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ARTICLE

Evaluation of Sample Design and Estimation Methods for Great Lakes Angler Surveys

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Abstract

The waters of the Great Lakes support outstanding recreational fishing opportunities. Total catch and effort estimates obtained from on-site angler surveys are essential for the management of the recreational fisheries. However, quality of angler survey estimates can be greatly affected by the survey design and estimation approaches used. Using Monte Carlo simulation techniques, we evaluated the effects of two potential sources of bias (disproportional sampling of angler trips and subsampling of the fishing day) on two catch estimators: (1) a multiple-day estimator that ignores day effects and pools the angler trip data over a multiple-day period, and (2) a daily estimator that treats the trip data in each day separately. When catch rates are constant among different time periods of the fishing day, the daily estimator produces total catch estimates with little bias, whereas the multiple-day estimator is prone to bias caused by disproportional sampling of angler trips. When catch rates vary among different periods of a fishing day, the daily estimator produces biased estimates of total catch when the fishing day is subsampled, whereas the multiple-day estimator is less affected by the variation in daily time-period catch rates and subsampling of fishing days. Quality of total catch and effort estimates, in terms of root mean square error and coverage probability of confidence intervals, is poor when the number of days sampled each month is low and fishing days are subsampled.

The waters of the Great Lakes support outstanding recreational fishing opportunities (Bence and Smith 1999). Recreational fishing also constitutes the majority of the fishing activities in these waters. These recreational fisheries are monitored through on-site angler surveys and charter boat reporting systems. Because of the importance and high cost of on-site angler surveys, sampling and estimation methods have been regularly evaluated and refined (Fabrizio et al. 1991; Lockwood 1997). However, several sampling and estimation issues remain unresolved due to the complex nature of recreational fisheries and angler surveys. Primary among these are (1) how to choose the appropriate estimation methods for calculating catch estimates over a multiple-day period (Lockwood et al. 1999), and (2) determining the potential effects of disproportional sampling of daily angler trips (NRC 2006) and subsampling of the fishing day on catch estimates. The purpose of this study is to use Monte-Carlo simulation techniques to evaluate and quantify the effects of these issues on catch estimates under a broad range of conditions.

Angler surveys for the Great Lakes waters in Michigan follow a stratified multistage sampling design (Fabrizio et al. 1991; Lockwood 1997). Two estimation methods—a daily estimator and a multiple-day estimator—are currently used in Michigan to calculate catch estimates for a stratum defined by survey month, day type (weekday or weekend day), and site. The daily estimator uses interviews in each sampled day to calculate a daily catch rate, which is multiplied by a separate estimate of angling effort for that day to obtain a daily catch estimate. These daily catch estimates are then expanded to obtain a stratum catch estimate. In contrast, the multiple-day estimator uses all

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interviews within the stratum to calculate a single catch rate. That catch rate is multiplied by an estimate of angling effort for that stratum to produce a total catch estimate.

The daily estimator explicitly takes into account day effects, but a large number of daily interviews are needed to obtain precise daily catch rate and catch estimates (Jones et al. 1995). However, fishing activities fluctuate throughout a fishing season and across areas, so it can be difficult to obtain adequate sample sizes over the season and for different areas. Daily estimates become unreliable when sample sizes are small, and this will affect the precision of stratum estimates.

The multiple-day estimator has been suggested as a way to deal with the problem of low sample size (Lockwood et al. 1999; Rasmussen et al. 1998). However, this approach ignores potential day effects in catch rates. If actual differences in catch rates exist among days, catch rates in the same day tend to be similar and correlated and are not independent. This may cause the multiple-day estimator to underestimate the variance of the stratum catch rate and catch estimates.

Furthermore, the multiple-day estimator ignores the multistage sampling process and may be subject to bias caused by disproportional sampling of daily angler trips. It treats all the interview data within the stratum as if they were independently selected with equal probability of selection, i.e., from "self-weighting" sampling (Lee and Forthofer 2006). However, self-weighting is often hard to achieve because a creel clerk can only interview a certain number of trips each day, and he or she may be swamped by anglers on peak fishing days and at peak fishing times (Austen et al. 1995; NRC 2006). As a result, trips from low-activity days may be more likely to be selected into the sample than those from high-activity days. Additionally, selection of which trips to interview is determined, to a certain extent, subjectively by creel clerks. This means that angler trip samples are not true random samples. Nonrandom and disproportional sampling of daily angler trips, coupled with possible associations between daily effort and daily catch rate can lead to biased multiple-day estimates (Austen et al. 1995). There are two obvious options to deal with potential bias caused by disproportional sampling in the multiple-day estimator: (1) interview all exiting anglers (rarely feasible); or (2) systematic sampling of every *n*th angler trip (Lester et al. 2005). We examine these two alternative sampling procedures along with the procedure currently used—disproportional sampling—in the simulations.

The daily and multiple-day estimators may also be subject to bias caused by subsampling a portion (e.g., morning or afternoon) of each sampled day. When a sampled day is subsampled, during the morning shift there is no chance to interview angler parties that started fishing in the morning and completed in the afternoon (middle-day trips), but effort for some of these trips might be counted in the morning shift. In an afternoon shift, middle-day trips could be both interviewed and counted. If the middle-day trips had different catch rates than those that fished during the morning or afternoon only, catch estimates from the daily estimators may be biased. Rasmussen et al. (1998) found evidence for this type of bias in a daily estimator. We evaluate this issue for both estimators for Michigan's surveys over a broader range of conditions than Rasmussen et al. (1998) considered.

The statistical properties of catch and catch rate estimates can be potentially affected by these sampling issues and the estimation method used under different angler population dynamics. However, the responses of the two estimators to these different conditions have not been studied thoroughly and quantitatively (Lockwood et al. 1999). Knowledge about these responses can help us to improve angler survey designs and choose appropriate estimators.

Specifically, we developed a simulation framework that generates angler trip populations with various characteristics, such as variation in daily angler trips, variation in daily catch rates, and temporal patterns in catch rates within fishing days. Several aspects of sampling design were also considered, for example, number of days to be sampled, options to subsample days, and different sampling protocols to select angler trips for interviewing. We evaluated the statistical properties of the two estimators under various combinations of these population characteristics and sampling options. We evaluated the estimators in terms of relative bias, root mean square error, and the quality of variance estimators in terms of coverage probability of the confidence interval. We sought to identify the estimator that is most robust to a wide variety of conditions.

Complete creel census (Rasmussen et al. 1998) and angler survey data (Lockwood 1997) have been used in some simulation studies to evaluate on-site angler surveys. However, complete census is often infeasible for complex fisheries and thus is rarely used. Both complete census and sampling survey data are limited to specific fishery situations. Our simulation approach is more general and enables us to generate and evaluate different angler populations with specific characteristics.

METHODS

Estimation Methods

The formulas currently used in Michigan for estimating total angling effort (i.e., angler-hours) and catch by species by the daily and multiple-day estimation methods are detailed in Lockwood et al. (1999). The estimators differ mainly in how catch rate and catch are calculated. Effort is estimated similarly for both methods (Lockwood et al. 1999). Here, we only present formulas related to calculating catch rate and total catch from completed-trip interviews obtained from access site surveys. The calculations are the same for different types of catch: catch kept (harvest), catch released, or total catch. We use "catch" to refer to these three types of catch for brevity and define catch rate as catch per angler-hour.

Daily estimator.—For the daily estimator, catch rate of a particular species is calculated for each day and multiplied by effort for that day to estimate the daily catch for that species. For completed-trip interviews, the estimated catch rate for a species on day d is calculated using the ratio-of-means estimator (Jones et al. 1995; Lockwood 1997):

$$\hat{R}_d = \frac{\sum_{i=1}^{t_d} c_{d,i}}{\sum_{i=1}^{t_d} h_{d,i}}, \qquad (1)$$

where, t_d = total number of angler trips interviewed on day d, $c_{d,i}$ = total number of fish caught for a particular species by angler trip i on day d, and $h_{d,i}$ = total hours fished by angler trip i on day d. Here, $h_{d,i} = A_{d,i}L_{d,i}$, where $A_{d,i}$ is party size and $L_{d,i}$ is trip length. An estimator of variance of $\hat{R}_d$ (Cochran 1977) is

$$\hat{V}(\hat{R}_d) = \frac{1 - f_d}{(\bar{h}_d)^2 t_d} \frac{\sum_{i=1}^{t_d} (c_{d,i} - \hat{R}_d h_{d,i})^2}{t_d - 1}, \qquad (2)$$

where $\bar{h}_d$ is the average of $h_{d,i}$ (i.e., $\bar{h}_d = \sum_{i=1}^{t_d} h_{d,i}/t_d$), f_d is the sampling proportion t_d/T_d, and T_d is the total number of angler trips fished on day d. The finite population correction ($1 - f_d = 1 - t_d/T_d$) in equation (2) is set to 1 in our calculations because T_d is unknown and t_d is often much smaller than T_d, especially for an area with multiple access sites (Rasmussen et al. 1998).

Estimated day-d catch, $\hat{C}_d$, is the product of estimated catch rate, $\hat{R}_d$, and estimated effort, $\hat{E}_d$, for that day, or

$$\hat{C}_d = \hat{R}_d \hat{E}_d; \qquad (3)$$

its estimated variance $\hat{V}(\hat{C}_d)$ is

$$\hat{V}(\hat{C}_d) = (\hat{E}_d)^2 \hat{V}(\hat{R}_d) + (\hat{R}_d)^2 \hat{V}(\hat{E}_d) - \hat{V}(\hat{E}_d)\hat{V}(\hat{R}_d), \qquad (4)$$

where $\hat{V}(\hat{E}_d)$ is the estimated variance of $\hat{E}_d$ (Lockwood et al. 1999). Equation (4) is based on the assumption that catch rate and effort are independent.

The estimated catch for a stratum is

$$\hat{C} = \frac{M}{m} \sum_{d=1}^{m} \hat{C}_d, \qquad (5)$$

where M = total number of days in the stratum and m = number of sampled days in that stratum.

The estimated catch rate for the stratum is

$$\hat{R} = \hat{C}/\hat{E} = \sum_{d=1}^{m} \left(\hat{E}_d \Big/ \sum_{d=1}^{m} \hat{E}_d \right) \hat{R}_d = \sum_{d=1}^{m} w_d \hat{R}_d, \qquad (6)$$

where $\hat{E}$ is the estimated angler-hours for the stratum (Lockwood et al. 1999). That is, $\hat{R}$ is a weighted mean of daily catch rate estimates with a sampling weight for day d defined as $w_d = \hat{E}_d / \sum_{d=1}^{m} \hat{E}_d$.

When each sampled day is set as an entire sampling period and is not subsampled, an estimator of variance for $\hat{C}$ follows equations describing two-stage (i.e., day and trip) sampling designs (Thompson 2002):

$$\hat{V}(\hat{C}) = \frac{M^2}{m}\left(1 - \frac{m}{M}\right) V_{\mathrm{PSU}} + \frac{M}{m} \sum_{d=1}^{m} \hat{V}(\hat{C}_d), \qquad (7)$$

where, $V_{\mathrm{PSU}} = \sum_{d=1}^{m} (\hat{C}_d - \bar{C})^2/(m-1)$, which is the sampling variance of the estimated catches for the primary sample units (days) and $\bar{C} = \sum_{d=1}^{m} \hat{C}_d/m$.

When each sampled day is subsampled and one shift is selected in each sampled day, the variance component due to subsampling of days cannot be calculated. In that case, there is no exact three-stage (i.e., day, day part, and trip) variance estimator for the catch estimate, and equation (7) is an approximation to the actual variance estimate of $\hat{C}$.

The variance estimator $\hat{V}(\hat{C}_d)$ (equation 4) depends on $\hat{V}(\hat{E}_d)$, which is not defined when one count is made per sampling period (i.e., shift; Lockwood et al. 1999). In that case, $\hat{V}(\hat{C})$ cannot be calculated based on equation (7) either. To overcome this problem, we propose use of the following variance estimator for $\hat{C}$ when one count is made per shift:

$$\hat{V}(\hat{C}) = \frac{M^2}{m} \frac{\sum_{d=1}^{m} (\hat{C}_d - \bar{C})^2}{m-1} = \frac{M^2}{m} V_{\mathrm{PSU}}. \qquad (8)$$

Equation (8) is an approximate and conservative variance estimator (Pollock et al. 1994). It is simply a random sample variance among the estimated primary sampling unit values and is often used for calculating variance of totals in complex surveys. In the case of Michigan angler survey sites with one count per day, a similar estimator is used in the calculation of the estimated variance of stratum effort estimates (Lockwood et al. 1999), but it is not used in calculating estimated variance for the stratum catch estimates. Here, we used equation (8) to calculate variance for the daily catch estimator for cases with one count per day.

Multiple-day estimator.—For the multiple-day estimator, catch rate is estimated for the entire multiple-day period defined for a stratum by pooling all interviews in that period, and is then multiplied by estimated effort for that period to estimate the stratum catch estimate. Estimated catch rate for the stratum is calculated as

$$\tilde{R} = \frac{\sum_{i=1}^{t} c_i}{\sum_{i=1}^{t} h_i} = \frac{\sum_{i=1}^{t} w_i c_i}{\sum_{i=1}^{t} w_i h_i}, \qquad (9)$$

where t = number of interviews collected in the stratum. Unlike the daily estimator in equation (6), all the trips are given equal weight ($w_i = 1$) in equation (9) when calculating the total catch and total angler hours for all trips in the stratum. The estimated variance of $\tilde{R}$, $\hat{V}(\tilde{R})$, is calculated as

$$\hat{V}(\tilde{R}) = \frac{1}{(\bar{h})^2 t}\,\frac{\sum_{i=1}^{t}(c_i - \tilde{R}h_i)^2}{t-1}, \tag{10}$$

where $\bar{h} = \sum_{i=1}^{t} h_i/t$.

For the multiple-day estimator, estimated catch is

$$\tilde{C} = \hat{E} \times \tilde{R}, \tag{11}$$

and the estimated variance for $\tilde{C}$ is

$$\hat{V}(\tilde{C}) = \hat{E}^2\hat{V}(\tilde{R}) + \tilde{R}^2\hat{V}(\hat{E}) - \hat{V}(\hat{E})\hat{V}(\tilde{R}), \tag{12}$$

where $\hat{E}$ is the estimated angler-hours for the stratum and $\hat{V}(\hat{E})$ is the estimated variance of $\hat{E}$ (Lockwood et al. 1999).

Simulation Study

We developed a simulation framework that included four components: (1) generation of "true" angler trip populations with known characteristics, (2) implementation of multistage sampling on the simulated population, (3) estimation of the total catch of a stratum (see Estimation Methods), and (4) comparison of estimates with true population values to determine statistical properties for an estimator. Herein we describe components 1, 2, and 4 along with the simulation scenarios considered.

Generation of "true" angler-trip populations.—To examine the statistical properties of the two estimators, we developed a simulation model that was used to generate different monthly angler trip populations. The populations were generated to simulate Michigan Great Lakes fisheries data (Benjamin and Bence 2003).

We generated a monthly angler trip population based on the hierarchical structure of the data (day, trip). First, at the day level, we generated the "true" daily number of angler trips T_d using a negative binomial (NB) distribution, $\mathrm{NB}(\mu = \bar{T}, \theta = \theta_T)$, where μ and θ are the mean and dispersion parameter of the distribution, respectively (Venables and Ripley 2002). Variance of the NB distribution is $V = \mu + \mu^2/\theta$. Therefore, large θ leads to small V and vice versa for a given μ. In addition, $\bar{T}$ is a prespecified mean level of daily angler trips, and θ_T is a prespecified dispersion parameter value. The "true" daily catch rate R_d for a species was generated by a lognormal (LN) distribution (Laurent 1963): $R_d \sim \mathrm{LN}(\mu = \log(\bar{R}), \sigma^2 = S_R^2)$ or equivalently $\log(R_d) \sim N(\mu, \sigma^2)$, where μ and σ^2 are the mean and variance of the normally distributed $\log(R_d)$, respectively, and "log" is the natural logarithm. Here, the mean is $\exp(\bar{R} + S_R^2/2)$, the median is $\bar{R}$, the variance is $\exp(2\bar{R} + S_R^2)(\exp(S_R^2) - 1)$, and the coefficient of variation of R_d is $\sqrt{\exp(S_R^2) - 1}$ (Laurent 1963). We also examined situations in which T_d and R_d were correlated. In this case, we first generated R_d and then generated T_d using $\mathrm{NB}(\mu = \beta_0 + \beta_1 R_d, \theta = \theta_T)$, where β_0 and β_1 are two prespecified parameters. Negative-binomial distributions are commonly used probability distributions for modeling catch, as are lognormal distributions for modeling catch rate data (Power and Moser 1999; Maunder and Punt 2004).

Second, at the trip level, we generated starting time, trip length, and party size based on the patterns observed in Michigan Great Lakes fisheries. In these fisheries, a large proportion of anglers started their fishing in the morning, and a smaller proportion of anglers started their fishing in the afternoon (Figure 1). Anglers who started their trips late in a day also fished for a shorter period than those starting their trips early in the day (Figure 2). Because the distribution of starting times is nonstandard, we generated starting times randomly according to their cumulative distribution function (CDF) (Wade et al. 1991). Party sizes were also generated using their CDF. The joint CDF of trip length and starting time was used to generate trip length from a given starting time to take into account any relationships between these two variables (Figure 2).

The catch of each trip in a day, $c_{d,i}$, was generated using $c_{d,i} \sim \mathrm{NB}(R_d h_{d,i}, \theta_C)$, where θ_C is the dispersion parameter, and $h_{d,i}$ is the total hours fished by an angler party in trip i.

We also considered cases where the mean catch rate of the middle-day trips of each day (denoted as $R_d^{(2)}$), differed from that of pure morning ($R_d^{(1)}$), or afternoon ($R_d^{(3)}$), trips. In this case, $c_{d,i}$ in a day was generated using $c_{d,i} \sim \mathrm{NB}(R_d^{(\cdot)}\, h_{d,i}, \theta_C)$, where $R_d^{(\cdot)}$ represents the mean catch rate of trips for the period in which trip i belongs.

Sample design.—Angler surveys for Michigan Great Lakes waters follow a stratified multistage sampling design. In this design, a survey for a lake over a fishing season is stratified by fishing area (a port or a section of coast line), month, and day type (weekday or weekend day) to increase precision and reduce potential bias for survey estimates. A multistage sample design is carried out within each stratum to minimize cost and facilitate the arrangement of work schedules for the creel clerks. In the multistage sampling, fishing days are first randomly sampled from a stratum and from which either the morning or afternoon, selected randomly, is sampled. Finally, angler parties are counted at one or multiple randomly selected times for the entire fishery, and those angler parties that have completed their fishing trips are interviewed at an access point. Counting and interviewing are done separately.

The Michigan angler survey design was replicated for simulated angler populations. We evaluated five sampling design options at each of the three stages of the sampling design in the simulation. First, at the day level, we examined three levels of the number of days sampled (n_{days}): 10, 20, and 30. Second, for a month with each fishing day lasting from 0400–2200 hours (18 h), we either set each sampled fishing day as the entire sampling period (denoted as ENTIRE), or divided it into two 9-h nonoverlapping periods (PART) and randomly selected one of them (morning or afternoon) as the sampling period.

Three additional design options were evaluated. First, we examined three methods for selecting angler parties for interviewing: disproportional sampling of daily angler trips (this

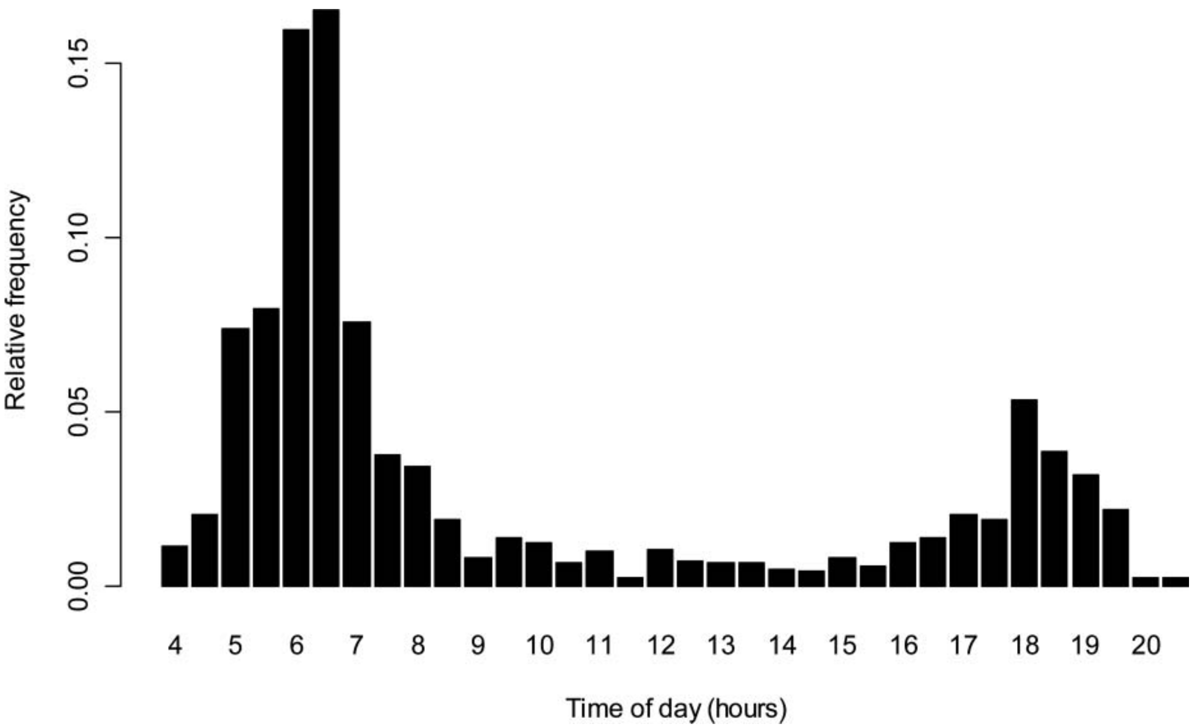

FIGURE 1. Distribution of starting times of fishing trips for a typical Michigan Great Lakes fishery.

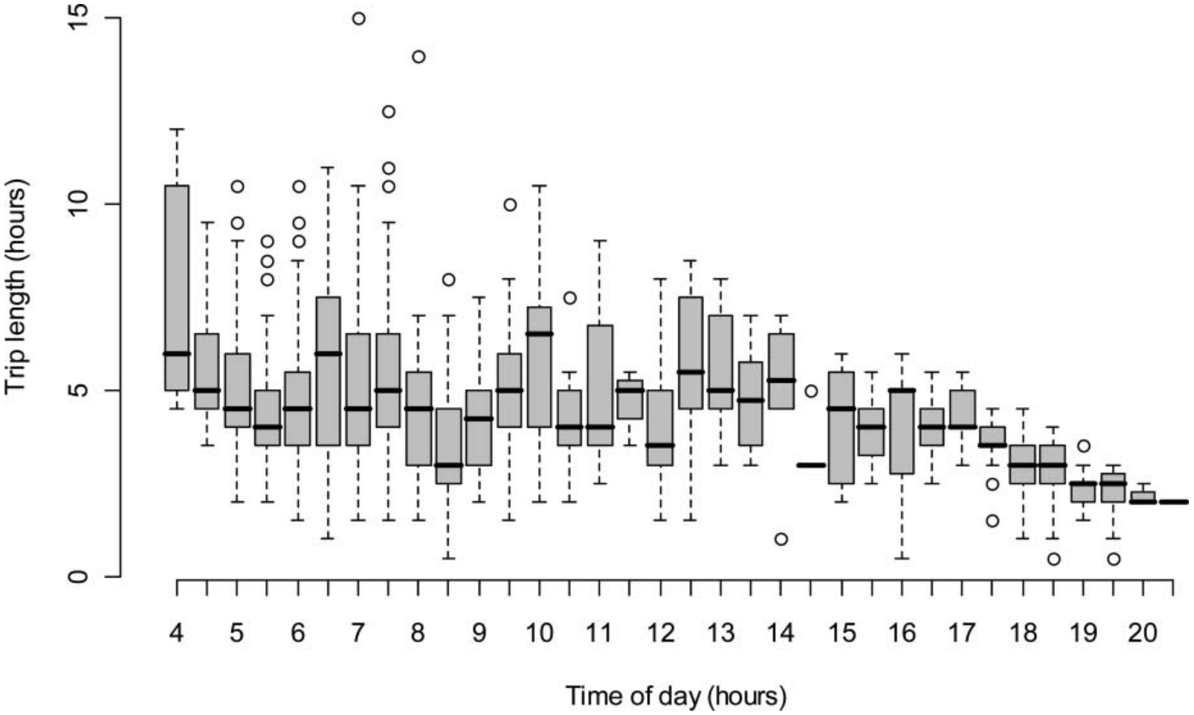

FIGURE 2. Trip length versus starting time of fishing trips for a typical Michigan Great Lakes fishery. The gray box in each boxplot represents the interquartile range (IQR; the lower edge of the box showing the first quartile, the upper edge of the box showing the third quartile), the black line in the center of the box represents the median of the distribution, and whiskers extend to the most extreme data point (no more than 1.5 times the IQR); outliers are shown as open circles beyond the whiskers.

TABLE 1. Relative biases (RB) of two catch estimators (multiple-day and daily) with constant within-day time-period catch rates (CONST: $R_d^{(2)} = R_d^{(1)} = R_d^{(3)}$) and disproportional sampling (DISPROP), under two levels of standard deviation of the logarithm of daily catch rate R_d (S_R: high or low) and two levels of variation in the daily angler trips T_d determined by the dispersion parameter θ_T ($V(T_d)$: high or low) for two situations of fishing-day subsampling (ENTIRE or PART), given that the mean level of daily angler trips is $\bar{T} = 200$, median of daily catch rates is $\bar{R} = 0.3$, the regression coefficient is $\beta_1 = 200$, the number of days sampled is $n_{\text{days}} = 10$, the maximum number of interviews collected each day is $n_{\text{m\_int}} = 10$, and the number of counts is $n_{\text{cnt}} = 2$. The primary sampling units used in the multistage sampling design are PART (a day part, morning or afternoon, is sampled from a sampled fishing day) and ENTIRE (the entire sampled fishing day is treated as a sampling period). Values with |RB| > 5% are indicated with bold italics.

	RB (%) at S_R high (0.15)				RB (%) at S_R low (0.05)			
	Multiple-day estimator		Daily estimator		Multiple-day estimator		Daily estimator	
$V(T_d)$	PART	ENTIRE	PART	ENTIRE	PART	ENTIRE	PART	ENTIRE
High ($\theta_T = 1.003$)	***−9.4***	***−11.1***	−1.1	−0.9	−3.2	−2.7	1.5	0.2
Low ($\theta_T = 100$)	***−5.2***	−4.2	1.0	0.3	−1.5	−1.8	−0.4	0.4

is the design currently used, denoted as DISPROP), complete sampling (ALL), and proportional sampling (FIXPROP). In the ALL sampling, all exiting parties during a sampling period were interviewed. For the FIXPROP sampling, we selected a fixed proportion of trips for each sampling period by systematically sampling 1/3 of the angler trips. For the disproportional sampling, we investigated scenarios in which we randomly selected and interviewed at most 10, 50, or 100 angler trips per shift ($n_{\text{m\_int}}$). Finally, we also considered three levels of the number of counts made per sampling period (n_{cnt}): 1, 2, or 4.

Simulation scenarios.—We examined five angler population characteristics that might affect the statistical properties of the two estimators: (1) variation in daily fishing trips T_d determined by θ_T, i.e., low (θ_T high) or high (θ_T low), (2) variation in daily catch rates determined by S_R, i.e., low (SR low) or high (SR high), (3) correlation between daily trips T_d and catch rate R_d determined by β_1, i.e., low (β_1 low) or high (β_1 high), and (4) variation in catch rate $R_d^{(.)}$ within day d, i.e., constant ($R_d^{(2)} = R_d^{(1)} = R_d^{(3)}$, denoted as CONST) or different ($R_d^{(2)} <> R_d^{(1)} = R_d^{(3)}$, denoted as DIFF), and (5) several levels of mean fishing activity ($\bar{T}$). Values used for the parameters defining these population characteristics were chosen based on Lake Michigan fisheries data and are given in Tables 1–4 and Figures 3–5.

There are 5 design factors, 5 population factors, and about 20,000 combinations of these factors. To simplify our analysis, we organize our results based on the following four key factors: variation associated with daily time-period catch rate (CONST or DIFF), effects of subsampling fishing day (ENTIRE or PART), variation in daily catch rates (S_R), and variation in daily fishing trips (θ_T). Only selected results for these factors are shown to demonstrate our major findings.

Simulation procedures.—For each simulation scenario of a combination of angler population characteristics and sampling options, we conducted $S = 3{,}000$ replicate samplings. For each simulated data set, we calculated daily effort and total stratum effort and then separately calculated total catch by the two estimators. For each scenario and estimator, we calculated the average of S estimates of $\hat{\mu}_i$, $\bar{\mu} = \sum_{i=1}^{S} \hat{\mu}_i / S$, where $\hat{\mu}_i$ is the value of an estimator from the ith sample. The raw and relative biases were then calculated for $\hat{\mu}$ as $B(\hat{\mu}) = \bar{\mu} - \mu$ and $\text{RB}(\hat{\mu}) = 100B(\hat{\mu})/\mu$, where μ is the true value of $\hat{\mu}$. The mean square error (MSE) of an estimator is defined as the average of the squared deviations of $\hat{\mu}$ from its true value μ, $\text{MSE}(\hat{\mu}) = E(\hat{\mu} - \mu)^2$, which is equal to the variance $V(\hat{\mu})$ plus the bias squared, i.e., $\text{MSE} = V(\hat{\mu}) + B(\hat{\mu})^2$. In each simulation, we approximated $V(\hat{\mu})$ by $V(\hat{\mu}) \approx \sum_{i=1}^{S} (\hat{\mu}_i - \bar{\mu})^2 / S$. The MSE measures the accuracy or average closeness of an estimator to its true value. A good estimator has a small MSE, which implies that it has both little or no bias and a small

TABLE 2. Relative biases (RB; %) of two catch estimators with constant time-period catch rates (CONST: $R_d^{(2)} = R_d^{(1)} = R_d^{(3)}$) when the variation in T_d and R_d are both high ($S_R = 0.15$ and $\theta_T = 1.003$), for four levels of mean daily angler trips ($\bar{T}$) and different levels of correlation (Corr) between T_d and R_d obtained by changing β_1. All other conditions are the same as in Table 1. Values with |RB| > 5% are indicated with bold italics.

Estimator		Multiple-day		Daily	
$\bar{T}$	Corr	PART	ENTIRE	PART	ENTIRE
300	0.27	***−6.7***	***−6.5***	−0.7	−0.1
	−0.15	***6.9***	***7.5***	0.5	0.3
200	0.36	***−11.0***	***−11.0***	0.5	0.5
	a	−0.8	−0.4		
	0.14	−1.6	−3.8	0.4	−0.9
	−0.39	***24.2***	***23.4***	2.0	−1.4
100	0.40	***−11.5***	***−11.7***	−1.7	−0.7
	0.22	***−9.4***	***−9.2***	0.2	−0.2
	−0.34	***13.4***	***14.7***	−0.7	−0.3
20	0.46	***−5.6***	***−7.7***	−2.8	−2.3
	−0.26	***6.4***	***7.6***	−0.4	−1.4
	−0.50	***10.5***	***11.2***	2.6	1.8

[a] FIXPROP: a fixed proportion of interviews was taken each shift.

TABLE 3. Relative biases (RB) of two catch estimators under disproportional sampling (DISPROP) when the middle-day mean catch rate $R_d^{(2)}$ is one-half of the morning or afternoon mean catch rate (DIFF: $R_d^{(2)} = 0.5R_d^{(1)} = 0.5R_d^{(3)}$), under two levels of variation in R_d (S_R: high or low) and in the daily angler trips T_d ($V(T_d)$: high or low), given that $\bar{T} = 200$, $\bar{R} = 0.3$, $\beta_1 = 200$, $n_{\text{days}} = 10$, $n_{\text{m\_int}} = 10$, and $n_{\text{cnt}} = 2$, (see explanation in Table 1). Values with |RB| > 5% are indicated with bold italics.

	RB (%) at S_R high (0.15)				RB (%) at S_R low (0.05)			
	Multiple-day estimator		Daily estimator		Multiple-day estimator		Daily estimator	
$V(T_d)$	PART	ENTIRE	PART	ENTIRE	PART	ENTIRE	PART	ENTIRE
High ($\theta_T = 1.003$)	***−7.1***	***−6.1***	***−9.3***	−0.1	−3.7	−0.1	***−8.9***	−1.2
		[a]	***6.2***	1.2				
Low ($\theta_T = 100$)	−3.7	−0.1	***−7.8***	−1.6	−3.1	−1.2	***−9.7***	−1.3

[a] For $R_d^{(2)} = 2R_d^{(1)} = 2R_d^{(3)}$.

variance (Pollock et al. 1994). We used root mean square error (RMSE), $\text{RMSE}(\hat{\mu}) = \sqrt{\text{MSE}}$, to compare the accuracy of the two catch estimators. We also calculated the estimated variance ($\hat{V}(\hat{\mu})$) of $\hat{\mu}$ at each replicate sampling using equation (7) for $n_{\text{cnt}} > 1$ or equation (8) for $n_{\text{cnt}} = 1$ for the daily estimator and equation (12) for the multiple-day estimator, respectively, and the estimated standard error, $\text{SE}(\hat{\mu})$, of $\hat{\mu}$ was calculated as $\sqrt{\hat{V}}$. Then, an asymptotic (large sample approximate) 95% confidence interval (CI) for μ was calculated as $\hat{\mu} \pm 1.96\text{SE}(\hat{\mu})$. Such an approximate confidence interval is routinely used in angler surveys to measure the uncertainty associated with an estimator (Pollock et al. 1994). However, its quality has rarely been evaluated. In this study, we used the actual coverage probability of the asymptotic 95% CI to assess the quality of the CI. The coverage probability was calculated as the percentage of 95% CIs that included μ. In repeated sampling, 95% of the CIs should contain the true value μ.

All the calculations were performed using R code (R Development Core Team 2012) developed by the first author (ZS). The source code is available upon request.

RESULTS

The effort estimator is theoretically unbiased (Lockwood et al. 1999). All the relative percent bias (RB) values of the effort estimates obtained from all simulation scenarios were less than 3.0% in absolute values, confirming that theoretical property. In the following, we only present the results for the catch estimates obtained from the multiple-day and daily catch estimators.

TABLE 4. Relative biases (RB; %) of the daily catch estimator for three levels of n_{days} under PART (the entire sampled fishing day is treated as a sampling period), when $R_d^{(2)}$ is $x = 0.3$, 0.5, or 0.8 of the morning or afternoon mean catch rate (DIFF: $R_d^{(2)} = xR_d^{(1)} = xR_d^{(3)}$) and when the variation in T_d and R_d are both high ($S_R = 0.15$ and $\theta_T = 1.003$; see Table 1). All other conditions are the same as in Table 3. Values with |RB| > 5% are indicated with bold italics.

n_{days}	$x = 0.3$	$x = 0.5$	$x = 0.8$
10	***−15.3***	***−9.3***	−2.2
20	***−16.3***	***−8.3***	−2.2
30	***−15.8***	***−8.7***	−2.1

Bias

Effects of disproportional sampling of daily angler trips.—In this section, we examine the effect of three methods of selecting angler trips for interviewing (DISPROP, ALL, or FIXPROP) on the two estimators when the mean catch rate of the middle-day trips is the same as that of pure morning or afternoon trips (CONST).

As expected, the daily estimator was not affected by how angler trips were selected. The daily estimator produced total catch estimates with negligible relative bias values (<4% in absolute values) under all three methods of selecting angler trips (Tables 1, 2; Figure 3).

In contrast, the multiple-day estimator can be biased under disproportional sampling (DISPROP, corresponding to $n_{m\_\text{int}} \neq$ ALL; Tables 1, 2; Figure 3). In this case, the magnitude of the bias depends on the level of variation in both the number of daily angler trips T_d and daily catch rate R_d (Table 1). For populations with relatively high variation in both T_d and R_d, the multiple-day estimator was biased under DISPROP (Table 1; Figure 3). On the other hand, for populations with relative low variation in either T_d or R_d or both, the multiple-day estimator produced catch estimates with negligible bias (Table 1).

Several patterns are noticed regarding the bias in the multiple-day estimator (Table 2; Figure 3). First, the bias in the multiple-day estimator decreases with increasing maximum number of interviews ($n_{\text{m\_int}}$) collected during each sampling period (Figure 3). When all exiting parties in a sampling period (ALL) were interviewed, the bias became negligible. Second, the bias generally increases with increasing correlation between T_d and R_d (Table 2). Third, the direction of the bias in the multiple-day estimator depends on the sign of the correlation

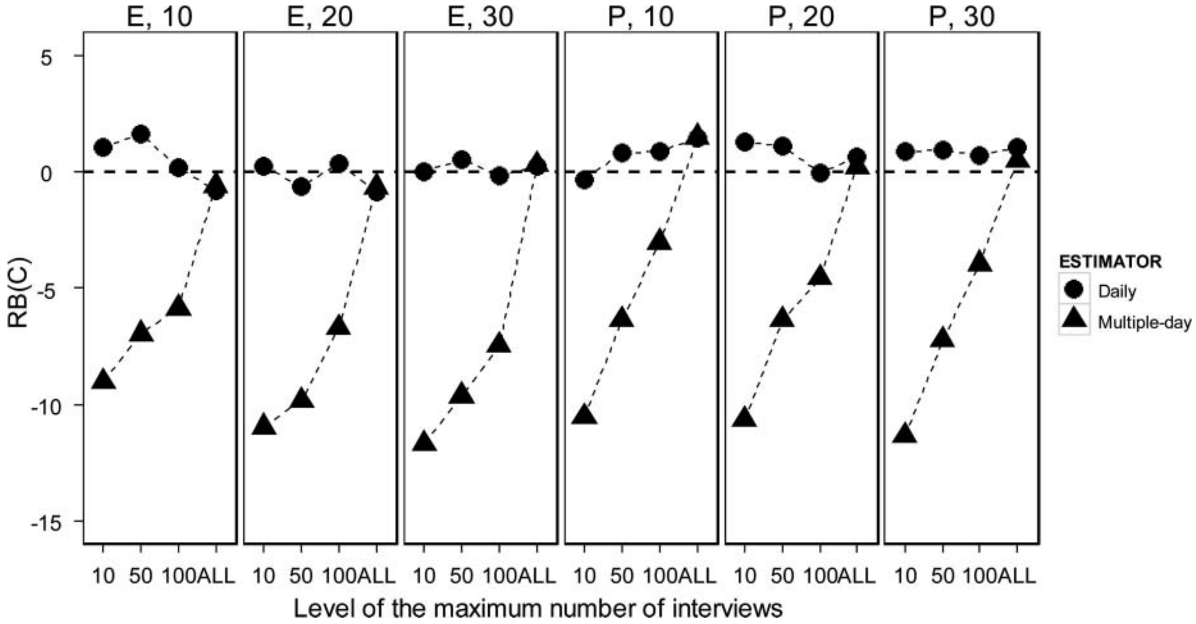

FIGURE 3. Relative biases (RB) of two catch estimators (daily and multiple-day) with constant time-period catch rates (CONST: $R_d^{(2)} = R_d^{(1)} = R_d^{(3)}$) and disproportional sampling (DISPROP) or complete sampling (ALL) of angler trips, when the variation in T_d and R_d are both high ($S_R = 0.15$ and $\theta_T = 1.003$), for two situations of fishing-day subsampling (E or P), three levels of the number of days sampled (n_{days}: 10, 20, 30) and four levels of the maximum number of interviews collected each day ($n_{\text{m\_int}}$: 10, 50, 100, ALL), given that the mean level of daily angler trips is $\bar{T} = 200$, median of daily catch rates is $\bar{R} = 0.3$, the regression coefficient is $\beta_1 = 200$, and the number of counts is $n_{\text{cnt}} = 2$. A day part (P; morning or afternoon) is sampled from a sampled fishing day (PART); the entire sampled fishing day (E) is treated as a sampling period (ENTIRE).

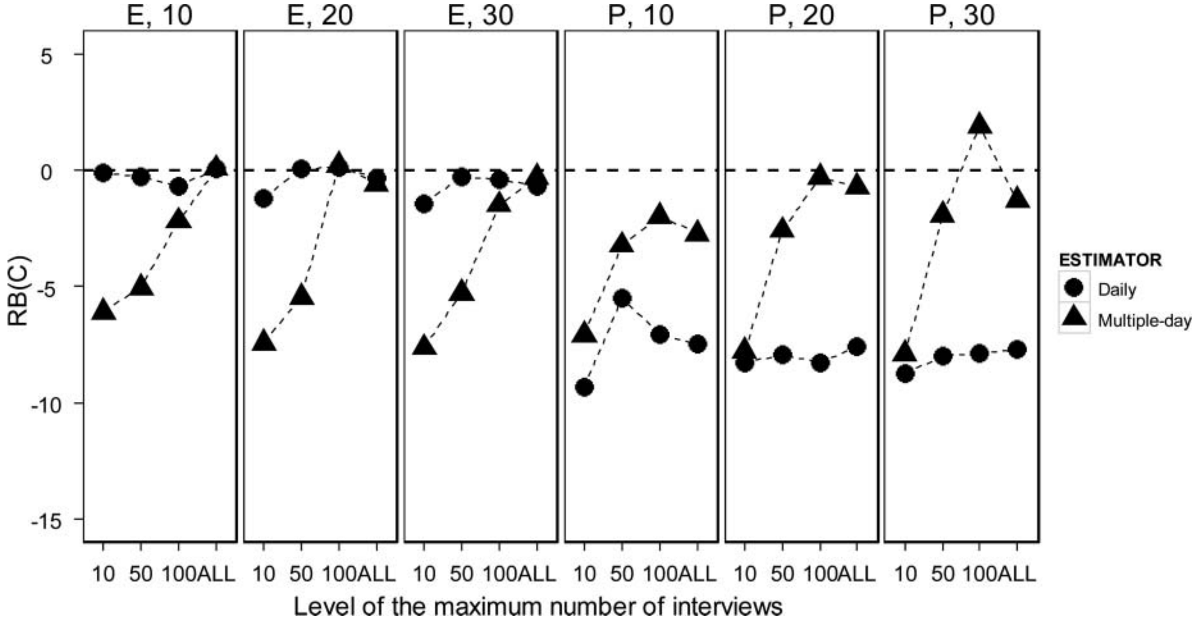

FIGURE 4. Relative biases (RB) of two catch estimators (daily and multiple-day) with disproportional sampling (DISPROP) or complete sampling (ALL) of angler trips when the middle-day mean catch rate $R_d^{(2)}$ is one-half of the morning or afternoon mean catch rate (DIFF:$R_d^{(2)} = 0.5R_d^{(1)} = 0.5R_d^{(3)}$), and when the variation in T_d and R_d are both high ($S_R = 0.15$ and and $\theta_T = 1.003$), for two situations of fishing-day subsampling (E or P), three levels of the number of days sampled (n_{days}: 10, 20, 30) and four levels of the maximum number of interviews collected each day ($n_{\text{m\_int}}$: 10, 50, 100, ALL), given that $\bar{T} = 200$, $\bar{R} = 0.3$, $\beta_1 = 200$, and $n_{\text{cnt}} = 2$. See Figure 3 caption for additional description.

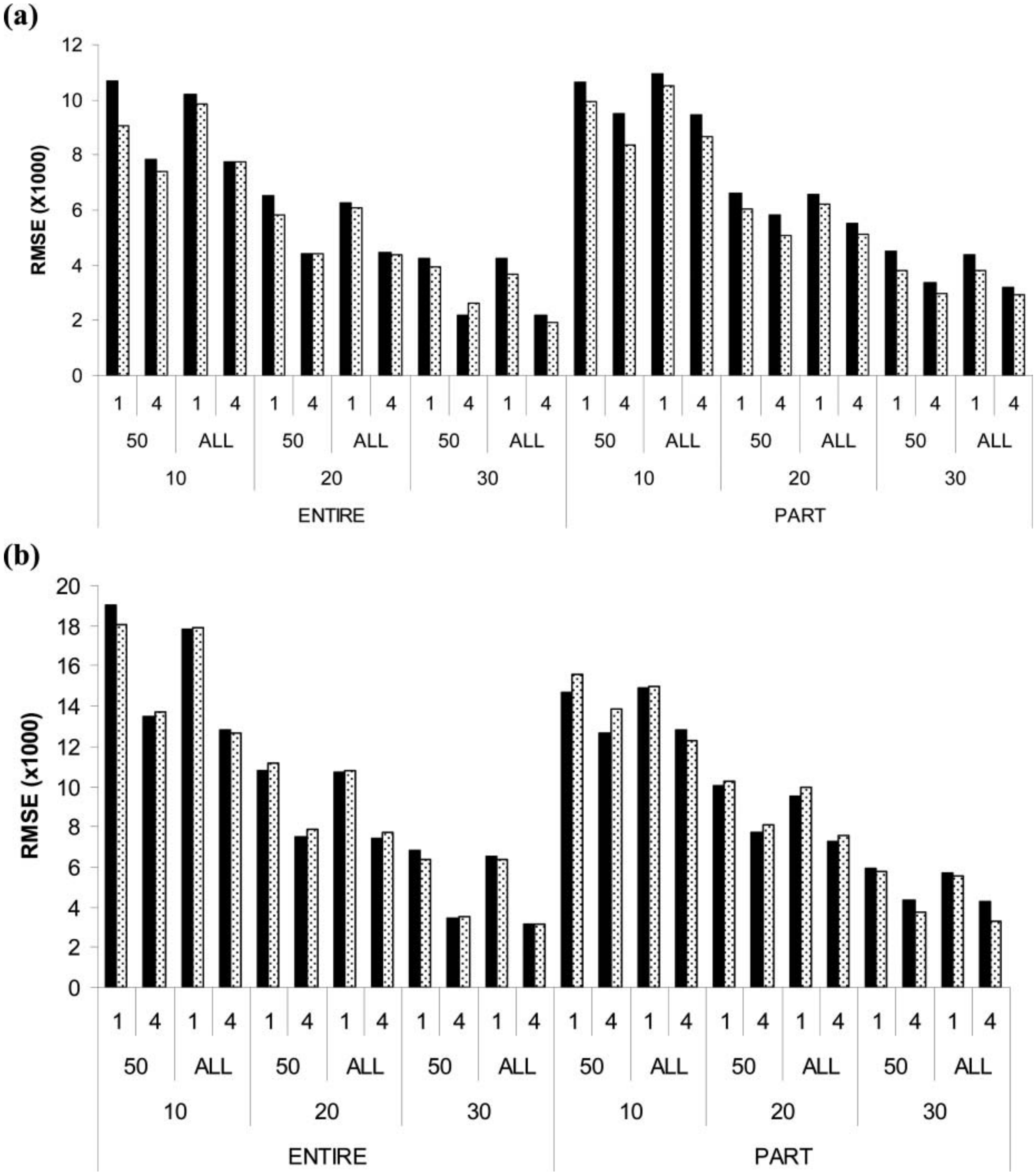

FIGURE 5. Root mean square error (RMSE) of two catch estimators (daily and multiple-day) with disproportional sampling (DISPROP) or complete sampling (ALL) of angler trips, when the variation in T_d and R_d are both high ($S_R = 0.15$ and $\theta_T = 1.003$), for two levels of number of counts (1, 4), two levels of maximum number of interviews collected each day (50, ALL), three levels of the number of days sampled (10, 20, 30), and two situations of fishing-day subsampling (ENTIRE or PART), given that $\bar{T} = 200$, $\bar{R} = 0.3$, and $\beta_1 = 200$ (see Figure 3). Black bars are the daily estimator and dotted bars are the multiple-day estimator for both scenarios displayed: **(a)** Constant daily time-period catch rates (CONST), and **(b)** variable daily time-period catch rates (DIFF).

between T_d and R_d. Positive correlations between T_d and R_d lead to negative bias, whereas negative correlations lead to positive bias (Table 2). Fourth, the mean level of T_d, $\bar{T}$, has little effect on the magnitude of the bias in the multiple-day estimator (Table 2).

Taking a fixed proportion (1/3; FIXPROP) of interviews each shift can alleviate the bias in the multiple-day estimator. For example, the RBs of total catch estimates from the multiple-day estimator from FIXPROP are −0.8% and −0.4% for PART (the sampled fishing day is subsampled) and ENTIRE (the fishing day is not subsampled; Table 2, row *a*), respectively, compared with those from DISPROP (−11.0% and −11.0%; Table 2, third row; $T = 200$, Corr = 0.36, multiple day).

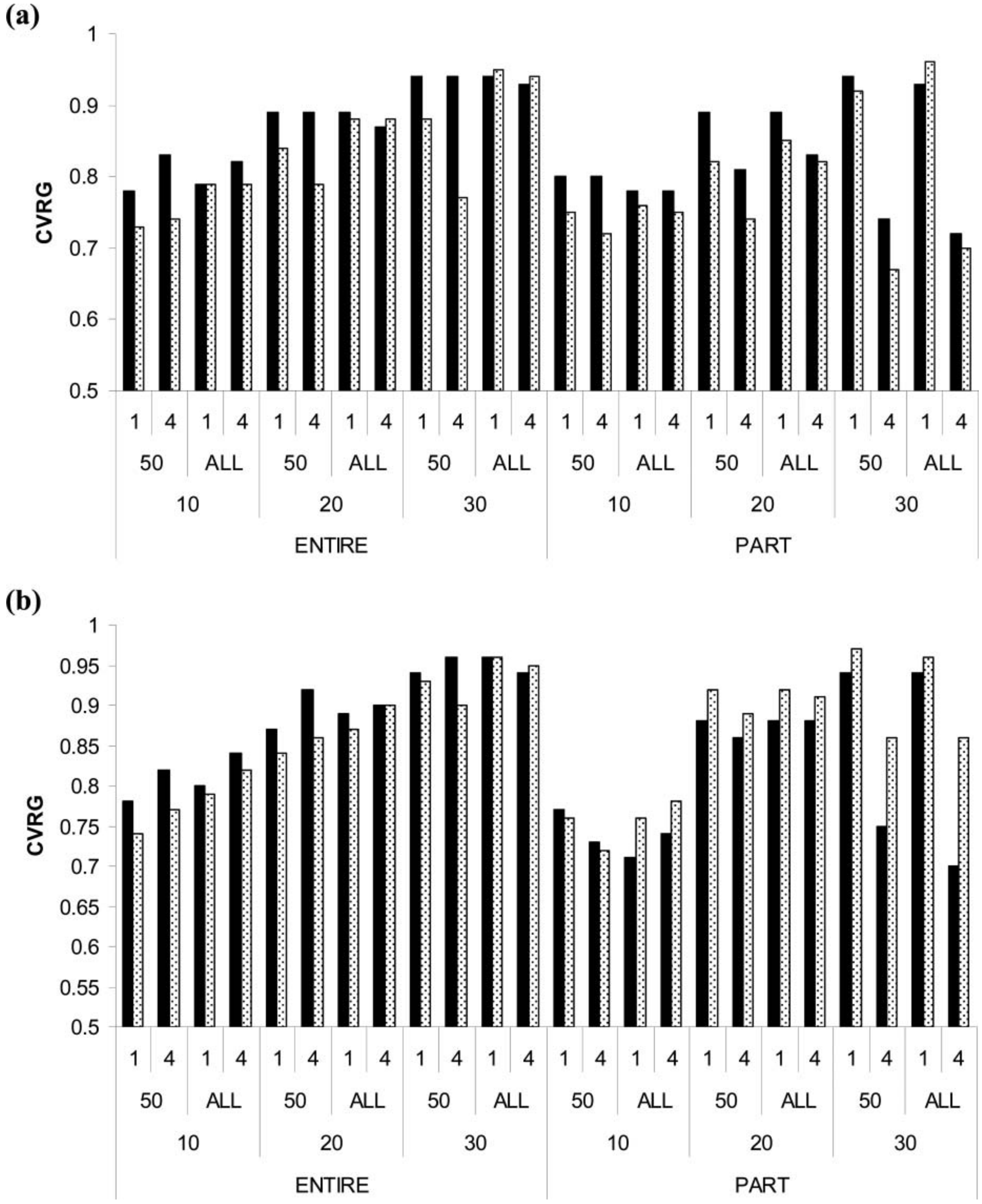

FIGURE 6. Coverage (CVRG) probability of the asymptotic 95% confidence interval of two catch estimators (daily and multiple-day) under the same conditions as in Figure 5. Black bars are the daily estimator and dotted bars are the multiple-day estimator for both scenarios displayed: **(a)** constant daily time-period catch rates (CONST), and **(b)** variable daily time-period catch rates (DIFF).

Effects of subsampling fishing days under variable daily time-period catch rates.—When the mean catch rate of the middle-day trips of each day, $R_d^{(2)}$, differs from that of the morning or afternoon trips (DIFF), subsampling the sampled fishing day (PART) can cause bias in the daily estimator (Table 3; Figure 4). On the other hand, when the fishing day is not subsampled and is treated as an entire sampling period (ENTIRE), the daily estimator has little bias (Table 3; Figure 4).

The direction and magnitude of the bias in the daily estimator are determined by how $R_d^{(2)}$ differs from $R_d^{(1)}$ and $R_d^{(3)}$; an $R_d^{(2)}$ lower than $R_d^{(1)}$ and $R_d^{(3)}$ results in negative bias (Table 3; Figure 4), whereas a $R_d^{(2)}$ higher than $R_d^{(1)}$ and $R_d^{(3)}$ results in positive bias (6.2% and 1.2%; Table 3, row *a*). The magnitude of the bias in the daily estimator increases as the difference between the middle-day catch rate $R_d^{(2)}$ and other two rates increases (Table 4). The bias is not affected by the way in which interviews were collected and does not vanish under either ALL (Figure 4) or FIXPROP.

The multiple-day estimator is less affected by fishing-day subsampling (PART) and variable daily time-period catch rates (DIFF; Table 3). However, it is still subject to bias caused by disproportional sampling (DISPROP) of daily angler trips under the conditions identified in the previous section (i.e., large variation in both T_d and R_d and high correlation between them; Table 3; Figure 4).

Efficiency, Coverage, and Sample Size

The number of days sampled (n_{days}) has a large effect on the root mean square error (RMSE) of both estimators (Figure 5). Increasing n_{days} can lower the RMSE substantially. Increasing the number of counts (n_{cnt}) can also reduce the RMSE to some extent. In contrast, the maximum number of interviews ($n_{\text{m\_int}}$) collected has less effect on the RMSE. With constant daily time-period catch rates (CONST), the multiple-day estimator is slightly more efficient (lower RMSE) than the daily estimator in most cases (Figure 5a). However, with variable daily time-period catch rates (DIFF), the multiple-day estimator is less efficient than the daily estimator when the sampled fishing day was subsampled (PART) and $n_{\text{days}} < 30$ (Figure 5b).

The daily estimator has better coverage probability (CVRG) than the multiple-day estimator in most cases with CONST (Figure 6a), and with DIFF at ENTIRE (Figure 6b). Overall, the CVRG of both estimators is poor when $n_{\text{days}} = 10$ (Figure 6). Additionally, with PART, $n_{\text{days}} = 30$ and $n_{\text{cnt}} = 4$, the actual CVRGs of both estimators were around 70%, well under the nominal value of 95% (Figure 6). This may be caused partially by the uneven distribution of entry times (Figure 1). For a fishery with a uniform entry distribution, the actual CVRG's of both estimators are much better than those from the uneven distribution (Table 5). The uneven entry distribution led to larger underestimates of estimated standard errors of effort and catch, which in turn caused under-coverage of their CIs (Table 5).

DISCUSSION

In this study, we developed an angler survey simulation and evaluation framework and used it to evaluate the effects of two potential sources of bias (disproportional sampling and subsampling of the fishing day) on two stratum catch estimators under an extensive range of population and sampling scenarios. We found that neither estimator was uniformly better than the other one. The multiple-day estimator is prone to bias caused by disproportional sampling of daily angler trips, whereas the daily estimator is biased when the fishing day is subsampled and when the mean catch rate of the middle-day trips of each fishing day differs from those of two other time periods. We also found that the coverage probability of the asymptotic 95% CI of both estimators was poor when the number of days sampled was low and fishing days were subsampled (PART).

To overcome the bias of the multiple-day estimator caused by disproportional sampling of daily angler trips, a self-weighting sampling scheme is needed. For the multistage sampling design used in Michigan and most creel surveys elsewhere, self-weighting can only be accomplished by sampling all or a fixed proportion of angler trips from every sampled day in a stratum because fishing days and shifts are selected with equal probability. A fixed proportion of angler trips from each day may be obtained by systematically sampling, say every third angler party in a day, as demonstrated in this paper. However, proportional sampling may be highly impractical for fisheries with multiple access sites. Additionally, fewer interviews would be obtained than when no such requirement is imposed, and that would affect the precision of catch estimates.

An inherent problem associated with subsampling the fishing day is that middle-day trips that span both the morning and afternoon periods in a day are inaccessible for interviewing but may be counted if the morning period is selected for sampling, whereas they can be both counted and interviewed if the afternoon period is selected. As a result, middle-day trip information is not available for calculating daily catch rates by the daily estimator for days with the morning shift selected. This will cause biased daily catch estimates ($\hat{C}_d$) for those days when the morning and middle-day trips differ in their mean catch rates. On the other hand, for days with the afternoon shift selected, the daily catch estimates ($\hat{C}_d$) can also be biased because the middle-day and afternoon trips are not weighted properly when calculating the daily catch rates. The biased daily estimates in either case can cause biased stratum catch estimates ($\hat{C}$) for the daily estimator. In contrast, when the fishing day is subsampled, the multiple-day estimator makes use of the catch rate information from all sampled days to calculate a single value of catch rate. Therefore, the multiple-day catch estimator may be more resistant to the effect of varying catch rates in different time periods of the fishing day than the daily estimator.

There is no easy way to correct the bias in the daily estimator caused by varying daily time-period catch rates when the fishing day is subsampled. For critical surveys, additional sampling effort should be added to survey the entire fishing period of each

TABLE 5. Comparison of coverage probability of the asymptotic 95% confidence interval of total effort (CVRG(E)) and two catch estimators (CVRG(C)) under a uniform starting time distribution (Uniform) or an uneven starting time distribution (Uneven) used as default in other scenarios (Figure 1) with constant within-day time-period catch rates CONST ($R_d^{(2)} = R_d^{(1)} = R_d^{(3)}$) and disproportionate sampling DISPROP, where variation in T_d and R_d are both high ($S_R = 0.15$ and $\theta_T = 1.003$), for two situations of fishing-day subsampling (ENTIRE or PART), given $\bar{T} = 200$, $\bar{R} = 0.3$, $n_{\text{days}} = 10$, $n_{\text{m\_int}} = 10$, and $n_{\text{cnt}} = 2$ (see Table 1). The ratio of the average of estimated standard errors (ESE) to the average of standard errors (SE $= \sqrt{V(\hat{\mu})}$) is across 3,000 samples.

	Uniform			Uneven		
Estimator	ESE/SE	CVRG(E)	CVRG(C)	ESE/SE	CVRG(E)	CVRG(C)
Daily						
PART	0.99	0.93	0.93	***0.65***	***0.76***	***0.76***
ENTIRE	1.01	0.93	0.94	0.97	0.90	0.91
Multiple						
PART	0.99	0.93	0.87	***0.66***	***0.76***	***0.77***
ENTIRE	1.01	0.92	0.92	0.97	0.91	0.92

sampled day. Bernard et al. (1998) demonstrated that the daily estimator could produce biased harvest estimates for migratory fish population fisheries that might exhibit dramatic short-term temporal trends in harvest rates when fishing days were subsampled. They also suggested setting the sampling period equal to the fishing day to avoid such a bias.

Rasmussen et al. (1998) studied several catch estimators using simulations based on complete creel census data of a small inland lake with only one access point, and evaluated the effect of varying harvest rates among daily time periods on the estimators. However, they did not consider the effect of disproportional sampling on their estimators. They found their daily estimator was biased and a "stratum" estimator, which is the same as our multiple-day estimator, was not biased in this case. We obtained similar results in the case where all exiting angler parties were interviewed. However, we also found that the multiple-day estimator was prone to bias caused by disproportional sampling when only a portion of exiting angler parties was interviewed. Therefore, the conclusions made by Rasmussen et al. (1998) did not apply to cases where sampling rate of angler trips varies widely among days.

For aerial surveys and inland creel surveys in Michigan, one count is usually made per shift to reduce survey cost. In this case, the variance estimator given in equation (7) used for the daily estimator is not applicable for such surveys. As a result, only the multiple-day estimator has been used to make estimates for the related fisheries (Lockwood et al. 1999). In our study, using an alternative variance estimator for stratum catch estimates (equation 8) allowed the daily estimator to be applied to make estimates for these fisheries as well.

We assumed that counts were taken at randomly selected times during each sampling period (i.e., shift was either a day part or a day) and that sampling over the multiple-day period covered the length of the fishing days (here, 18 h). Under these assumptions, the effort estimator was unbiased. However, if sampling cannot cover the length of the fishing days (e.g., starting a morning shift at 0600 hour rather than 0400 hours), biased effort estimates may result.

In summary, because of these complicated results, it is difficult for us to make general recommendations for choosing either the multiple-day or the daily estimator. Nevertheless, for critical fisheries we recommend surveying the entire fishing period of each sampled fishing day and using the daily estimator to make catch estimates. Fixed proportional sampling of angler trips coupled with the multiple-day estimator may be used as an alternative survey approach to obtain less biased catch estimates for one-access-site fisheries. Additionally, to obtain sound catch estimates, a certain number of sampled days should be guaranteed (say >5 d a month). Furthermore, both estimators can be used to make catch estimates for a survey, and any large discrepancies in their results would be indicative of issues in survey design or underlying fisheries characteristics, which should be examined.

Our results show that the performance of the two estimators is affected in some complicated ways by both angler population and sampling design characteristics. Therefore, we advocate the use of simulation experiments as a cost-effective way to evaluate angler survey sampling when analytical guidelines are not available.

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