary because of additional daylight hours during the summer salmon fishery. For the salmon fisheries, clerks did not work during two randomly selected weekdays each week. For the steelhead fisheries, clerks did not work Tuesdays or Wednesdays. With the exception of this study, IDFG estimates the steelhead harvest based on a state-wide phone survey of anglers.

Creel clerks were assigned to individual river location codes and drove highways adjacent to the river until they encountered anglers at boat ramps or fishing sites. For both salmon and steelhead fisheries, clerks followed schedules developed from randomly selected times to conduct counts of anglers throughout the day. Count methodology was the same for all fisheries with the exception that three counts per day were conducted during steelhead fisheries, but four or six counts per day were conducted for salmon fisheries to account for the increased day length. At least 2 h of time occurred between individual counts, and approximately 1 h of time was required to conduct an "instantaneous" count. During most of the day, the directions of counts were randomized. However, counts that were scheduled at the beginning of a work shift were always conducted in a direction away from the work station, and counts at the end of the workday were conducted toward the workstation because of time constraints. We stratified angler count and interview data by river reach.

When we interviewed anglers, we concurrently collected the data needed to generate harvest estimates using both traditional and mark–recapture methods. To accommodate the mark–recapture method, only two additional survey questions were required beyond those already needed for traditional methods: (1) Had the interviewee been previously interviewed during that week (Monday–Sunday)? (2) How many days did the interviewee plan to fish during that week? Anglers who were uncertain about the number of days they planned to fish during the week were excluded from the data set. For salmon fisheries, clerks who worked the P.M. shift asked an additional question: Was the interviewee interviewed by a clerk from the A.M. work shift? Clerks asked this additional question to avoid counting anglers interviewed during the A.M. work shift as "recaptured" during the P.M. work shift. We used angler responses regarding the number of fish caught in both methods used to estimate harvest. In the case of salmon anglers interviewed twice in the same day, only their catch data from the second interview was used in harvest calculations.

The number of anglers "captured" on a given day was the total number of unique anglers interviewed on that day. An angler was considered "marked" upon the first interview with that angler during the week. Thus, the number of marked anglers at the beginning of a given survey day was the total number of unique anglers that had been interviewed on a previous day during that week. Each daily encounter of an angler who had previously been interviewed was considered a "recapture."

Statistical Analyses

Traditional method.— For both salmon and steelhead fisheries, interview and count data were entered into Creel Application Software (CAS; Soupir and Brown 2008) for automated calculation of traditional roving-creel harvest estimates and CIs. Harvest estimates were calculated for each week of the fishing season.

Mark–recapture method.— The weekly estimate of harvest, H, is given by

$$H = N \cdot D \cdot V, \tag{1}$$

where N is the estimated population of anglers in the fishery that week, D is the estimated mean number of days fished that week per angler, and V is the estimated daily harvest per angler during that week.

We have used V instead of the more traditional C for catch because we use the variable C to denote "number captured" in standard formulas for the mark–recapture estimators (see Appendix A for details). We note that because effort in this model is measured in angler-days rather than angler-hours and because some harvest data were obtained from completed trips and others from incomplete trips, we did not attempt to use harvest estimators from incomplete trips as is done in traditional surveys (Pollock et al. 1997) and instead treated angler-reported harvest from incomplete trips the same as those reported from completed trips. However, we did conduct a formal test of whether daily harvest estimates differed between completed and incomplete trips, using a paired t-test to compare estimates between the two trip types for 38 different days during the fall 2013 season.

Because we "recaptured" anglers on more than 1 d during each week and did not uniquely identify individual anglers, we used the Schnabel mark–recapture estimate of the weekly angling population N (Seber 2002). During weeks in which we recaptured anglers on more than 2 d, we also calculated the Shumacher–Eschmeyer estimate (Seber 2002) of the angler population. For use in the harvest calculations, we selected the mark–recapture estimator that produced the smallest 95% CI for the estimate of weekly angler population. We modified the code in the R (R Core Team 2016) package "fishmethods" (Nelson 2014) to calculate the Schnabel and Schumacher–Eschmeyer estimates and 95% CIs. The code in that package uses the mathematical formulas in Krebs (1989); those formulas are reproduced in the Appendix. When using the Schnabel estimator with a small number of recaptures, the 0.025–probability quantile of the Poisson distribution appears in the denominator of the formula for the upper 95% confidence bound. This quantile is zero when the total number of weekly recaptures is ≤ 3, producing an infinite upper confidence bound. In these rare cases, we replaced the Poisson distribution by its continuous version (Ilienko 2013) to obtain an approximate but finite upper confidence limit (Appendix).

Interview data for estimating number of days fished per week per angler consisted of integers between 1 and 7, inclusive. Preliminary analysis of these data showed that the variance was very nearly equal to the mean, indicating a Poisson distribution. For example, for the Chinook Salmon fishery in location code 18 during 2015, the sample of 160 observations of days fished per week had a mean of 2.46 d/week and a variance of 2.12 d/week. Thus, we used Poisson log-linear models to estimate D (Pawitan 2001; Ramsey and Schafer 2002). This method produces an estimate of the logarithm of the mean, which, when exponentiated, yields the arithmetic mean of the data. This is an unbiased estimate of the population mean. Because the Poisson distribution is right-skewed, the sampling distribution of the mean is not normally distributed. However, the sampling distribution of the logarithm is normally distributed so that the normal distribution can be used for calculation of CIs for the logarithm (Pawitan 2001). Exponentiation then yields right-skewed CIs for D

that can never include values ≤0. To assess whether this method accurately estimated days fished per week, we used vehicle-mounted video cameras to record license plate numbers of all vehicles observed at access sites during each day of the 10-week spring 2014 season in one river reach. We used a paired *t*-test to compare estimates of days fished per week from angler interviews with those made directly from the license plate observations.

Because the daily bag limit for Chinook Salmon is two fish and for steelhead is three fish, creel data for estimating mean daily harvest per angler consisted of the integers 0, 1, 2, or 3. Again, these data had a Poisson distribution. Thus, we also used the Poisson log-linear method for estimating V and its CIs.

We used a bootstrap method to estimate CIs for the estimate of weekly harvest H. We randomly selected 2,000 independent values from the appropriate sampling distributions of N, D, and V, multiplied them together, and then took the $100 \times \alpha/2$ and $100 \times (1\text{-}\alpha/2)$ percentiles of the resulting 2,000 products as the lower and upper bounds of a $100 \times (1\text{-}\alpha)\%$ CI for H. In very rare cases in which the lower bound on H was lower than the total number of harvested fish observed in the sample of creel interviews, the lower limit was set at the observed harvest in the sample. Sampling distributions for D and V were normal in the logarithms, as described above. Sampling distributions for N depended on the mark–recapture method used (see Appendix). A seasonal total estimate of harvest can be obtained by summing weekly harvest estimates over all weeks of the season. A CI around the seasonal total estimate of H is obtained from the boostrap method. In this case, random values for the appropriate sampling distributions were drawn for each week, multiplied within each week to obtain random weekly values of H, and then the random weekly values summed to produce a random value of the total estimate for the season. The appropriate percentiles of the resulting 2,000 values are the endpoints of the CI.

We used the mark–recapture method to estimate angler effort and harvest over 92 different weeks across both species, five river reaches (location codes 15–19; Figure 1), and 4 years (2013–2016). In all, we conducted 2,753 and 8,363 interviews of salmon and steelhead anglers, respectively. We summarized estimates of angler population, number of days per week fished, daily harvest rate, and weekly harvest over these 92 weeks.

Comparison of methods.— The sample for comparison consisted of 48 of these 92 weeks for which weekly harvest was estimated by both traditional and mark–recapture methods: 33 weeks for salmon and 15 for steelhead distributed across 4 years (2013–2016) and four river reaches (location codes 16–19). The sample for CI comparisons consisted of 47 unique weeks because CIs could not computed for the traditional method in 1 week because of small estimated harvest. Point estimates for weekly harvest were right-skewed, so data were $\log_e$ transformed before analysis. Post hoc residual diagnostics showed that model assumptions were met with log-transformed data. An ANOVA was used for all tests, and week was treated as a fixed block factor to eliminate variability across weeks (e.g., each week is treated as a pair of observations—one using the CAS method and one using the mark–recapture method). We first tested whether differences between methods differed between species and then tested for a significant difference between methods. We also compared the width of 95% CIs around the weekly harvest estimates between the two methods. Again, data were right-skewed and were $\log_e$ transformed before analysis. The same ANOVA methods were used for the comparison of CI width as were used for comparison of the point estimates. The significance level for all hypothesis tests was set at $\alpha = 0.05$. All data analysis and calculations were implemented in R (R Core Team 2016).

We estimated mileage savings from using the interview-based mark–recapture method by analyzing actual daily mileage reports for two different year–location combinations. In each of these two surveys, total mileage included that for both interviews and for count-only vehicle trips. The difference between total mileage and that driven strictly for instantaneous counts provided an estimate of mileage savings.

RESULTS

Over the full sample duration of 92 weeks, the estimated weekly angler population per river reach ranged from 26 to 631, with a mean of 213. Anglers fished a mean number of 2.3 d/week. Over the 10 weeks in which we compared estimates of effort between the interview-based method and direct observation of license plates, mean number of days per week fished was 2.4 d/week from interviews and 2.3 d/week from license plate observations, and this difference was not significant ($t_9 = 0.234$, $P = 0.820$). Over all 92 weeks, anglers harvested an average of 0.17 fish/d. Over the 38 d in which we compared daily harvest rate between incomplete- and completed-trip interviews, mean daily harvest per angler was 0.10 from incomplete-trip interviews and 0.13 from completed-trip interviews, and this difference was not significant ($t_{37} = -0.624$, $P = 0.536$). Weekly harvest estimates ranged from 2 to 624, with a mean of 94 fish harvested per week. The Schnabel estimator most precisely estimated angler populations in 87% of the 92 weeks (e.g., Table 1). Bootstrap CIs around weekly and seasonal total harvest estimates were right-skewed, as expected. The width of the 95% CI on weekly harvest estimates averaged three times the magnitude of the point estimates themselves.

There was no evidence that the difference in point estimates between the traditional and mark–recapture methods differed between salmon and steelhead ($F_{1,\ 45} = 0.00914$, $P = 0.924$). With species pooled, there was no significant difference in point estimates between the two methods ($F_{1,\ 46} = 0.440$, $P = 0.510$; Figure 2). There was also no evidence that the difference in CI width between methods differed between species ($F_{1,\ 45} = 0.650$, $P = 0.139$). With species pooled, CI width differed significantly between the two methods ($F_{1,\ 46} = 18.2$, $P < 0.001$; Figure 3). Average width of the 95% CIs generated by the mark–recapture method was 1.61 times that of the 95% CIs generated by CAS for the traditional method. The relative CI width (width of 95% CI divided by point estimate) averaged 1.64 for the CAS method and 3.06 for the mark–recapture method, and this difference was statistically significant ($F_{1,\ 46} = 28.1$, $P < 0.001$). The CIs generated from the mark–recapture method are right-skewed, whereas those from the traditional method are symmetric. Larger CI width for the mark–recapture estimates was generally the result of higher upper bounds on the intervals (e.g., Figure 4).

During the June–July Chinook Salmon season in reach 19 in 2016, creel clerks drove an average of 620 km/d (385 mi/d). Of that, an average of 277 km/d (172 mi/d) was driven strictly for the purposes of conducting instantaneous counts, in that case four counts per day. In 2014 in reach 17, when six counts per day were conducted, average distance traveled was 741 km/d (460 mi/d), of which 396 km (246 miles) were strictly for counts. In these cases, eliminating counts would have reduced mileage by 45–53%.

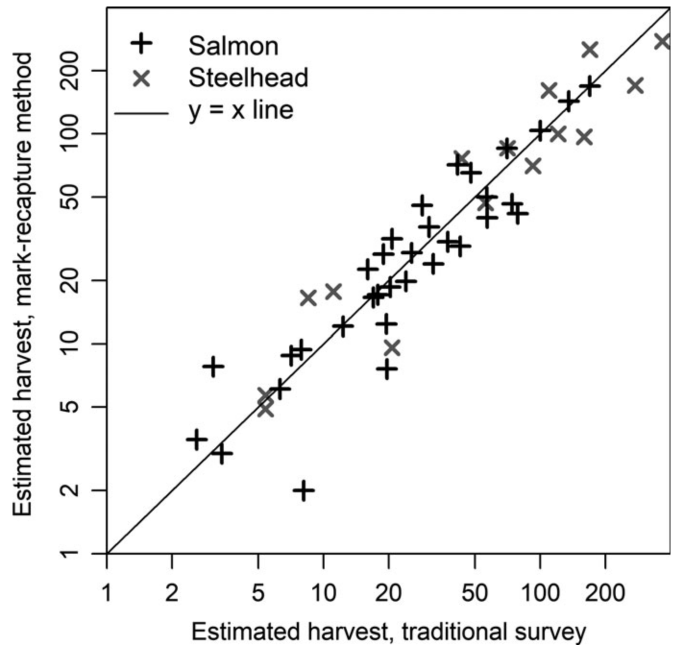

FIGURE 2. Comparison of weekly harvest estimates between traditional creel survey and mark–recapture methods. Note logarithmic scales.

DISCUSSION

The need for more efficient and effective methods of monitoring fishery use has recently motivated development of new statistical and technological methods for estimating fishing effort and related parameters (Chizinksi et al. 2014; Hartill et al. 2016; McCormick 2017; Pope et al. 2017). Such needs motivated us to develop a mark–recapture-based method that combined estimates of angler population, number of days fished per week, and catch per day to produce estimates of weekly harvest at substantial savings in vehicle mileage and risk. The mark–recapture method also produced estimates of weekly angler population by river reach, which will be useful to agencies other than those focused on fisheries (Pope et al. 2017).

On average, the mark–recapture-based harvest estimates were no different than those produced by

TABLE 1. Example of tabular output for a whole season, in this case the fall 2013 steelhead season in location 16. The entry in the Method column indicates the mark–recapture method that produced the most precise estimate of N (S–E indicates Schumacher–Eschmeyer). N = estimate of angler population, D = mean number of days fished per week per angler, V = mean harvest per day fished per angler, H = estimated harvest. The abbreviations LC and UC indicate the upper and lower limits, respectively, of the 95% CI for the given estimate. NA = not applicable; indicating weekly rates that were not extrapolated to the whole season.

Week	Method	N	N LC	N UC	D	D LC	D UC	V	V LC	V UC	H	H LC	H UC
1	Schnabel	201	118	502	1.88	1.59	2.22	0.015	0.002	0.108	6	1	51
2	Schnabel	409	273	736	1.74	1.53	1.98	0.120	0.072	0.199	85	46	187
3	Schnabel	164	116	263	2.14	1.88	2.44	0.200	0.124	0.322	70	39	142
4	Schnabel	320	217	553	1.74	1.53	1.98	0.180	0.117	0.275	100	57	201
5	Schnabel	465	273	1162	1.70	1.47	1.97	0.204	0.133	0.313	161	83	403
6	Schnabel	159	63	1716	1.48	1.10	2.00	0.200	0.090	0.445	47	12	503
7	S–E	143	89	363	1.31	0.98	1.74	0.088	0.029	0.274	17	5	71
Total		1,860	1,608	4,161	NA	NA	NA	NA	NA	NA	486	392	1,154

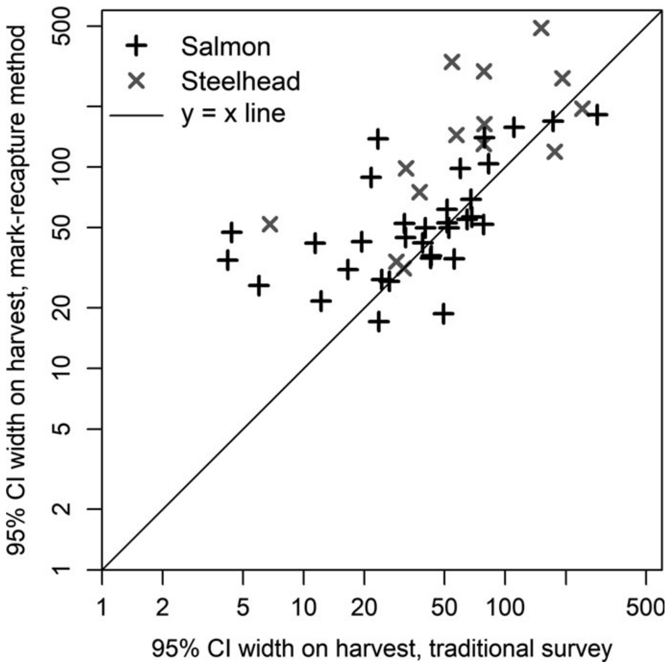

FIGURE 3. Comparison of 95% CI width around weekly harvest estimates between traditional creel survey and mark–recapture methods. Note logarithmic scales.

traditional creel survey methods. However, the mark–recapture method produced CIs that were wider than those produced by the traditional method, primarily because of higher upper confidence bounds. These higher upper confidence bounds resulted from right-skewness inherent in estimates of all three factors in our estimator. For weeks with low harvest, the symmetric CIs produced by traditional estimates can result in lower limits that are ≤0, indicating that sample sizes were too small for appropriate application of the *t*-distribution to estimate uncertainty. In these cases, the right-skewed CIs produced by the mark–recapture method are likely to be more consistent in coverage of the true uncertainty in the harvest estimate.

In our fishery, eliminating angler counts reduced vehicle mileage by as much as 53%. The time saved on the vehicle-based counts could be used to conduct more interviews at any given location, while still reducing overall distance driven. In this case, resource savings would be realized in mileage expense and driving risk but not necessarily in personnel time. The increased number of interviews could result in similar precision between traditional and mark–recapture estimates at lower driving expense and risk. Similarly, the elimination of counts may allow mangers to reallocate resources and personnel to water bodies that currently do not receive any surveys of angler harvest (Costello et al. 2012).

Despite consistency with the traditional method in estimating weekly harvest and the advantages of cost savings, the mark–recapture method is subject to bias in estimating all three factors in the harvest equation. First, in fisheries with highly transient or open populations of anglers, it may be difficult to mark anglers or recover marks. Thus, using closed-population methods in certain fisheries may bias the estimated angler population component of the mark–recapture method either high or low (Tillings 2001; Sutherland 2006). Bias associated with estimating open populations with closed-population estimators can be reduced by conducting sampling events over a short time frame, as we did (Lettink and Armstrong 2003; Zischke and Griffiths 2014) and by using appropriate sampling design (Gwinn et al. 2011).

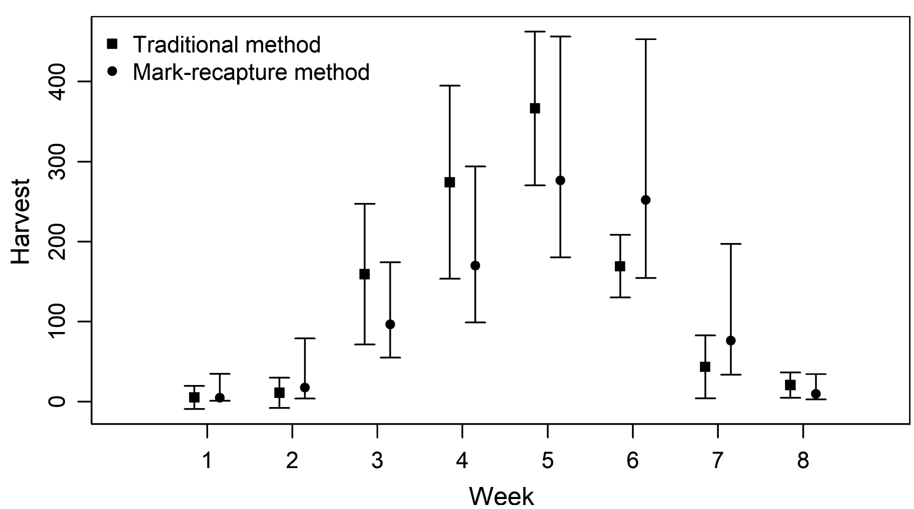

FIGURE 4. Example of comparison of weekly harvest estimates and 95% CIs between traditional creel survey and mark–recapture methods (error bars represent upper and lower limits to CI). This example is from reach 17 for the spring 2014 steelhead season.

When estimated fish harvest occurs over an extended period of time or in open populations, bias may be reduced by individually marking anglers with a unique identifier such as fishing license number so that methods such as the Jolly–Seber method can be used to estimate the population of anglers. Also, it is important to interview all segments of anglers in a fishery to maintain accurate estimates of angler populations (Pope et al. 2017). In traditional roving-roving surveys, isolated segments of anglers can be accommodated with surrogate counts of boat trailers or vehicles, and appropriate expansion calculations applied to arrive at the number of anglers. However, failing to interview segments of anglers in the mark–recapture method could lead to biased estimates of angler populations (Krebs 1989; Tillings 2001). Thus, successful application of the mark–recapture method requires appropriate sampling design to ensure that all anglers are equally likely to be encountered.

Estimates of the other two factors in the harvest calculation—days per week fished and daily harvest—are obtained from angler reporting of days fished and harvest. Day of week or time of day of the interview could introduce bias into estimation of these factors.

Our tracking of individual angler vehicles during the spring of 2014 provided evidence that no bias in estimating number of days fished per week was introduced by the difference between actual and intended days of fishing activity by anglers. This lack of bias may have occurred because people were expected to project or recall the number of days they intended to fish or actually fished only over a short, 1-week period of time. Additionally, even local anglers often travel 1 to 2 h to reach fishing sites. Therefore, it is not unusual for people to plan time off from work to fish, and this prior planning is likely to result in accurate estimates of intended fishing days, even among anglers interviewed early in the week. However, bias from the difference between intended and actual fishing days could increase as the duration of the stratum increases.

Bias and precision in estimating harvest rate from a mixture of completed- and incomplete-trip interviews has been well described (e.g., Pollock et al. 1997; McCormick et al. 2012). The metric of estimated daily harvest per angler in fisheries with low bag limits avoids pitfalls associated with incomplete angler trips of short duration and with highly successful anglers. However, the estimate of daily harvest is susceptible to underestimation if large numbers of unsuccessful anglers interviewed early in the day continue fishing and harvest fish after being interviewed. Our paired comparison of harvest estimates from completed- and incomplete-trip interviews data did not show a significant difference. In our fishery, this consistency is most likely due to low bag limits (2–3 fish/d), low daily success (mean of 0.17 fish/d; the vast majority of anglers reported zero harvest regardless of trip status), and pooling of catch data across large numbers of anglers interviewed on different days (Rasmussen et al. 1998). In any case, bias associated with incomplete-trip data could be eliminated or reduced by eliminating incomplete-trip interviews from the calculations or collecting and analyzing finer-scale data on angler trip duration and catch.

Our mark–recapture-based method provided acceptable accuracy in weekly estimation of harvest at lower cost than the traditional method, albeit at somewhat lower precision. This method is expected to provide a good alternative to traditional methods when applied over relatively short time periods in fisheries where angler counts are expensive or dangerous. When considering which method to use, managers can easily conduct a paired test of the mark–recapture-based method against traditional methods because both can be conducted simultaneously by adding only a few additional questions to the interview instrument. Time and resource savings can be estimated by subtracting the cost of instantaneous counts from the total cost of the traditional survey. Precision of the mark–recapture estimator could be improved by devoting time saved on counts to more effort in obtaining interviews (and hence more marks and recaptures). This improvement in precision could be quantified through analysis of sample size (number of marks and recaptures) as a function of interview effort and substitution of expected sample data into the CI formulas we have provided in the Appendix. Our method extends previous mark–recapture-based estimates of angling effort and offers a new addition to the growing number of nontraditional methods for monitoring fisheries.

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Appendix: Mark–Recapture Formulas

Notation Used in Formulas

N = Estimated number of anglers in the population.
M_i = Number of anglers in the marked population at the beginning of sample day i.
C_i = Number of unique anglers interviewed on sample day i.
R_i = Number of unique anglers recaptured on sample day i.
S = Number of days sampled during a given week.
α = Probability of type I error (statistical significance level).
$t_{p,\mathrm{df}}$ = Quantile of the t-distribution with left-tail probability P and df degrees of freedom.
$Q_{Pois}(P;\lambda)$ = Quantile of the Poisson distribution with left-tail probability P and mean λ.

Schnabel Estimate

The Schnabel estimate of the weekly population of anglers is

$$N = \frac{\sum_{i=1}^{S} M_i C_i}{\sum_{i=1}^{S} R_i}. \tag{A.1}$$

If $\sum_{i=1}^{S} R_i<50$, then the Poisson method is used for calculating confidence bounds around N. The lower $(1-\alpha)\times100\%$ confidence bound is

$$\frac{\sum_{i=1}^{S} M_i C_i}{Q_{Pois}(1-\alpha/2;\sum_{i=1}^{S} R_i}, \tag{A.2}$$

and the upper $(1-\alpha)\times100\%$ confidence bound is

$$\frac{\sum_{i=1}^{S} M_i C_i}{Q_{Pois}(\alpha/2;\sum_{i=1}^{S} R_i}, \tag{A.3}$$

For small enough values of $\alpha/2$. and $\sum_{I=1}^{S} R_i$, $Q_{Pois}\left(\frac{\alpha}{2};\sum_{i=1}^{S} R_i\right)=0$, resulting in an infinite upper confidence bound. To avoid this, we replaced the Poisson distribution in equation (A.3) with its continuous analog in those cases where the denominator in equation (A.3) was zero. The continuous Poisson distribution (Ilienko 2013) has cumulative distribution function

$$\frac{\Gamma(x,\lambda)}{\Gamma(x)}, \tag{A.4}$$

where $\Gamma(x,\lambda)$ is the incomplete gamma function, λ is the Poisson parameter (given by $\sum_{I=1}^{S} R_i$ in equation A.3), and $\Gamma(x)$ is the gamma function (Gradshteyn and Ryzhik 2000). For example, if $\frac{\alpha}{2}=0.025$ and $\lambda=\sum_{i=1}^{S} R_i=2$, $Q_{\mathrm{Pois}}\left(\frac{\alpha}{2};\sum_{i=1}^{S} R_i\right)=0$, resulting in an infinite value of equation (A.3). The 0.025-probability quantile of the continuous Poisson distribution with $\lambda=2$ is 0.24 (Figure A.1), which would be used in the denominator of equation (A.3) instead of 0, thereby producing a large but finite value.

If $\sum_{i=1}^{S} R_i\geq 50$, then the t distribution can be used. The $(1-\alpha)\times100\%$. CI around $1/N$ is

$$\frac{1}{N}\pm t_{\frac{\alpha}{2},S-1}\cdot\sqrt{\frac{\sum_{i=1}^{S} R_i}{\sum_{i=1}^{S}(M_i C_i)^2}}. \tag{A.5}$$

Reciprocating the endpoints of this interval yields an interval around N.

Analogous formulas are used in the bootstrap calculations of CIs around the harvest estimates, except that instead of fixed quantiles (cumulative probability $\alpha/2$ or $1-\alpha/2$), random numbers drawn from the appropriate Poisson or t distribution were used. The continuous Poisson analog described above was used in the bootstrap where needed to avoid infinite values for the upper confidence limit.

Schumacher–Eschmeyer Estimate

The Schumacher–Eschmeyer estimate of the weekly population of anglers is

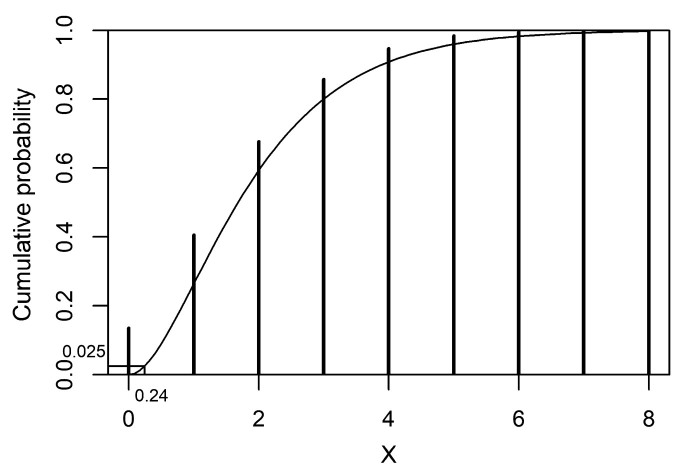

FIGURE A.1. Cumulative distribution functions for the Poisson distribution (vertical bars) and its continuous analog (curve), with Poisson parameter λ = 2. The 0.025-probability quantile of the Poisson distribution is 0, whereas that of the continuous Poisson distribution is 0.24, as shown by line segments at P = 0.025 and X = 0.24.

$$N = \frac{\sum_{i=1}^{S} C_i M_i^2}{\sum_{i=1}^{S} R_i M_i}, \tag{A.6}$$

with variance on $1/N$ equal to

$$Var\left(\frac{1}{N}\right) = \frac{\sum_{i=1}^{S} \frac{R_i^2}{C_i} - \left(\sum_{i=1}^{S} R_i M_i\right)^2}{\frac{\sum_{i=1}^{S} C_i M_i^2}{S-2}}. \tag{A.7}$$

The $(1-\alpha)\times100\%$ CI around $1/N$ is

$$\frac{1}{N} \pm t_{\frac{\alpha}{2}} \cdot \sqrt{\frac{Var\left(\frac{1}{N}\right)}{\sum_{i=1}^{S} C_i M_i^2}}. \tag{A.8}$$

Reciprocating the endpoints of this interval yields an interval around N. Occasionally, the lower bound for $1/N$ calculated in this way was negative, in which case it was set to 10^{-14}. This always results in selection of the Schnabel method as most precise.